Material	K (Dielectric constant)
Air	1.0
Resin	2.5
Asbestos paper	2.7
Hard rubber	2.8
Dry paper	3.5
Isolantite	3.5
Common glass	4.2
Quartz	4.5
Mica	4.5–7.5
Porcelain	5.5
Flint glass	7.0
Crown glass	7.9

FIGURE 8–178. Dielectric constants.

alternating current is impressed on the circuit (figure 8–179), the charge on the plates constantly changes. This means that electricity must flow first from *Y* clockwise around to *X*, then from *X* counterclockwise around to *Y*, then from *Y* clockwise around to *X*, and so on. Although no current flows through the insulator between the plates of the capacitor, it constantly flows in the remainder of the circuit between *X* and *Y*. In a circuit in which there is only capacitance, current leads the impressed voltage as contrasted with a circuit in which there is inductance, where the current lags the voltage.

The unit of measurement of capacitance is the farad, for which the symbol is the letter "f." The farad is too large for practical use, and the units generally used are the microfarad (μf.), one millionth of a farad, and the micromicrofarad (μμf.), one millionth of a microfarad.

Types of Capacitors

Capacitors may be divided into two groups: fixed and variable. The fixed capacitors, which have approximately constant capacitance, may then be further divided, according to the type of dielectric used, into the following classes: paper, oil, mica, and electrolytic capacitors. Ceramic capacitors are also used in some circuits.

When connecting electrolytic capacitors in a circuit, the proper polarity *must* be observed. Paper capacitors may have one terminal marked "ground," which means that this terminal connects to the outside foil. Polarity does not ordinarily have to be observed in connecting paper, oil, mica, or ceramic capacitors.

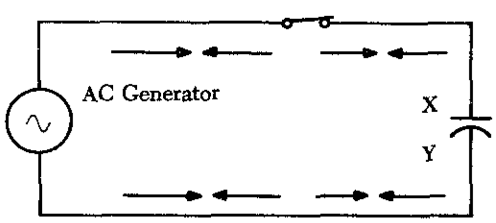


FIGURE 8–179. Capacitor in an a.c. circuit.

Paper Capacitors

The plates of paper capacitors are strips of metal foil separated by waxed paper (figure 8–180). The capacitance of paper capacitors ranges from about 200 μμf. to several μf. The strips of foil and paper are rolled together to form a cylindrical cartridge, which is then sealed in wax to keep out moisture and to prevent corrosion and leakage. Two metal leads are soldered to the plates, one extending from each end of the cylinder. The assembly is enclosed either in a cardboard cover or in a hard, molded plastic covering.

Bathtub-type capacitors consist of paper-capacitor cartridges hermetically sealed in metal containers. The container often serves as a common terminal for several enclosed capacitors, but when not a terminal, the cover serves as a shield against electrical interference (figure 8–181).

Oil Capacitors

In radio and radar transmitters, voltages high enough to cause arcing, or breakdown, of paper dielectrics are often employed. Consequently, in these applications capacitors that use oil or oil-impregnated paper for the dielectric material are preferred. Capacitors of this type are considerably more expensive than ordinary paper capacitors, and their use is generally restricted to radio and radar transmitting equipment (figure 8–182).

Mica Capacitors

The fixed mica capacitor is made of metal foil plates that are separated by sheets of mica, which form the dielectric. The whole assembly is covered in molded plastic, which keeps out moisture. Mica is an excellent dielectric and will withstand higher voltages than paper without allowing arcing between the plates. Common values of mica

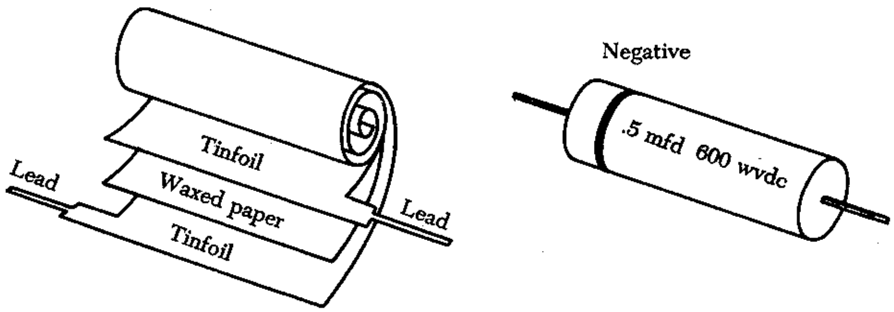


FIGURE 8–180. Paper capacitors.

capacitors range from approximately 50 $\mu\mu f$, to about 0.02 μf. Mica capacitors are shown in figure 8–183.

Electrolytic Capacitors

For capacitances greater than a few microfarads, the plate areas of paper or mica capacitors must become very large; thus, electrolytic capacitors are usually employed instead. These units provide large capacitance in small physical sizes. Their values range from 1 to about 1,500 microfarads. Unlike the other types, electrolytic capacitors are generally polarized, and should be subjected to direct voltage, or pulsating direct voltage only; however, a special type of electrolytic capacitor is made for use in motors.

The electrolytic capacitor is widely used in electronic circuits and consists of two metal plates separated by an electrolyte. The electrolyte in contact with the negative terminal, either in paste or liquid form, comprises the negative electrode. The dielectric is an exceedingly thin film of oxide deposited on the positive electrode of the capacitor. The positive electrode, which is an aluminum sheet, is folded to achieve maximum area. The capacitor is subjected to a forming process during manufacture, in which current is passed through it. The flow of current results in the deposit of the thin coating of oxide on the aluminum plate.

The close spacing of the negative and positive electrodes gives rise to the comparatively high capacitance value, but allows greater possibility of voltage breakdown and leakage of electrons from one electrode to the other.

Two kinds of electrolytic capacitors are in use: (1) Wet-electrolytic and (2) dry-electrolytic capacitors. In the former, the electrolyte is a liquid and the container must be leakproof. This type should always be mounted in a vertical position.

The electrolyte of the dry-electrolytic unit is a paste contained in a separator made of an absorbent material such as gauze or paper. The separator not only holds the electrolyte in place but also prevents short-circuiting the plates. Dry-electrolytic capacitors are made in both cylindrical and rectangular-block form and may be contained either within cardboard or metal covers. Since the electrolyte cannot spill, the dry capacitor may be mounted in any convenient position. Electrolytic capacitors are shown in figure 8–184.

Capacitors in Parallel and in Series

Capacitors may be combined in parallel or series to give equivalent values, which may be either the

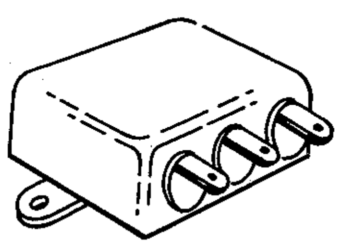


FIGURE 8–181. Bathtub-case paper capacitor.

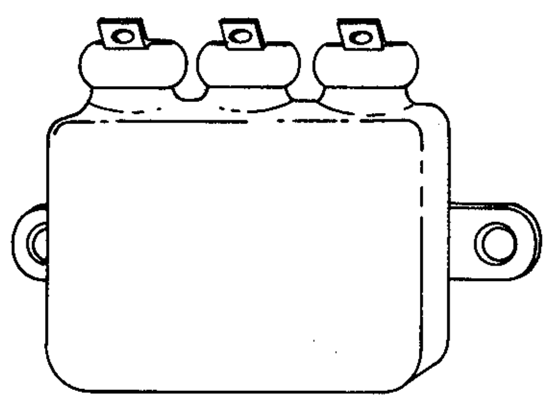


FIGURE 8–182. Oil capacitor.

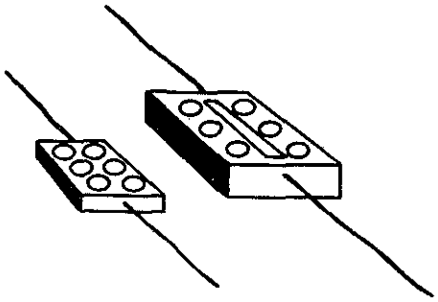


FIGURE 8–183. Mica capacitors.

sum of the individual values (in parallel) or a value less than that of the smallest capacitance (in series). Figure 8–185 shows the parallel and series connections.

Two units used in the measurement of capacitance are the farad and the coulomb. As previously defined, the farad is the amount of capacitance present in a capacitor when one coulomb of electrical energy is stored on the plates and one volt is applied across the capacitor. One coulomb is the electrical charge of 6.28 billion billion electrons. From this it can be seen that

$$C \text{ (in farads)} = \frac{Q \text{ (in coulombs)}}{E \text{ (in volts)}}.$$

In *A* of figure 8–185 the voltage, E, is the same for all the capacitors. The total charge, Q_t, is the sum of all the individual charges, Q_1, Q_2, and Q_3.

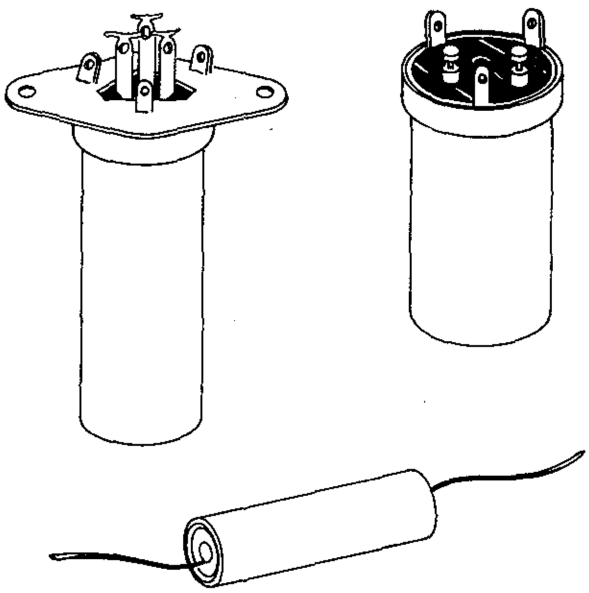
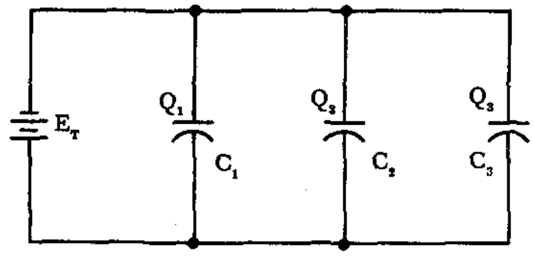
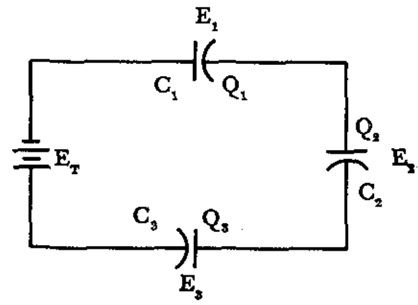


FIGURE 8–184. Electrolytic capacitors.



$C_t + C_1 + C_2 + C_3$

A Parallel



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

B Series

FIGURE 8–185. Capacitors in parallel and in series.

Using the basic equation for the capacitor,

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

The total charge is $Q_t = C_tE$, where C_t is the total capacitance. Since the total charge on capacitors in parallel is the sum of the individual capacitor charges,

$$Q_t = Q_1 + Q_2 + Q_3.$$

Using both equations for total charge develops the equation

$$C_tE = C_1E + C_2E + C_3E.$$

Dividing both sides of this equation by E gives

$$C_t = C_1 + C_2 + C_3.$$

This formula is used to determine the total capacitance of any number of capacitors in parallel.

In the series arrangement, (*B* of figure 8–185), the current is the same in all parts of the circuit.

Each capacitor develops a voltage during charge, and the sum of the voltages of all the capacitors must equal the applied voltage, E. By the capacitor equation, the applied voltage, E, is equal to the total charge divided by the total capacitance, or

$$E = \frac{Q_t}{C_t}.$$

The total charge, Q_t, is equal to the charge on any one of the capacitors because the same current flows in all for the same length of time, and because the charge equals current multiplied by time in seconds ($Q_t = I \times T$). Therefore,

$$Q_t = Q_1 = Q_2 = Q_3\,,$$

and, since in a circuit with capacitors in series

$$E_t = E_1 + E_2 + E_3\,,$$

where E_1, E_2, and E_3 are the voltages of the three capacitors. Then

$$\frac{Q_t}{C_t} = \frac{Q_t}{C_1} + \frac{Q_t}{C_2} + \frac{Q_t}{C_3}.$$

Dividing both sides of the equation by Q_t gives

$$\frac{1}{C_t} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}.$$

The reciprocal of the total capacitance of any number of capacitors in series is equal to the sum of the reciprocals of the individual values.

Parallel capacitors combine by a rule similar to that used to combine resistors in series. Series capacitors combine by a rule similar to that for combining parallel resistors.

In the series arrangement of two capacitors, C_1 and C_2, the total capacitance is given by the equation:

$$C_t = \frac{C_1 \times C_2}{C_1 + C_2}.$$

Voltage Rating of Capacitors

In selecting or substituting a capacitor for use in a particular circuit, the following must be considered: (1) The value of capacitance desired and (2) the amount of voltage to which the capacitor is to be subjected. If the voltage applied across the plates is too great, the dielectric will break down and arcing will occur between the plates. The capacitor is then short-circuited, and the possible flow of direct current through it can cause damage to other parts of the equipment. Capacitors have a voltage rating that should not be exceeded.

Dielectric	K	Dielectric Strength (volts per .001 inch)
Air	1.0	80
Paper		
(1) Paraffined	2.2	1,200
(2) Beeswaxed	3.1	1,800
Glass	4.2	200
Castor oil	4.7	380
Bakelite	6.0	500
Mica	6.0	2,000
Fiber	6.5	50

FIGURE 8–186. Strength of some dielectric materials.

The working voltage of the capacitor is the maximum voltage that can be steadily applied without danger of arc-over. The working voltage depends on (1) the type of material used as the dielectric and (2) the thickness of the dielectric.

The voltage rating of the capacitor is a factor in determining the capacitance because capacitance decreases as the thickness of the dielectric increases. A high-voltage capacitor that has a thick dielectric must have a larger plate area in order to have the same capacitance as a similar low-voltage capacitor having a thin dielectric. The strength of some commonly used dielectric materials is listed in figure 8–186. The voltage rating also depends on frequency because the losses, and the resultant heating effect, increase as the frequency increases.

A capacitor that can be safely charged to 500 volts d.c. cannot be safely subjected to a.c. or pulsating d.c. whose effective values are 500 volts. An alternating voltage of 500 volts (r.m.s.) has a peak voltage of 707 volts, and a capacitor to which it is applied should have a working voltage of at least 750 volts. The capacitor should be selected so that its working voltage is at least 50 percent greater than the highest voltage to be applied to it.

Capacitance Reactance

Capacitance, like inductance, offers opposition to the flow of current. This opposition is called capacitive reactance and is measured in ohms. The symbol for capacitive reactance is X_c. The equation,

$$\text{Current} = \frac{\text{Voltage}}{\text{Capacitive reactance}}, \text{ or}$$

$$I = \frac{E}{X_c},$$

is similar to Ohm's law and the equation for current in an inductive circuit. The greater the frequency, the less the reactance. Hence, the capacitive reactance,

$$X = \frac{1}{2\pi \times f \times C}$$

where: f = frequency in c.p.s.
C = capacity in farads.
2π = 6.28.

Problem:

A series circuit is assumed in which the impressed voltage is 110 volts at 60 c.p.s., and the capacitance of a condenser is 80 μf. Find the capacitive reactance and the current flow.

Solution:

To find capacitive reactance, the equation $X_c = \frac{1}{2\pi fC}$ is used. First, the capacitance, 80 μf., is changed to farads by dividing 80 by 1,000,000, since 1 million microfarads is equal to 1 farad. This quotient equals .000080 farad. This is substituted in the equation and

$$X_c = \frac{1}{6.28 \times 60 \times .000080}$$

$$X_c = 33.2 \text{ ohms reactance.}$$

Find the current flow:

$$I = \frac{E}{X_c}$$

$$I = \frac{110}{33.2}$$

$$I = 3.31 \text{ amperes.}$$

Capacitive Reactances in Series and in Parallel

When capacitors are connected in series, the total reactance is equal to the sum of the individual reactances. Thus,

$$X_{ct} = (X_c)_1 + (X_c)_2.$$

The total reactance of capacitors connected in parallel is found in the same way total resistance is computed in a parallel circuit:

$$(X_c)_t = \frac{1}{\frac{1}{(X_c)_1} + \frac{1}{(X_c)_2} + \frac{1}{(X_c)_3}}.$$

Phase of Current and Voltage in Reactive Circuits

When current and voltage pass through zero and reach maximum value at the same time, the current and voltage are said to be in phase (*A* of figure 8–187). If the current and voltage pass through zero and reach the maximum values at different times, the current and voltage are said to be out of phase. In a circuit containing only inductance, the current reaches a maximum value later than the voltage, lagging the voltage by 90°, or one-fourth cycle (*B* of figure 8–187). In a circuit containing only capacitance, the current reaches its maximum value ahead of the voltage and the current leads the voltage by 90°, or one-fourth cycle (*C* of figure 8–187). The amount the current lags or leads the voltage in a circuit depends on the relative amounts of resistance, inductance, and capacitance in the circuit.

OHM'S LAW FOR A. C. CIRCUITS

The rules and equations for d.c. circuits apply to a.c. circuits only when the circuits contain resistance alone, as in the case of lamps and heating elements. In order to use effective values of voltage and current in a.c. circuits, the effect of inductance and capacitance with resistance must be considered.

The combined effect of resistance, inductive reactance, and capacitive reactance makes up the total opposition to current flow in an a.c. circuit. This total opposition is called impedance and is represented by the letter "*Z*." The unit for the measurement of impedance is the ohm.

Series A. C. Circuits

If an a.c. circuit consists of resistance only, the value of the impedance is the same as the

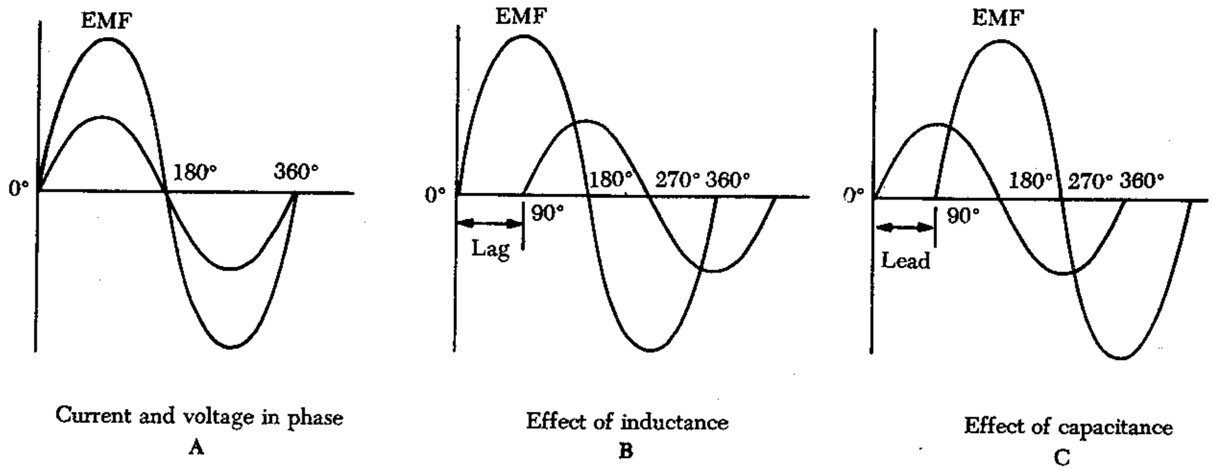


FIGURE 8–187. Phase of current and voltage.

resistance, and Ohm's law for an a.c. circuit, $I = \frac{E}{Z}$, is exactly the same as for a d.c. circuit. In figure 8–188 a series circuit containing a lamp with 11 ohms resistance connected across a source is illustrated. To find how much current will flow if 110 volts d.c. are applied and how much current will flow if 110 volts a.c. are applied, the following examples are solved:

$$I = \frac{E}{R} \qquad\qquad I = \frac{E}{Z} \text{ (where } Z = R\text{)}$$

$$= \frac{110V}{11\Omega} \qquad\qquad = \frac{110V}{11\Omega}$$

$$= 10 \text{ amperes d.c.} \qquad\qquad = 10 \text{ amperes a.c.}$$

When a.c. circuits contain resistance and either inductance or capacitance, the impedance, Z, is not the same as the resistance, R. The impedance of a circuit is the circuit's total opposition to the flow of current. In an a.c. circuit, this opposition consists of resistance and reactance, either inductive or capacitive, or elements of both.

Resistance and reactance cannot be added directly, but they can be considered as two forces acting at right angles to each other. Thus, the relation between resistance, reactance, and impedance may be illustrated by a right triangle, as shown in figure 8–189.

Since these quantities may be related to the sides of a right triangle, the formula for finding the impedance, or total opposition to current flow in an a.c. circuit, can be found by using the law of right triangles. This theorem, called the Pythagorean theorem, applies to any right triangle. It states that the square of the hypotenuse is equal to the sum of the squares of the other two sides. Thus, the value of any side of a right triangle can be found if the other two sides are known. If an a.c. circuit contains resistance and inductance, as shown in figure 8–190, the relation between the sides can be stated as:

$$Z^2 = R^2 + X_L^2.$$

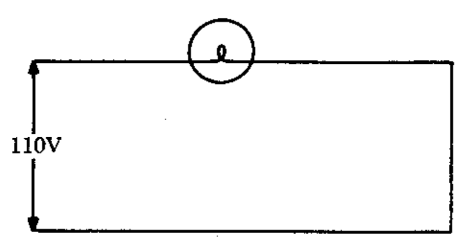


FIGURE 8–188. Applying d.c. and a.c. to a circuit.

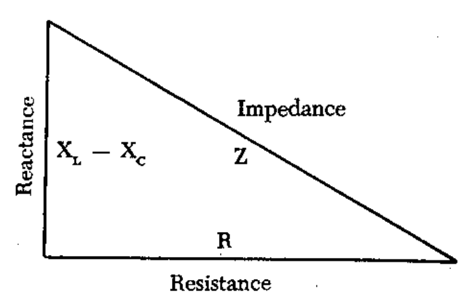


FIGURE 8–189. Impedance triangle.

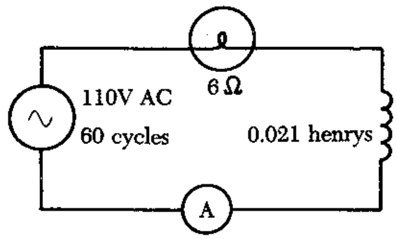


FIGURE 8–190. A circuit containing resistance and inductance.

The square root of both sides of the equation gives

$$Z = \sqrt{R^2 + X_L^2}.$$

This formula can be used to determine the impedance when the values of inductive reactance and resistance are known. It can be modified to solve for impedance in circuits containing capacitive reactance and resistance by substituting X_C in the formula in place of X_L. In circuits containing resistance with both inductive and capacitive reactance, the reactances can be combined, but because their effects in the circuit are exactly opposite, they are combined by subtraction:

$X = X_L - X_C$ or $X = X_C - X_L$ (the smaller is always subtracted from the larger).

In figure 8–190, a series circuit consisting of resistance and inductance connected in series is connected to a source of 110 volts at 60 cycles per second. The resistive element is a lamp with 6 ohms resistance, and the inductive element is a coil with an inductance of 0.021 henry. What is the value of the impedance and the current through the lamp and the coil?

Solution:

First, the inductive reactance of the coil is computed:

$$X_L = 2\pi \times f \times L$$
$$X_L = 6.28 \times 60 \times 0.021$$
$$X_L = 8 \text{ ohms inductive reactance.}$$

Next, the total impedance is computed:

$$Z = \sqrt{R^2 + X_L^2}$$
$$Z = \sqrt{6^2 + 8^2}$$
$$Z = \sqrt{36 + 64}$$
$$Z = \sqrt{100}$$
$$Z = 10 \text{ ohms impedance.}$$

Then the current flow,

$$I = \frac{E}{Z}$$
$$I = \frac{110}{10}$$
$$I = 11 \text{ amperes current.}$$

The voltage drop across the resistance (E_R) is

$$E_R = I \times R$$
$$E_R = 11 \times 6 = 66 \text{ volts.}$$

The voltage drop across the inductance (E_{X_L}) is

$$E_{X_L} = I \times X_L$$
$$E_{X_L} = 11 \times 8 = 88 \text{ volts.}$$

The sum of the two voltages is greater than the impressed voltage. This results from the fact that the two voltages are out of phase and, as such, represent the maximum voltage. If the voltage in the circuit is measured by a voltmeter, it will be approximately 110 volts, the impressed voltage. This can be proved by the equation

$$E = \sqrt{(E_R)^2 + (E_{X_L})^2}$$
$$E = \sqrt{66^2 + 88^2}$$
$$E = \sqrt{4356 + 7744}$$
$$E = \sqrt{12100}$$
$$E = 110 \text{ volts.}$$

In figure 8–191, a series circuit is illustrated in which a capacitor of 200 μf. is connected in series with a 10-ohm lamp. What is the value of the impedance, the current flow, and the voltage drop across the lamp?

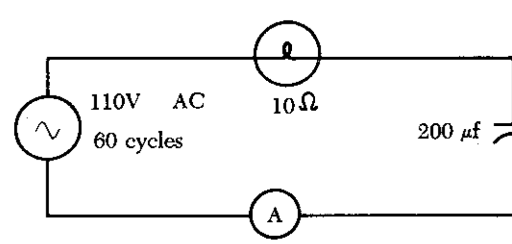


FIGURE 8–191. A circuit containing resistance and capacitance.

Solution:

First the capacitance is changed from μf. to farads. Since 1 million microfarads equal 1 farad, then

$$200\ \mu\text{f.} = \frac{200}{1{,}000{,}000} = .000200 \text{ farads.}$$

$$X_C = \frac{1}{2\pi f C}$$

$$X_C = \frac{1}{6.28 \times 60 \times .000200 \text{ farads}}$$

$$X_C = \frac{1}{.07536}$$

$$X_C = 13 \text{ ohms capacitive reactance.}$$

To find the impedance,

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

$$Z = \sqrt{10^2 + 13^2}$$

$$Z = \sqrt{100 + 169}$$

$$Z = \sqrt{269}$$

$$Z = 16.4 \text{ ohms capacitive reactance.}$$

To find the current,

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

$$I = \frac{110}{16.4}$$

$$I = 6.7 \text{ amperes.}$$

The voltage drop across the lamp (E_R) is

$$E_R = 6.7 \times 10$$

$$E_R = 67 \text{ volts.}$$

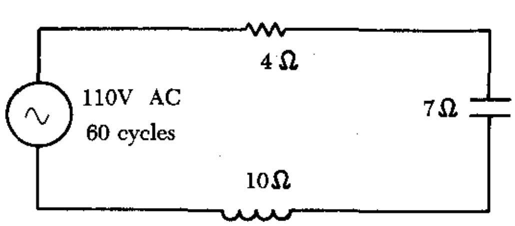


FIGURE 8–192. A circuit containing resistance, inductance, and capacitance.

The voltage drop across the capacitor (E_{X_C}) is

$$E_{X_C} = I \times X_C$$

$$E_{X_C} = 6.7 \times 13$$

$$E_{X_C} = 86.1 \text{ volts.}$$

The sum of these two voltages does not equal the applied voltage, since the current leads the voltage. To find the applied voltage, the formula $E_T = \sqrt{(E_R)^2 + (E_{X_C})^2}$ is used.

$$E_T = \sqrt{67^2 + 86.1^2}$$

$$E_T = \sqrt{4489 + 7413}$$

$$E_T = \sqrt{11902}$$

$$E_T = 110 \text{ volts.}$$

When the circuit contains resistance, inductance, and capacitance, the equation

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

is used to find the impedance.

Example:

What is the impedance of a series circuit (figure 8–192), consisting of a capacitor with a reactance of 7 ohms, an inductor with a reactance of 10 ohms, and a resistor with a resistance of 4 ohms?

Solution:

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

$$Z = \sqrt{4^2 + (10 - 7)^2}$$

$$Z = \sqrt{4^2 + 3^2}$$

$$Z = \sqrt{25}$$

$$Z = 5 \text{ ohms.}$$

Assuming that the reactance of the capacitor is 10 ohms and the reactance of the inductor is 7 ohms, then X_C is greater than X_L. Thus,

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

$$Z = \sqrt{4^2 + (7 - 10)^2}$$

$$Z = \sqrt{4^2 + (-3)^2}$$

$$Z = \sqrt{16 + 9}$$

$$Z = \sqrt{25}$$

$$Z = 5 \text{ ohms.}$$

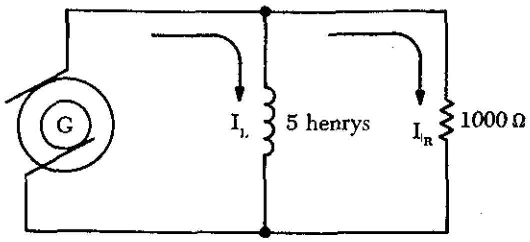


FIGURE 8–193. A.C. parallel circuit containing inductance and resistance.

Parallel A. C. Circuits

The methods used in solving parallel a.c. circuit problems are basically the same as those used for series a.c. circuits. Out-of-phase voltages and currents can be added by using the law of right triangles, but in solving circuit problems, the currents through the branches are added, since the voltage drops across the various branches are the same and are equal to the applied voltage. In figure 8–193, a parallel a.c. circuit containing an inductance and a resistance is shown schematically. The current flowing through the inductance, I_L, is 0.0584 ampere, and the current flowing through the resistance is 0.11 ampere. What is the total current in the circuit?

Solution:

$$I_T = \sqrt{I_L^2 + I_R^2}$$
$$= \sqrt{(0.0584)^2 + (0.11)^2}$$
$$= \sqrt{0.0155}$$
$$= 0.1245 \text{ ampere.}$$

Since inductive reactance causes voltage to lead the current, the total current, which contains a component of inductive current, lags the applied voltage. If the current and voltages are plotted, the angle between the two, called the phase angle, illustrates the amount the current lags the voltage.

In figure 8–194, a 110-volt generator is connected to a load consisting of a 2-μf. capacitance and a 10,000-ohm resistance in parallel. What is the value of the impedance and total current flow?

Solution:

First, find the capacitive reactance of the circuit:

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

Changing 2μf. to farads and entering the values into the formula given:

$$= \frac{1}{2 \times 3.14 \times 60 \times 0.000002}$$

$$= \frac{1}{0.00075360} \text{ or } \frac{10,000}{7.536}$$

$$= 1,327\Omega \text{ capacitive reactance.}$$

To find the impedance, the impedance formula used in a series a.c. circuit must be modified to fit the parallel circuit:

$$Z = \frac{RX_C}{\sqrt{R^2 + X_C^2}}$$

$$= \frac{10,000 \times 1327}{\sqrt{(10,000)^2 + (1327)^2}}$$

$$= 0.1315\Omega \text{ (approx.).}$$

To find the current through the capacitance:

$$I_C = \frac{E}{X_C}$$

$$= \frac{110}{1327}$$

$$= 0.0829 \text{ ampere.}$$

To find the current flowing through the resistance:

$$I_R = \frac{E}{R}$$

$$= \frac{110}{10,000}$$

$$= 0.011 \text{ ampere.}$$

To find the total current in the circuit:

$$I_T^2 = \sqrt{I_R^2 + I_C^2}$$

$$I_T = \sqrt{(0.011)^2 + (.0829)^2}$$

$$= 0.0836 \text{ ampere (approx.).}$$

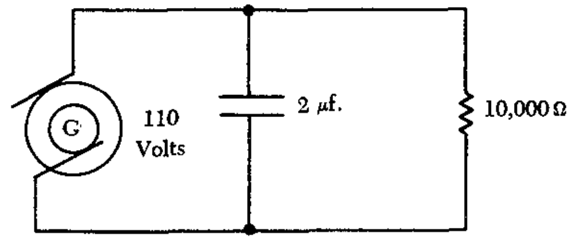


FIGURE 8–194. A parallel a.c. circuit containing capacitance and resistance.

Resonance

It has been shown that both inductive reactance ($X_L = 2\pi fL$) and capacitive reactance

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

are functions of an alternating current frequency. Decreasing the frequency decreases the ohmic value of the inductive reactance, but a decrease in frequency increases the capacitive reactance. At some particular frequency, known as the resonant frequency, the reactive effects of a capacitor and an inductor will be equal. Since these effects are the opposite of one another, they will cancel, leaving only the ohmic value of the resistance to oppose current flow in a circuit. If the value of resistance is small or consists only of the resistance in the conductors, the value of current flow can become very high.

In a circuit where the inductor and capacitor are in series, and the frequency is the resonant frequency, or frequency of resonance, the circuit is said to be "in resonance" and is referred to as a series resonant circuit. The symbol for resonant frequency is Fn.

If, at the frequency of resonance, the inductive reactance is equal to the capacitive reactance, then

$$X_L = X_C \text{ , or}$$

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

Dividing both sides by 2 fL,

$$F\text{n}^2 = \frac{1}{(2\pi)^2 LC}$$

Extracting the square root of both sides gives

$$F\text{n} = \frac{1}{2\pi \sqrt{LC}},$$

Where F_n is the resonant frequency in cycles per second, C is the capacitance in farads, and L is the inductance in henrys. With this formula the frequency at which a capacitor and inductor will be resonant can be determined.

To find the inductive reactance of a circuit use

$$X_L = 2\ (\pi)\ fL$$

The impedance formula used in a series ac circuit must be modified to fit a parallel circuit.

$$Z = \frac{R_{XL}}{\sqrt{R^2 = XL^2}}$$

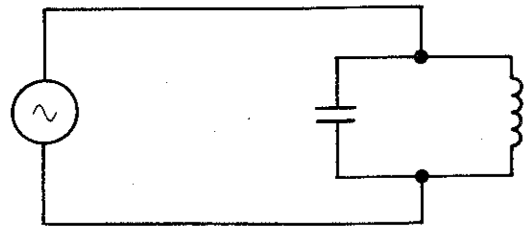


FIGURE 8–195. A parallel resonant circuit.

To find the parallel networks of inductanee and capacitive reactors use

$$X = \frac{X_L\ X_C}{\sqrt{X_L + X_C}}$$

To find the parallel networks with resistance capacitive and inductance use:

$$Z = \frac{R\ X_L\ X_C}{\sqrt{X_L^2 X_C^2 + (RX_L - RX_C)^2}}$$

Since at the resonant frequency X_L cancels X_C, the current can become very large, depending on the amount of resistance. In such cases, the voltage drop across the inductor or capacitor will often be higher than the applied voltage.

In a parallel resonant circuit (figure 8–195), the reactances are equal and equal currents will flow through the coil and the capacitor.

Since the inductive reactance causes the current through the coil to lag the voltage by 90°, and the capacitive reactance causes the current through the capacitor to lead the voltage by 90°, the two currents are 180° out of phase. The cancelling effect of such currents would mean that no current would flow from the generator and the parallel combination of the inductor and the capacitor would appear as an infinite impedance. In practice, no such circuit is possible, since some value of resistance is always present, and the parallel circuit, sometimes called a tank circuit, acts as a very high impedance. It is also called an antiresonant circuit, since its effect in a circuit is opposite to that of a series-resonant circuit, in which the impedance is very low.

Power in A. C. Circuits

In a d.c. circuit, power is obtained by the equation, $P = EI$, (watts equal volts times amperes). Thus, if 1 ampere of current flows in a circuit at a pressure of 200 volts, the power is 200 watts. The product of the volts and the amperes is the true power in the circuit.

In an a.c. circuit, a voltmeter indicates the effective voltage and an ammeter indicates the

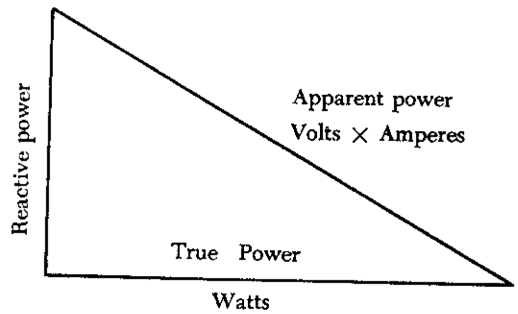


FIGURE 8–196. Power relations in a.c. circuit.

effective current. The product of these two readings is called the apparent power. Only when the a.c. circuit is made up of pure resistance is the apparent power equal to the true power (figure 8–196). When there is capacitance or inductance in the circuit, the current and voltage are not exactly in phase, and the true power is less than the apparent power. The true power is obtained by a wattmeter reading. The ratio of the true power to the apparent power is called the power factor and is usually expressed in percent. In equation form, the relationship is:

$$\text{Power Factor } (PF) = \frac{100 \times \text{Watts (True Power)}}{\text{Volts} \times \text{Amperes (Apparent Power)}}.$$

Problem:

A 220-volt a.c. motor takes 50 amperes from the line, but a wattmeter in the line shows that only 9,350 watts are taken by the motor, What is the apparent power and the power factor?

Solution:

Apparent power = Volts × Amperes.

Apparent power = 220 × 50 = 11,000 watts or volt-amperes.

$$PF = \frac{\text{Watts (True Power)} \times 100}{VA \text{ (Apparent Power)}}$$

$$PF = \frac{9{,}350 \times 100}{11{,}000}$$

$$PF = 85, \text{ or } 85\%.$$

TRANSFORMERS

A transformer changes electrical energy of a given voltage into electrical energy at a different voltage level. It consists of two coils which are not electrically connected, but which are arranged in such a way that the magnetic field surrounding one coil cuts through the other coil. When an alternating voltage is applied to (across) one coil, the varying magnetic field set up around that coil creates an alternating voltage in the other coil by mutual induction. A transformer can also be used with pulsating d.c., but a pure d.c. voltage cannot be used, since only a varying voltage creates the varying magnetic field which is the basis of the mutual induction process.

A transformer consists of three basic parts, as shown in figure 8–197. These are an iron core which provides a circuit of low reluctance for magnetic lines of force, a primary winding which receives the electrical energy from the source of applied voltage, and a secondary winding which receives electrical energy by induction from the primary coil.

The primary and secondary of this closed-core transformer are wound on a closed core to obtain maximum inductive effect between the two coils.

There are two classes of transformers: (1) Voltage transformers used for stepping up or stepping down voltages, and (2) current transformers used in instrument circuits.

In voltage transformers the primary coils are connected in parallel across the supply voltage, as shown in *A* of figure 8–198. The primary windings of current transformers are connected in series in the primary circuit (*B* of figure 8–198). Of the two types, the voltage transformer is the more common.

There are many types of voltage transformers. Most of these are either step-up or step-down transformers. The factor which determines whether a transformer is a step-up or step-down type is the "turns" ratio. The turns ratio is the ratio of the number of turns in the primary winding to the number of turns in the secondary winding. For example, the turns ratio of the step-down transformer shown in *A* of figure 8–199 is 5 to 1, since there are five times as many turns in the primary as in the secondary. The step-up

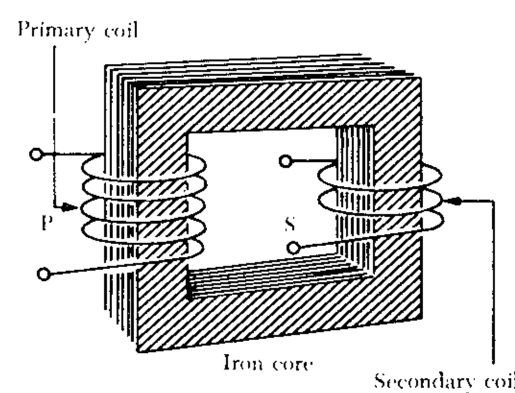


FIGURE 8–197. An iron-core transformer.

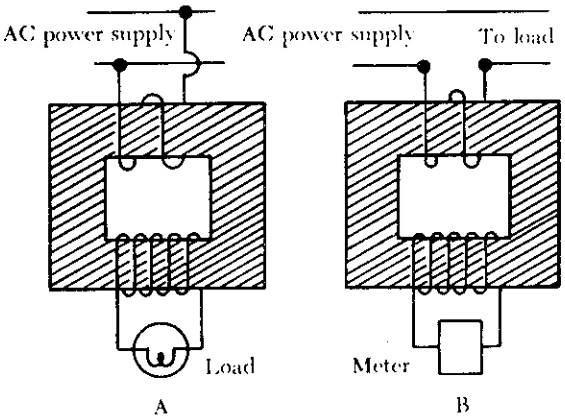


FIGURE 8–198. Voltage and current transformers.

transformer shown in *B* of figure 8–199 has a 1-to-4 turns ratio.

The ratio of the transformer input voltage to the output voltage is the same as the turns ratio if the transformer is 100 percent efficient. Thus, when 10 volts are applied to the primary of the transformer shown in *A* of figure 8–199, two volts are induced in the secondary. If 10 volts are applied to the primary of the transformer in *B* of figure 8–199, the output voltage across the terminals of the secondary will be 40 volts.

No transformer can be constructed that is 100 percent efficient, although iron-core transformers can approach this figure. This is because all the magnetic lines of force set up in the primary do not cut across the turns of the secondary coil. A certain amount of the magnetic flux, called leakage flux, leaks out of the magnetic circuit. The measure of how well the flux of the primary is coupled into the secondary is called the "coefficient of coupling." For example, if it is assumed that the primary of a transformer develops 10,000 lines of force and only 9,000 cut across the secondary, the coefficient of coupling would be .9 or, stated another way, the transformer would be 90 percent efficient.

When an a.c. voltage is connected across the primary terminals of a transformer, an alternating current will flow and self-induce a voltage in the primary coil which is opposite and nearly equal to the applied voltage. The difference between these two voltages allows just enough current in the primary to magnetize its core. This is called the exciting, or magnetizing, current. The magnetic field caused by this exciting current cuts across the secondary coil and induces a voltage by mutual induction. If a load is connected across the secondary coil, the load current flowing through the secondary coil will produce a magnetic field which will tend to neutralize the magnetic field produced by the primary current. This will reduce the self-induced (opposition) voltage in the primary coil and allow more primary current to flow. The primary current increases as the secondary load current increases, and decreases as the secondary load current decreases. When the secondary load is removed, the primary current is again reduced to the small exciting current sufficient only to magnetize the iron core of the transformer.

If a transformer steps up the voltage, it will step down the current by the same ratio. This should be evident if the power formula is considered, for the power ($I \times E$) of the output (secondary) electrical energy is the same as the input (primary) power minus that energy loss in the transforming process. Thus, if 10 volts and 4 amps (40 watts of power) are used in the primary to produce a magnetic field, there will be 40 watts of power developed in the secondary (disregarding any loss). If the transformer has a step-up ratio of 4 to 1, the voltage across the secondary will be 40 volts and the current will be 1 amp. The voltage is 4 times greater and the current is one-fourth the primary circuit value, but the power ($I \times E$ value) is the same.

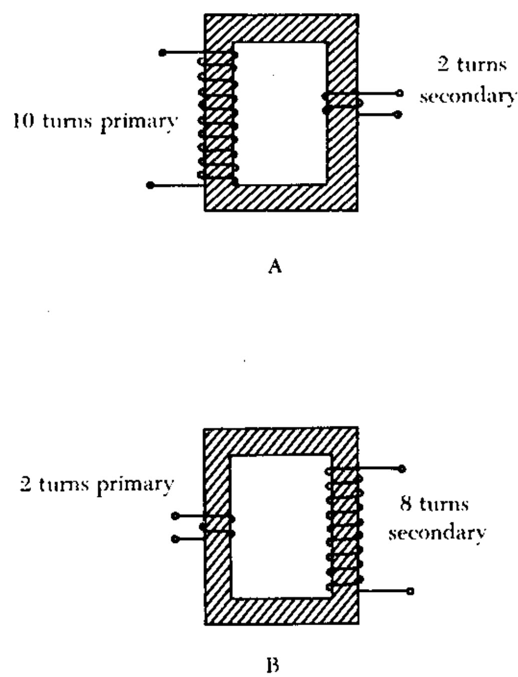


FIGURE 8–199. A step-down and a step-up transformer.

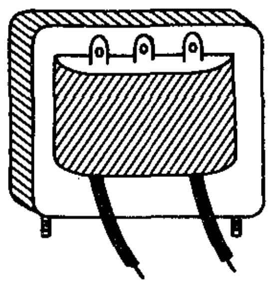


FIGURE 8–200. Power supply transformer.

When the turns ratio and the input voltage are known, the output voltage can be determined as follows:

$$\frac{E_2}{E_1} = \frac{N_2}{N_1}.$$

Where E is the voltage of the primary, E_2 is the output voltage of the secondary, and N_1 and N_2 are the number of turns of the primary and secondary, respectively.

Transposing the equation to find the output voltage gives:

$$E_2 = \frac{E_1 N_2}{N_1}.$$

The most commonly used types of voltage transformers are as follows:

(1) Power transformers are used to step up or step down voltages and current in many types of power supplies. They range in size from the small power transformer shown in figure 8–200 used in a radio receiver to the large transformers used to step down high-power line voltage to the 110–120 volt level used in homes.

In figure 8–201, the schematic symbol for an iron-core transformer is shown. In this case the secondary is made up of three separate windings. Each winding supplies a different circuit with a specific voltage, which saves the weight, space, and expense of three separate transformers. Each secondary has a midpoint connection, called a "center tap," which provides a selection of half the voltage across the whole winding. The leads from the various windings are color-coded by the manufacturer, as labeled in figure 8–201. This is a standard color code, but other codes or numbers may be used.

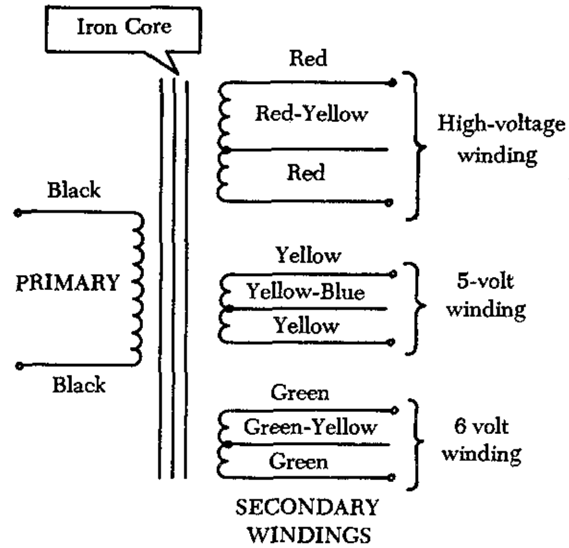


FIGURE 8–201. Schematic symbol for an iron-core power transformer.

(2) Audio transformers resemble power transformers. They have only one secondary and are designed to operate over the range of audio frequencies (20 to 20,000 c.p.s.).

(3) RF transformers are designed to operate in equipment that functions in the radio range of frequencies. The symbol for the RF transformer is the same as for an RF choke coil. It has an air core as shown in figure 8–202.

(4) Autotransformers are normally used in power circuits; however, they may be designed for other uses. Two different symbols for autotransformers used in power or audio circuits are shown in figure 8–203. If used in an RF communication or navigation circuit (*B* of figure 8–203), it is the same, except there is no symbol for an iron core. The autotransformer uses part of a winding as a primary; and, depending on whether it is step-up or step-down, it uses all or part of the same winding as the secondary. For example, the autotransformer shown in *A* of figure 8–203 could use the following possible choices for primary and secondary terminals.

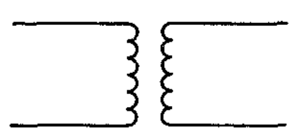


FIGURE 8–202. An air-core transformer.

Current Transformers

Current transformers are used in a.c. power supply systems to sense generator line current and to provide a current, proportional to the line current, for circuit protection and control devices.

The current transformer is a ring-type transformer using a current-carrying power lead as a primary (either the power lead or the ground lead of the a.c. generator). The current in the primary induces a current in the secondary by magnetic induction.

The sides of all current transformers are marked "H1" and "H2" on the unit base. The transformers must be installed with the "H1" side toward the generator in the circuit in order to have proper polarity. The secondary of the transformer should never be left open while the system is being operated; to do so could cause dangerously high voltages, and could overheat the transformer. Therefore, the transformer output connections should always be connected with a jumper when the transformer is not being used but is left in the system.

Transformer Losses

In addition to the power loss caused by imperfect coupling, transformers are subject to "copper" and "iron" losses. Copper loss is caused by the resistance of the conductor comprising the turns of the coil. The iron losses are of two types called hysteresis loss and eddy current loss. Hysteresis loss is the electrical energy required to magnetize the transformer core, first in one direction and then in the other, in step with the applied alternating voltage. Eddy current loss is caused by electric currents (eddy currents) induced in the transformer core by the varying magnetic fields. To reduce eddy current losses, cores are made of laminations coated with an insulation, which reduces the circulation of induced currents.

Primary		Secondary
1–2	used with	1–3
1–2	" "	2–3
1–3	" "	1–2
1–3	" "	2–3
2–3	" "	1–3
2–3	" "	1–2

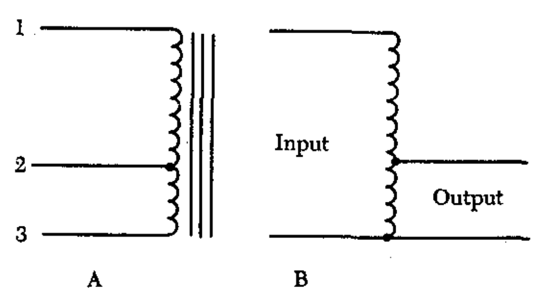


FIGURE 8–203. Autotransformers.

Power in Transformers

Since a transformer does not add any electricity to the circuit but merely changes or transforms the electricity that already exists in the circuit from one voltage to another, the total amount of energy in a circuit must remain the same. If it were possible to construct a perfect transformer, there would be no loss of power in it; power would be transferred undiminished from one voltage to another.

Since power is the product of volts times amperes, an increase in voltage by the transformer must result in a decrease in current and vice versa. There cannot be more power in the secondary side of a transformer than there is in the primary. The product of amperes times volts remains the same.

The transmission of power over long distances is accomplished by using transformers. At the power source the voltage is stepped up in order to reduce the line loss during transmission. At the point of utilization, the voltage is stepped down, since it is not feasible to use high voltage to operate motors, lights, or other electrical appliances.

Connecting Transformers in A. C. Circuits

Before studying the various means of connecting transformers in a.c. circuits, the differences between single-phase and three-phase circuits must be clearly understood. In a single-phase circuit the voltage is generated by one alternator coil. This single-phase voltage may be taken from a single-phase alternator, or from one phase of a three-phase alternator, as explained later in the study of a.c. generators.

In a three-phase circuit three voltages are generated by an alternator with three coils so spaced within the alternator that the three voltages generated are equal but reach their maximum values at different times. In each phase of a 400-cycle, three-phase generator, a cycle is generated every $\frac{1}{400}$ second.

In its rotation, the magnetic pole passes one

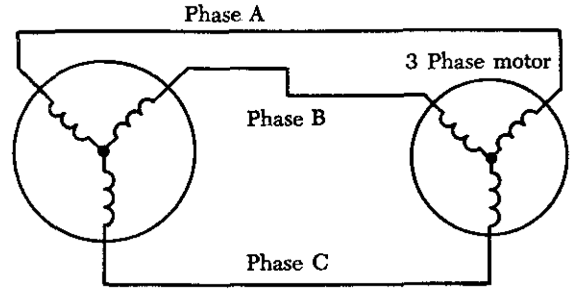


FIGURE 8–204. Three-phase generator using a three conductors.

coil and generates a maximum voltage; one-third cycle ($1/1200$ second) later, this same pole passes another coil and generates a maximum voltage in it; and the next one-third cycle later, it passes still another coil and generates a maximum voltage in it. This causes the maximum voltages generated in the three coils always to be one-third cycle ($1/1200$ second) apart.

The early three-phase generators were connected to their loads with six wires and all six leads in the circuit carried the current. Later, experiments proved that the generator would furnish as much power with the coils connected so that only three wires were needed for all three phases as shown in figure 8–204. The use of three wires is standard for the transmission of three-phase power today. The return current from any one alternator coil always flows back through the other two wires in the three-phase circuit.

Three-phase motors and other three-phase loads are connected with their coils or load elements arranged so that three transmission lines are required for delivery of power. Transformers that are used for stepping the voltage up or down in a three-phase circuit are electrically connected so

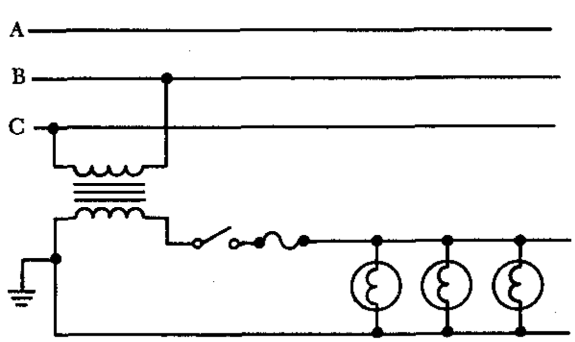


FIGURE 8–205. Step-down transformer using two-wire system.

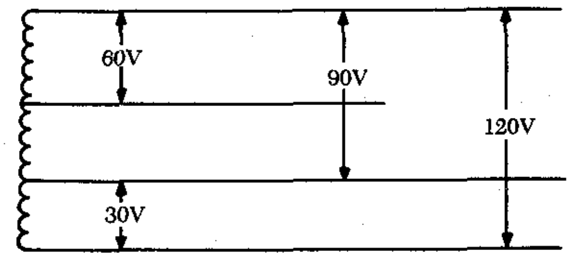


FIGURE 8–206. Tapped transformer secondary.

that power is delivered to the primary and taken from the secondary by the standard three-wire system.

However, single-phase transformers and single-phase lights and motors may be connected across any one phase of a three-phase circuit, as shown in figure 8–205. When single-phase loads are connected to three-phase circuits, the loads are distributed equally among the three phases in order to balance the loads on the three generator coils.

Another use of the transformer is the single-phase transformer with several taps in the secondary. With this type of transformer, the voltage can be lowered to provide several working voltages, as shown in figure 8–206.

A center tapped transformer, powering a motor requiring 220 volts along with four lights requiring 110 volts, is shown in figure 8–207. The motor is connected across the entire transformer output, and the lights are connected from the center tap to one end of the transformer. With this connection only half of the secondary output is used.

This type of transformer connection is used

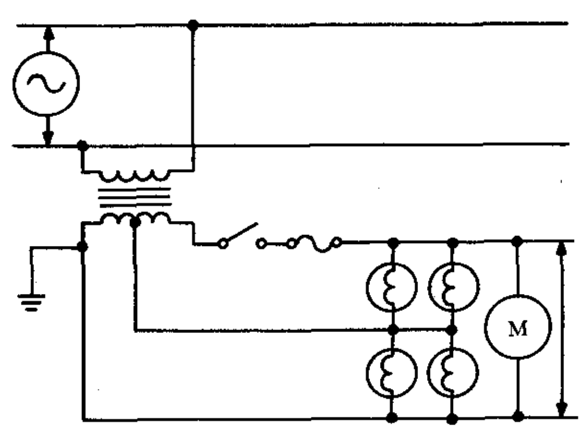


FIGURE 8–207. Step-down transformer using a three-wire system.

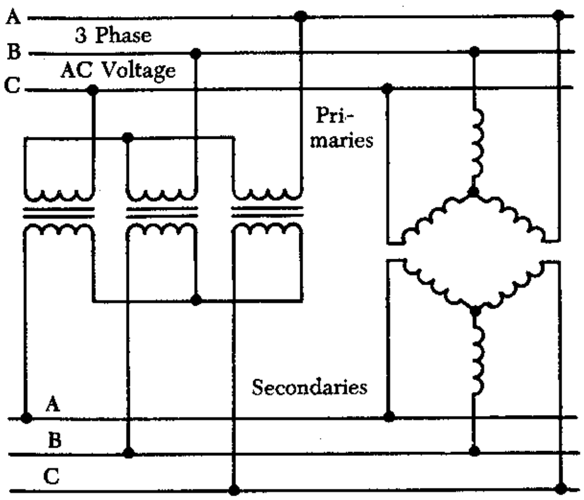


FIGURE 8–208. Wye-to-wye connection.

extensively on aircraft because of the combinations of voltages that can be taken from one transformer. Various voltages can be picked off the secondary winding of the transformer by inserting taps (during manufacture) at various points along the secondary windings.

The various amounts of voltage are obtained by connecting to any two taps or to one tap and either end.

Transformers for three-phase circuits can be connected in any one of several combinations of the wye (y) and delta (Δ) connections. The connection used depends on the requirements for the transformer.

When the wye connection is used in three-phase transformers, a fourth or neutral wire may be used. The neutral wire connects single-phase equipment to the transformer. Voltages (115v) between any one of the three-phase lines and the neutral wire can be used for power for devices such as lights or single-phase motors.

In combination, all four wires can furnish power at 208 volts, three-phase, for operating three-phase equipment, such as three-phase motors or rectifiers. When only three-phase equipment is used, the ground wire may be omitted. This leaves a three-phase, three-wire system as illustrated in figure 8–208.

Figure 8–209 shows the primary and secondary with a delta connection. With this type of connection the transformer has the same voltage output as the line voltage. Between any two phases the voltage is 240 volts. In this type of connection, wires A, B, and C can furnish 240-volt, three-phase power for the operation of three-phase equipment.

The type of connection used for the primary coils may or may not be the same as the type of connection used for the secondary coils. For example, the primary may be a delta connection and the secondary a wye connection. This is called a delta-wye-connected transformer. Other combinations are delta-delta, wye-delta, and wye-wye.

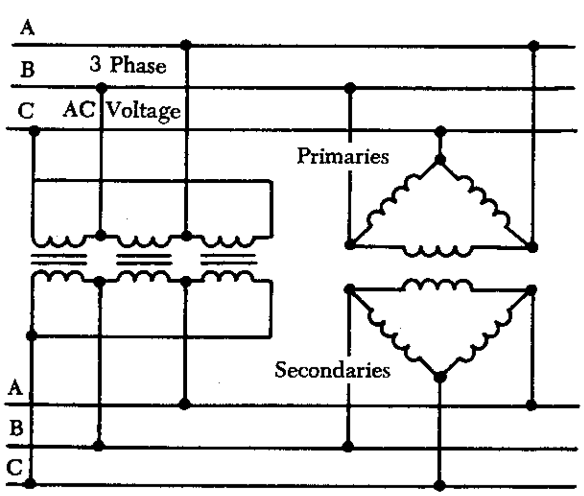


FIGURE 8–209. Delta-to-delta connection.

Troubleshooting Transformers

There are occasions when a transformer must be checked for opens or shorts, and it is often necessary to determine that a transformer is a step-up or step-down transformer.

An open winding in a transformer can be located by connecting an ohmmeter as shown in figure 8–210. Connected as shown, the ohmmeter would read infinity. If there were no open in the coil, the ohmmeter would indicate the resistance of wire in the coil. Both primary and secondary can be checked in the same manner.

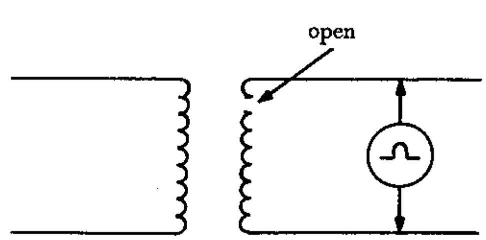


FIGURE 8–210. Checking for an open in a transformer winding.

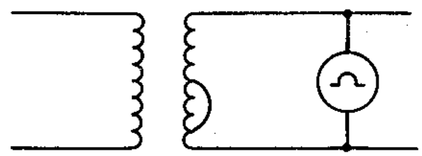


FIGURE 8–211. Checking for shorted transformer windings.

The ohmmeter may also be used to check for shorted windings, as shown in figure 8–211, however, this method is not always accurate. If, for example, the transformer had 500 turns and a resistance of 2 ohms, and 5 turns were shorted out, the resistance would be reduced to approximately 1.98 ohms, which is not enough of a change to be read on the ohmmeter. In this case, the rated input voltage can be applied to the primary to permit measurement of the secondary output voltage. If the secondary voltage is low, it can be assumed that the transformer has some shorted windings, and the transformer should be replaced. If the output voltage is then normal, the original transformer can be considered defective.

An ohmmeter can be used to determine whether a transformer is a step-up or step-down transformer. In a step-down transformer, the resistance of the secondary will be less than that of the primary, and the opposite will be true in the case of a step-up transformer. Still another method involves applying a voltage to the primary and measuring the secondary output. The voltages used should not exceed the rated input voltage of the primary.

If a winding is completely shorted, it usually becomes overheated because of the high value of current flow. In many cases, the high heat will melt the wax in the transformer, and this can be detected by the resulting odor. Also, a voltmeter reading across the secondary will read zero. If the circuit contains a fuse, the heavy current may cause the fuse to blow before the transformer is heavily damaged.

In figure 8–212 one point on a transformer winding is shown connected to ground. If the external circuit of the transformer circuit is grounded, a part of the winding is effectively shorted. A megger connected between one side of the winding and the transformer case (ground) will verify this condition with a low or zero reading. In such a case, the transformer must be replaced.

All transformers discussed in this section are designed with one primary winding. They operate on a single source of a.c. Transformers which operate from three voltages from an alternator, or a.c. generator, are called three-phase or polyphase transformers. These transformers will be discussed in the study of generators and motors.

MAGNETIC AMPLIFIERS

The magnetic amplifier is a control device being employed at an increasing rate in many aircraft electrical and electronic systems. This is because of its ruggedness, stability, and safety in comparison to vacuum tubes.

The principles on which the magnetic amplifier operates can best be explained by reviewing the operation of a simple transformer. If an a.c. voltage is applied to the primary of an iron core transformer, the iron core will be magnetized and demagnetized at the same frequency as that of the applied voltage. This, in turn, will induce a voltage in the transformer secondary. The output voltage across the terminals of the secondary will depend on the relationship of the number of turns in the primary and the secondary of the transformer.

The iron core of the transformer has a saturation point after which the application of a greater magnetic force will produce no change in the intensity of magnetization. Hence, there will be no change in transformer output, even if the input is greatly increased.

The magnetic amplifier circuit in figure 8–213 will be used to explain how a simple magnetic amplifier functions. Assume that there is 1 ampere of current in coil A, which has 10 turns of wire. If coil B has 10 turns of wire, an output of 1 ampere will be obtained if coil B is properly loaded. By applying direct current to coil C, the core of the magnetic amplifier coil can be further magnetized. Assume that coil C has the proper number of turns and, upon the application of 30 milliamperes, that the core is magnetized to the

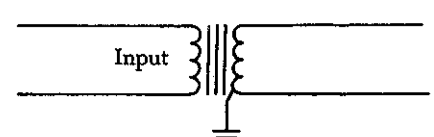


FIGURE 8–212. Part of a transformer winding grounded.

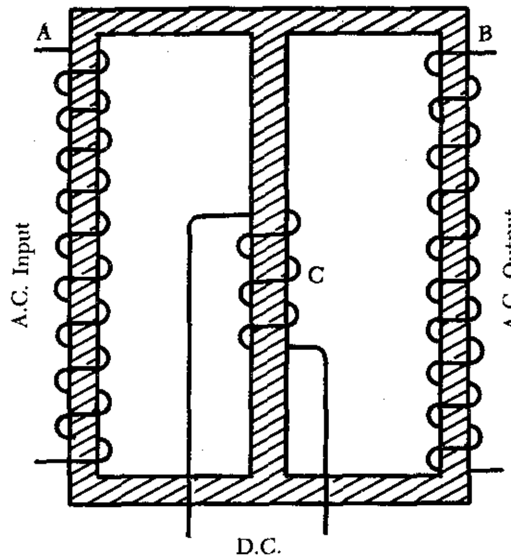


FIGURE 8–213. Magnetic amplifier circuit.

point where 1 ampere on coil A results in only 0.24 ampere output from coil B.

By making the d.c. input to coil C continuously variable from 0 to 30 milliamperes and maintaining an input of 1 ampere on coil A, it is possible to control the output of coil B to any point between 0.24 ampere and 1 ampere in this example. The term "amplifier" is used for this arrangement because, by use of a few milliamperes, control of an output of 1 or more amperes is obtained.

The same procedure can be used with the circuit shown in figure 8–214.

By controlling the extent of magnetization of the iron ring, it is possible to control the amount of current flowing to the load, since the amount of magnetization controls the impedance of the a.c. input winding. This type of magnetic amplifier is called a simple saturable reactor circuit.

Adding a rectifier to such a circuit would remove half the cycle of the a.c. input and permit a direct current to flow to the load. The amount of

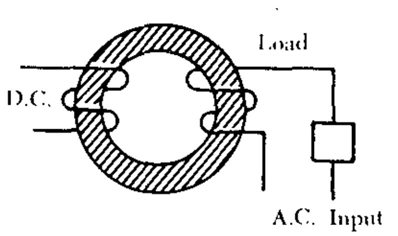


FIGURE 8–214. Saturable reactor circuit.

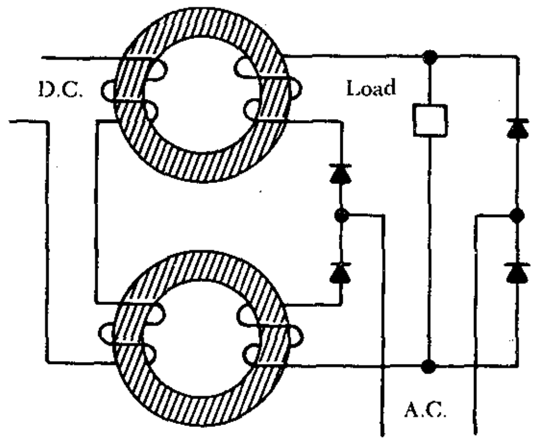


FIGURE 8–215. Self-saturating, full-wave magnetic amplifier.

d.c. flowing in the load circuit is controlled by a d.c. control winding (sometimes referred to as bias). This type of magnetic amplifier is referred to as being self-saturating.

In order to use the full a.c. input power, a circuit such as that shown in figure 8–215 may be used. This circuit uses a full-wave bridge rectifier. The load will receive a controlled direct current by using the full a.c. input. This type of circuit is known as a self-saturating, full-wave magnetic amplifier.

In figure 8–216 it is assumed that the d.c. control winding is supplied by a variable source, such as a sensing circuit. In order to control such a source and use its variations to control the a.c. output, it is necessary to include another d.c. winding that has a constant value. This winding, referred to as the reference winding, magnetizes the magnetic core in one direction.

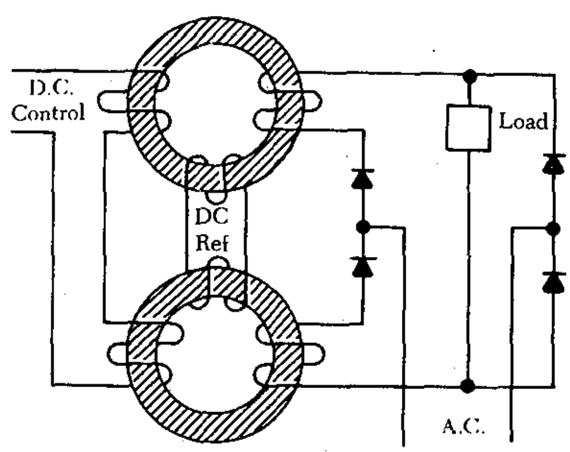


FIGURE 8–216. Basic preamplifier circuit.

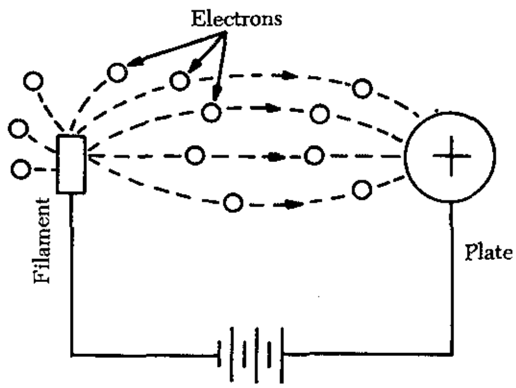


FIGURE 8–217. Principle of vacuum tube operation.

The d.c. control winding, acting in opposition to the reference winding, either increases (degenerative) or decreases (regenerative) the magnetization of the core to change the amount of current flowing through the load. This is essentially a basic preamplifier.

VACUUM TUBES

The use of vacuum tubes in aircraft electrical and electronic systems is rapidly declining because of the many advantages of using transistors. On the other hand, some systems still employ vacuum tubes in special applications, and a large number of older model aircraft still in service are equipped with devices that use vacuum tubes. For these reasons a general study of vacuum tubes is still considered a necessary part of the aviation maintenance program.

Originally, vacuum tubes were developed for radio work. They are used in radio transmitters as amplifiers for controlling voltage and current, as oscillators for generating audio and radio frequency signals, and as rectifiers for converting alternating current into direct current. Radio tubes are used for similar purposes in many electrical devices in aircraft, such as the automatic pilot and the turbosupercharger regulator.

When a piece of metal is heated, the speed of the electrons in the metal is increased. If the metal is heated to a high enough temperature, the electrons are accelerated to the point where some of them actually leave the surface of the metal, as shown in figure 8–217. In a vacuum tube, electrons are supplied by a piece of metal, called a cathode, which is heated by an electric current. Within limits, the hotter the cathode the greater the number of electrons it will give off or emit.

To increase the number of electrons emitted, the cathode is usually coated with special chemical compounds. If the emitted electrons are not drawn away by an external field, they form about the cathode into a negatively charged cloud called the space charge. The accumulation of negative electrons near the emitter repels others coming from the emitter. The emitter, if insulated, becomes positive because of the loss of electrons. This establishes an electrostatic field between the cloud of negative electrons and the now positive cathode. A balance is reached when only enough electrons flow from the cathode to the area surrounding it to supply the loss caused by diffusion of the space charge.

Types of Vacuum Tubes

There are many different types of vacuum tubes, most of which fall into four general types: (1) The diode, (2) the triode, (3) the tetrode, and (4) the pentode. Of these, the diode is used almost exclusively for changing a.c. current to d.c. current.

In some vacuum tubes, the cathode is heated by d.c. and is both the electron emitter and current carrying member, while in others the cathode is heated by a.c. Tubes designed for a.c. operation employ a special heating element which heats the electron emitter (cathode) indirectly.

When a d.c. potential is applied between the cathode and another element in the tube called a plate, with the positive side of the voltage connected to the plate, the electrons emitted by the cathode are attracted to the plate. These two elements constitute the simplest form of vacuum tube, which is the diode. In the diode, electrons are attracted to the plate, when it is more positive than the cathode, and are repelled when the plate is less positive than the cathode.

Current flows through the tube when it is connected in a circuit only when the plate is positive with respect to the cathode. Current does not flow when the plate is negative (less positive) with respect to the cathode as illustrated in figure 8–218. This characteristic gives the diode its principle use, that of rectification, or the changing of alternating current into direct current.

Diode rectifiers are used in aircraft electrical systems, especially when high voltage d.c. is desired for light loads. They may be used as either half-wave or full-wave rectifiers; they may be

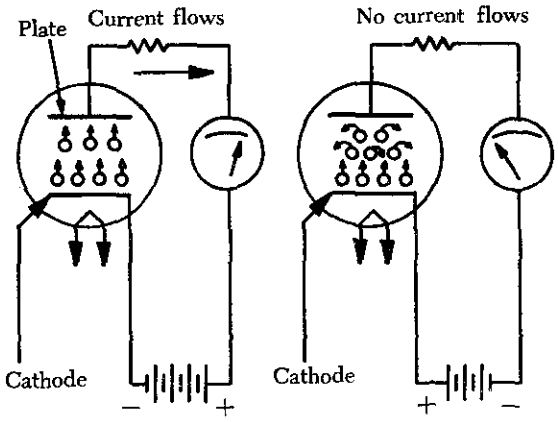


FIGURE 8–218. Diode tube operation.

used singly, in parallel, or in bridge circuits. As shown in figure 8–219, a half-wave rectifier contains two tube elements (plate and cathode). A full-wave rectifier contains three elements (two plates and a cathode).

In the half-wave circuit, current flows only during the positive half of the cycle of the applied voltage (plate positive, cathode negative for electron flow). It flows from the cathode to the plate and then through the load back to the cathode. On the negative cycle of the applied voltage, no current flows through the tube. As a result, the rectified output voltage is d.c., but it consists of pulses, or half cycles, of current.

In a vacuum tube connected as a full-wave rectifier, current flows to the load on both half cycles of the alternating voltage. In the full-wave rectifier, current flows from the top plate through the d.c. load on one alternation, and on the next

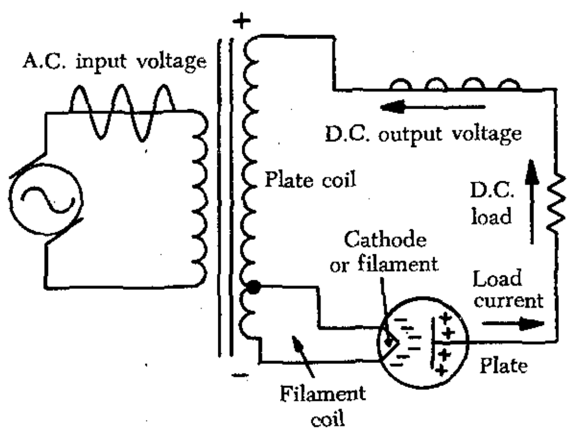


FIGURE 8–219. Half-wave vacuum tube rectifier circuit.

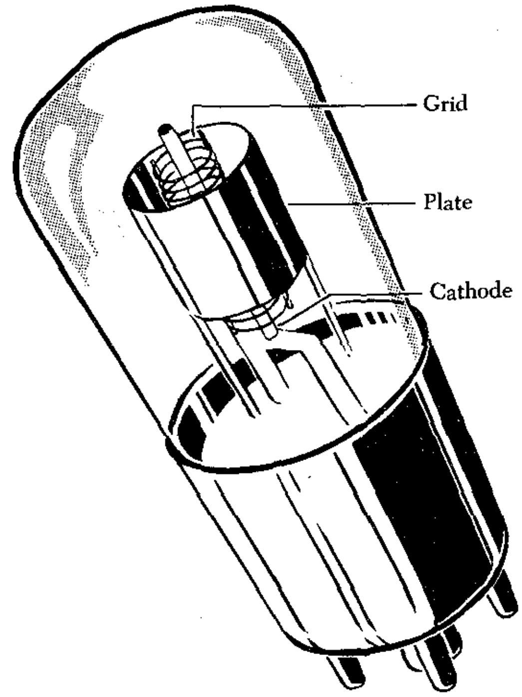


FIGURE 8–220. Triode tube.

alternation, current flows to the lower plate and through the load in the same direction.

Vacuum tube rectifiers have been replaced to a great degree in aircraft systems by dry-disk or semiconductor diodes. In the study of solid state devices the process of rectification is treated in greater detail.

The triode tube is a three-element tube. In addition to the plate and cathode, there is a third element, called the grid, located between the cathode and the plate as shown in figure 8–220. The grid is a fine-wire mesh or screen. It serves to control the electron flow between the cathode and the plate. Whenever the grid is made more positive than the cathode, there is an increase in the number of electrons attracted to the plate, resulting in an increase in plate current flow. If the grid is made negative with respect to the cathode, electron movement to the plate is retarded and plate current flow decreases.

Usually the grid is negative with reference to the cathode. One method of making the grid negative is to use a small battery connected in series with the grid circuit. This negative voltage applied to the grid is called bias.

The most important use of a triode is as an amplifier tube. When a resistance or impedance is connected in series in the plate circuit, the voltage

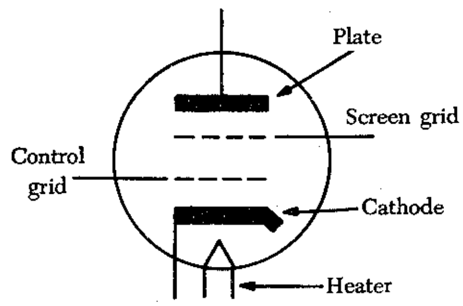


FIGURE 8–221. Tetrode tube schematic.

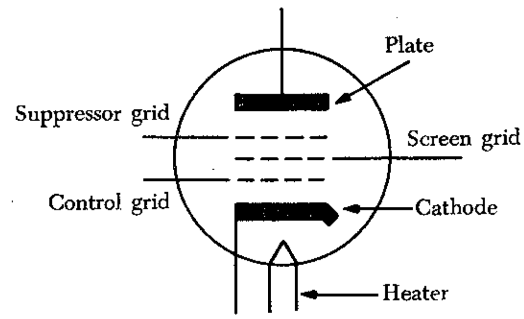


FIGURE 8–222. Pentode schematic.

drop across it, which depends upon the current flowing through it, can be changed by varying the grid voltage. A small change in grid voltage will cause a large change in the voltage drop across the plate impedance. Thus, the voltage applied to the grid is amplified in the plate circuit of the tube.

A tetrode tube is a four-element tube, the additional element being the screen grid (figure 8–221). This grid is located between the control grid and the plate. The screen grid is operated at a positive voltage somewhat lower than the plate voltage. It reduces the sometimes undesirable effect in tube operation caused by energy fed from the output of a tube back into the input (grid) circuit.

Under certain operating conditions, this feedback action is very pronounced in a triode and causes the tube to act as an oscillator instead of an amplifier. The chief advantages of tetrodes over triodes are greater amplification for smaller input voltages, and less feedback from the plate to the grid circuit.

An undesirable characteristic of the tetrode tube is secondary emission. Secondary emission is the term applied to the condition where electrons are knocked out of the plate into the space between the elements of a tube by rapidly moving electrons striking the plate. In triode tubes, since the grid is negative with respect to the cathode, it repels the secondary electrons and tube operation is undisturbed. In the tetrode, the effect of secondary emission is especially noticeable since the screen grid, which is positive with respect to the cathode, attracts the secondary electrons and causes a reverse current to flow between the screen and plate.

The effects of secondary emission are overcome by adding a third grid, called the suppressor grid, between the screen grid and the plate. This grid repels the secondary electrons toward the plate. A tube with three grids is called a pentode, which has a high amplification factor and is used to amplify weak signals. The schematic of a pentode is shown in figure 8–222.

Another type of vacuum tube is the gas tube. Gas-filled tubes are primarily diodes and are used mostly as rectifiers. In tubes of this type the gas should be one ten-thousandth as dense as air under normal atmospheric pressure. When an electron meets a gas molecule, the energy imparted by the impact can cause the molecule (or atom) to lose or gain one or more electrons. Consequently, ionization takes place.

Any gas or vapor having no ions is practically a perfect insulator. If two electrodes are placed in such a medium, no current will flow between them. However, gases always have some residual ionization because of cosmic rays, radioactive materials in the walls of the containers, or the action of light. If a potential is applied between two elements in such a gas, the ions migrate between them and give the effect of current flow. This is called the dark current because no visible light is associated with it.

If the voltage on the electrodes is increased, the current starts to rise. At a certain point, known as the threshold, the current suddenly begins to go up without any increase in applied voltage. If there is enough resistance in the external circuit to prevent the current from rising quickly, the voltage immediately drops to a lower value and breakdown occurs. This abrupt change takes place as a result of the ionization of the gas by electron collision.

The electrons released by the ionized gas join the stream and liberate other electrons. The process, then, is cumulative. Breakdown voltage is determined primarily by the type of gas, the materials used for the electrodes, and their size and spacing. Once ionization takes place, the current can rise to 50 milliamperes (ma.), or more, with little change in the voltage applied. If the voltage is increased, the current increases and the cathode is heated by the bombardment of the ions which strike it. When the tube gets hot enough, thermionic emission results.

This emission reduces the voltage loss in the tube, which, in turn, causes more current to flow and increases the rate of emission and ionization. This cumulative action causes a sudden decrease in the voltage drop across the tube and an extremely high rise in current flow. Unless the tube is designed to operate in this manner, it can be damaged by heavy current flow. This is basic to the formation of an arc; therefore, tubes that operate at these high currents are called arc tubes. For currents up to 50 milliamperes, the unit usually is small and is termed a glow tube because of the colored light it emits. An example of such a tube is the familiar neon light.

The principle of grid control can be applied to almost any gas tube, but it is used specifically with cold cathode, hot cathode, and arc types of triodes and tetrodes. The hot cathode type of three-element gas tube is given the general name of thyratron.

The phototube is another special type of vacuum tube. It is basically the same as the simple diode discussed earlier. It has an evacuated glass bulb, a cathode which emits electrons when light is allowed to fall upon it, and a plate which attracts electrons when a voltage is applied. The sensitivity of the tube depends on the frequency or color of the light used to excite it and is specified in these terms.

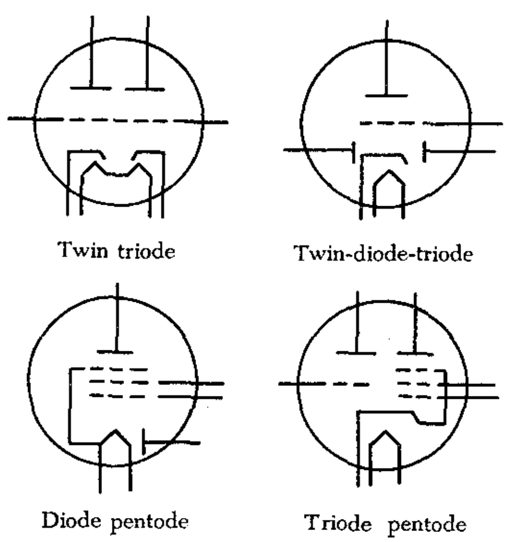


FIGURE 8–223. Multiunit tubes.

For example, some tubes are sensitive to red light, others to blue light. In most phototubes, the cathode resembles a half cylinder. It is covered with multiple layers of the rare metal, cesium, overlaid on cesium oxide, which, in turn, lies on a layer of silver. The plate is shaped like a small rod and is located in the center of the cathode.

Other types of vacuum tubes include those with the characteristics of several tubes incorporated into one, as shown in figure 8–223. Among these, for example, are twin triode tubes containing two triode sections in a single tube envelope, and diode-triode tubes with a rectifier diode and an amplifier triode in the same envelope. There are many other tube combinations.

TRANSISTORS

The transistor is an electronic device that is capable of performing most of the functions of vacuum tubes. It is very small, light in weight, and requires no heater. It is also mechanically rugged and does not pick up stray signals. Transistors have been in general use for more than a decade, but compared to some of the components they are replacing they are relatively new. As research progresses, new discoveries often cause some elements of transistor theory to be modified.

A transistor is a semiconductor device consisting of two types of materials each of which exhibits electrical properties. Semiconductors are materials whose resistive characteristics fall approximately midway between those of good conductors and insulators. The interface between the parts is called a junction. Selenium and germanium diodes (rectifiers) are examples of such devices and are called junction diodes. Most transistors are made of germanium to which certain impurities are added to impart certain characteristics. The impurities used are generally arsenic or indium.

The type of transistor which may be used in some applications in place of the triode tube is the "junction" transistor, which actually has two junctions. It has an emitter, base, and collector which correspond to the cathode, grid, and plate, respectively, in the triode tube. Junction transistors are of two types, the NPN type and the PNP type (see figure 8–224).

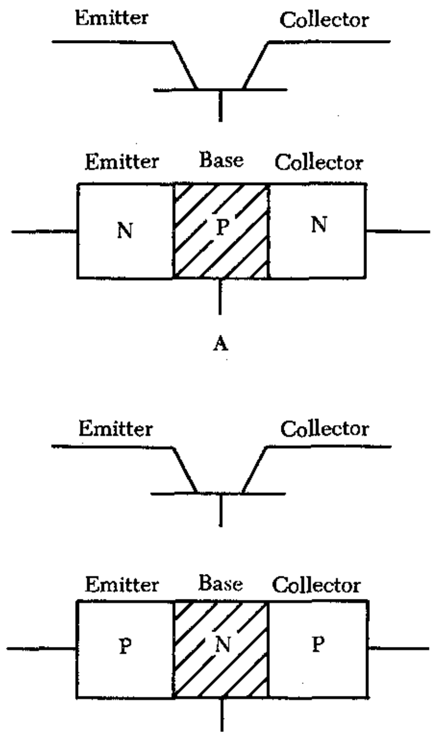


FIGURE 8–224. NPN and PNP transistors.

Theory of Transistor Operation

Before transistor operation and the meaning of "N" and "P" can be explained, it is necessary to consider the theory of transistor action.

An electron is a negatively charged particle. In any material, there are electrons separated from each other by some minute distance. Whenever there is an electron, there is a negative charge. An atom of the semiconductor material has a specified number of electrons, depending on the type of material. If one of the electrons is removed, the hole from which the electrons moved is more positive than the electron that was removed.

To hole is considered to have a positive charge. If an electron from a neighboring atom moves into the hole, the hole apparently moves to the place from which the electron came. The hole does not really move; it is filled in one place and formed in another. In A of figure 8–225, the electrons are represented as black dots and the holes as dotted circles.

In B of figure 8–225, the electrons have moved one space to the left of their position occupied in A of figure 8–225. In effect, the holes have, therefore, moved one space to the right.

The movement of the electrons is current. In the same sense, the movement of holes is current also. Electron current moves in one direction; hole current travels in the opposite direction. The movement of the charge is a current. In transistors both electrons and holes act as carriers of current.

In transistors, materials referred to as N-materials and P-materials are used. The N-materials are rich in electrons and, therefore, electrons act as the carriers. The P-material is lacking in electrons and, therefore, has holes as carriers.

An NPN transistor is not interchangeable with a PNP transistor and vice versa. However, if all power supplies are reversed, they may be interchanged.

Since temperature is critical in a transistor circuit, there must be sufficient cooling for the transistors. Another precaution to observe which applies to any circuit is: ***Power should never knowingly be applied to an open circuit.***

Diodes

Figure 8–226 illustrates a germanium diode and consists of two different types of semiconductor materials. With the battery connected as shown, positive holes and electrons are repelled by the battery toward the junction, causing an interaction between the holes and electrons. This results in electrons flowing through the junction to the holes and to the positive terminal of the battery. The holes move toward the negative terminal of the battery. This is called the forward direction and is a "high" current.

Connecting the battery as shown in figure 8–227 causes the holes and electrons to be pulled away from the junction, and little interaction between holes and electrons occurs at the junction. This results in very little current flow, called reverse current.

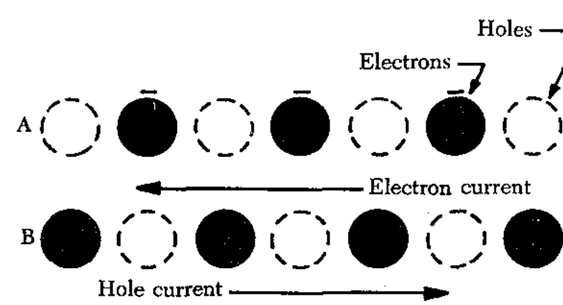


FIGURE 8–225. Electrons and holes in transistors.

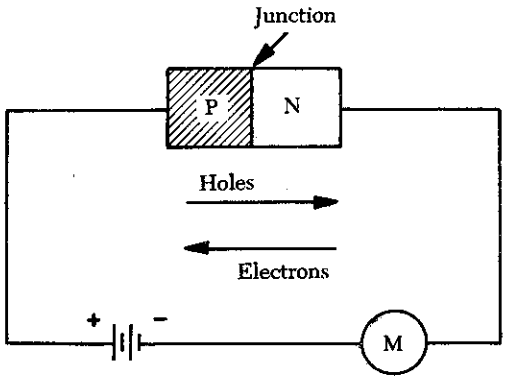


FIGURE 8–226. Electron and hole flow in a diode with forward bias.

The potential on the electrodes of the transistor diodes applied from the battery is called bias. It may be either forward or reverse bias, that is, in a high-current or a low-current direction.

The N-germanium is manufactured with an impurity, such as arsenic, added to give it an excess of electrons. Arsenic gives up its electrons readily and can be used as a carrier. The P-germanium has an impurity, such as indium, added. This takes the electrons from the germanium and leaves holes, or positive carriers.

Zener Diodes

Zener diodes (sometimes called "breakdown diodes") are used primarily for voltage regulation. They are designed so that they will break down (allow current to pass) when the circuit potential is equal to or in excess of the desired voltage. Below the desired voltage the zener blocks the circuit like any other diode biased in the reverse direction. Because the zener diode allows free flow in one direction when it is used in an a.c. circuit,

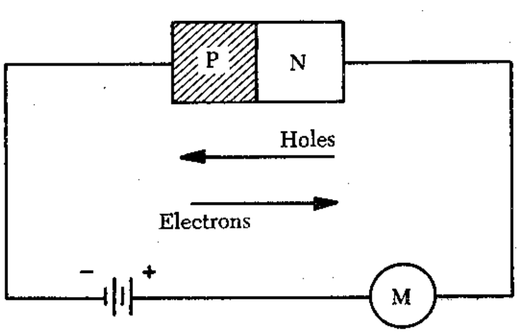


FIGURE 8–227. Electron and hole flow in a diode with reverse bias.

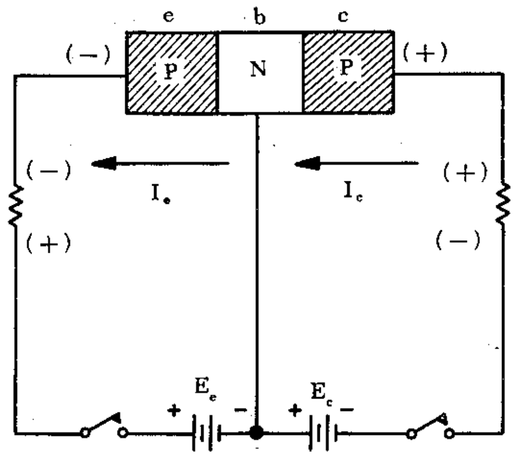


FIGURE 8–228. Transistor electron flow.

two diodes connected in opposite directions must be used. This takes care of both alternations of current.

The zener may be used in many places where a gas-filled vacuum tube cannot be used, because it is smaller in size and can be used in low voltage circuits. The gas-filled tube is used in circuits above 75 volts, but the zener diode may be used in regulating voltages as low as 3.5 volts.

PNP Transistor

Figure 8–228 shows a transistor circuit powered by batteries. The emitter circuit is biased by the battery E_e in the forward or high-current-flow direction. The collector circuit is biased by battery E_c in the reverse or low-current-flow direction.

If the switch in the emitter circuit were closed (collector switch open), a high emitter current would flow since it is biased in the forward direction. If the collector switch were closed (emitter switch open), a low current would flow since it is biased in the reverse direction.

At the same time, a hole current is flowing in the opposite direction in the same circuit, as shown in figure 8–229. Hole current flows from the positive terminal of the battery, whereas electron current originates at the negative terminal.

The operation with both switches closed is the same as with a PNP transistor, except that the emitter now ejects electrons instead of holes into the base, and the collector, being positive, will collect the electrons. There is again a large increase in collector current with the emitter switch closed. With the emitter switch open, the collector current will be small, since it is biased for reverse

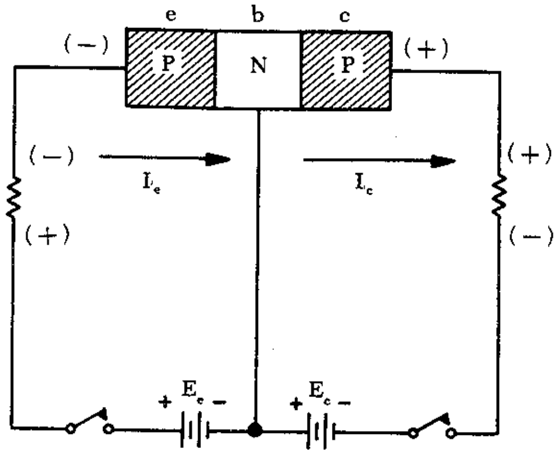


FIGURE 8–229. Transistor hole current flow.

flow. At first glance it may appear that the transistor cannot amplify, since there is less current in the collector than in the emitter circuit. Remember, however, that the emitter is biased in the forward direction and a small voltage causes a large current, which is equivalent to a low resistance. The collector circuit is biased in the reverse direction, and a large voltage causes a small current, which is the equivalent of a high resistance.

When both switches are closed, a phenomenon known as transistor action occurs. The emitter, biased in the forward direction, has its positive holes ejected through the junction into the "N" region of the base. (The positive battery terminal repels the holes through the junction.) The collector, being biased negatively, will now attract these holes through the junction from the base to the collector.

This collecting of holes by the collector causes a much greater reverse current than there would be if the emitter switch were open. The large increase of reverse collector current is caused by so-called transistor action, whereby holes from the emitter pass to the collector. Instead of holes flowing through the base and back to the emitter, they flow through the collector, E_c, and E_e to the emitter; the actual base current is very small.

The sum of collector current and base current equals the emitter current. In typical transistors the collector current can be 80–99 percent of the emitter current, with the remainder flowing through the base.

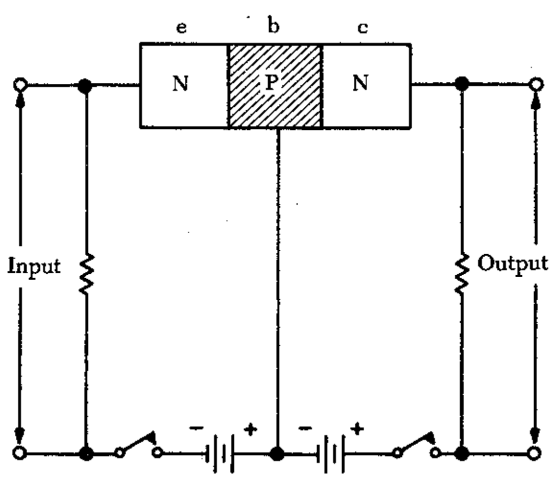


FIGURE 8–230. NPN transistor circuit.

NPN Transistor

In figure 8–230 an NPN transistor is connected into a circuit. Notice that the battery polarities are reversed from those for the PNP transistor. But with the types of transistor material reversed, the emitter is still biased in the forward direction, and the collector is still biased in the reverse direction.

In this circuit a small signal applied to the input terminal causes a small change in both emitter and collector currents; however, the collector, being a high-resistance, requires only a small current change to produce large voltage changes. Therefore, an amplified signal appears at the output terminals.

The circuit in this illustration is called a grounded base amplifier, because the base is common to input and output (emitter and collector) circuits.

Figure 8–231 shows a different type of circuit connection. This is called a grounded emitter amplifier, and is similar to a conventional triode amplifier. The emitter is like a cathode, the base like a grid, and the collector like a plate. The collector is biased for a reverse current flow.

If the input signal swings positive, as shown in figure 8–231, it will aid the bias and increase base and emitter current. This increases collector current, making the upper output terminal more negative. On the next half cycle, the signal will oppose the bias and decrease emitter and collector current. Therefore, the output will swing positive. It is 180° out of phase with the input just as in the conventional triode tube amplifier.

Since the base current is a very small part of

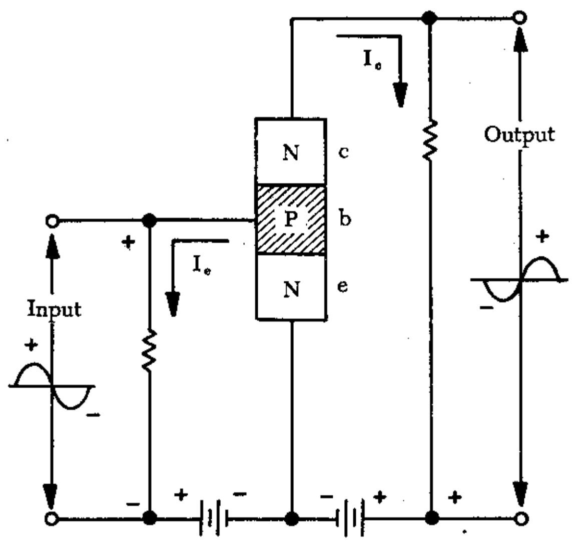


FIGURE 8–231. A grounded-emitter amplifier circuit.

the total emitter current, it requires only a very small change in base current to cause a large change in collector current. Therefore, it again amplifies the signal. This circuit has the highest gain (output/input) of the various transistor amplifiers. A PNP transistor could also be used if battery polarities were reversed.

Use of Transistors

Transistors can be used in all applications where vacuum tubes are used, within certain limitations imposed by their physical characteristics. The main disadvantage of transistors is their low power output and limited frequency range. However, since they are approximately one one-thousandth the physical size of a vacuum tube, they can be used in compact equipment. Their weight, approximately one one-hundredth that of a vacuum tube, makes the equipment much lighter. Their life is approximately three times that of a vacuum tube, and their power requirement is only about one-tenth that of a vacuum tube.

Transistors can be permanently damaged by heat or by reversed polarity of the power supply. For this reason, care must be exercised when installing them in a circuit to prevent these conditions.

Transistors can be installed in miniature tube sockets, or they can be soldered directly into the circuits. There is no maintenance to be performed on them other than to remove and replace them as necessary.

When first tracing transistor circuits, trouble may be experienced in understanding from the schematic whether a transistor is an NPN or a PNP. Refer to figure 8–232, which shows the schematic symbol for two types of transistors. Notice an arrow in the emitter line. When this arrow is pointing away from the base, it is an NPN; if the arrow is pointing toward the base, it is a PNP transistor.

A simple rule to determine whether the transistor is a PNP or an NPN is as follows: If it is a PNP, the center letter "N" indicates a negative base or, in other words, that the base will conduct more freely on a negative charge. If the transistor is an NPN, the "P" indicates a positive base and the transistor will conduct more freely on a positive base charge.

Since there are different types of transistors based on the method used in their manufacture, there are several means of identifying the transistor in a circuit as either an NPN or a PNP. One method used to identify the type of transistor, called the junction transistor, is illustrated in figure 8–233. In this case, the method used to determine which of the three wires connected to a transistor is the base lead, which is the collector lead, and which is the emitter lead is based on the physical spacing of the leads. Notice that there are two leads close together and one lead further apart. The center lead is always the base. The lead closest to the base is the emitter lead, and the lead further out is the collector lead. The schematic shown in this illustration holds true for all junction-type transistors. For detailed information on any transistor, the applicable manufacturer's publications should be consulted.

RECTIFIERS

Many devices in an aircraft require high-amperage, low-voltage d.c. for operation. This

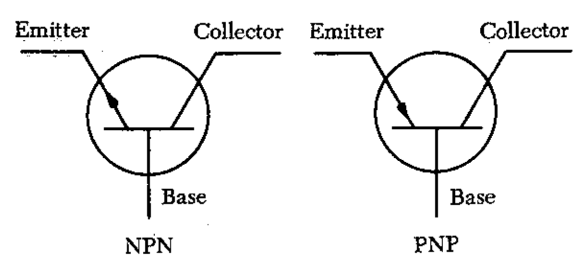


FIGURE 8–232. Transistor schematic symbols.

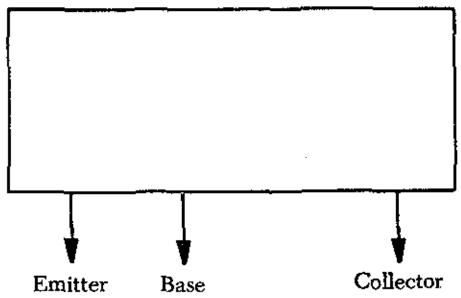


FIGURE 8–233. Junction transistor connections.

power may be furnished by d.c. engine-driven generators, motor-generator sets, vacuum tube rectifiers, or dry-disk or solid-state rectifiers.

In aircraft with a.c. systems, a special d.c. generator is not desirable since it would be necessary for the engine accessory section to drive an additional piece of equipment. Motor-generator sets, consisting of air-cooled a.c. motors that drive d.c. generators, eliminate this objection because they operate directly off the a.c. power system. Vacuum tube or various types of solid-state rectifiers provide a simple and efficient method of obtaining high voltage d.c. at low amperage. Dry-disk and solid-state rectifiers on the other hand are an excellent source of high amperage at low voltage.

A rectifier is a device which transforms alternating current into direct current by limiting or regulating the direction of current flow. The principal types of rectifiers are dry-disk, solid-state, and vacuum tube rectifiers. Solid-state, or semiconductor, rectifiers are rapidly replacing all other types; and, since dry-disk and vacuum tube rectifiers and motor-generators are largely limited to older model aircraft, the major part of the study of rectifiers will be devoted to solid-state devices used for rectification.

Motor-Generator

A motor-generator is an a.c. motor and a d.c. generator combined in one unit. This combination is often called a converter. Converters operate directly on either single-phase or three-phase voltage. Converters used on large aircraft are often operated by a three-phase, 208-volt, a.c. system and develop a direct current of 200 amperes at 30 volts with an approximate 28-ampere current drain on the a.c. system. Units similar to those used in airplanes with d.c. systems are provided for voltage regulation and paralleling of motor-generator sets.

A motor-generator offers a number of advantages as a source of d.c. power in an airplane. With a motor-generator, a momentary interruption of a.c. power does not cut off the d.c. power completely, since the inertia of the armature keeps it turning during the a.c. power interruption. Extreme temperature changes affect a motor-generator only slightly. Failure from overheating is negligible compared to that in a vacuum tube rectifier when it is operated above a safe temperature. In addition, a motor-generator can be operated at temperatures below those required by either dry-disk or vacuum tube rectifiers.

The greatest objection to a motor-generator is that, like all rotary devices, it requires considerable maintenance and creates a noise which is especially objectionable if the set is in the cabin of the airplane. For these reasons and, because of weight, space, and cost consideration, the motor-generator set is rapidly being replaced by various solid-state power sources.

Dry-Disk

Dry-disk rectifiers operate on the principle that electric current flows through a junction of two dissimilar conducting materials more readily in one direction than it does in the opposite direction. This is true because the resistance to current flow in one direction is low, while in the other direction it is high. Depending on the materials used, several amperes may flow in the direction of low resistance but only a few milliamperes in the direction of high resistance.

Three types of dry-disk rectifiers may be found in aircraft: the copper-oxide rectifier, the selenium rectifier, and the magnesium copper-sulfide rectifier. The copper-oxide rectifier (figure 8–234) consists of a copper disk upon which a layer of copper oxide has been formed by heating. It may also consist of a chemical copper-oxide preparation spread evenly over the copper surface. Metal plates, usually lead plates, are pressed against the two opposite faces of the disk to form a good contact. Current flow is from the copper to the copper oxide.

The selenium rectifier consists of an iron disk, similar to a washer, with one side coated with selenium. Its operation is similar to that of the copper-oxide rectifier. Current flows from the selenium to the iron.

The magnesium copper-sulfide rectifier is made of washer-shaped magnesium disks coated with a

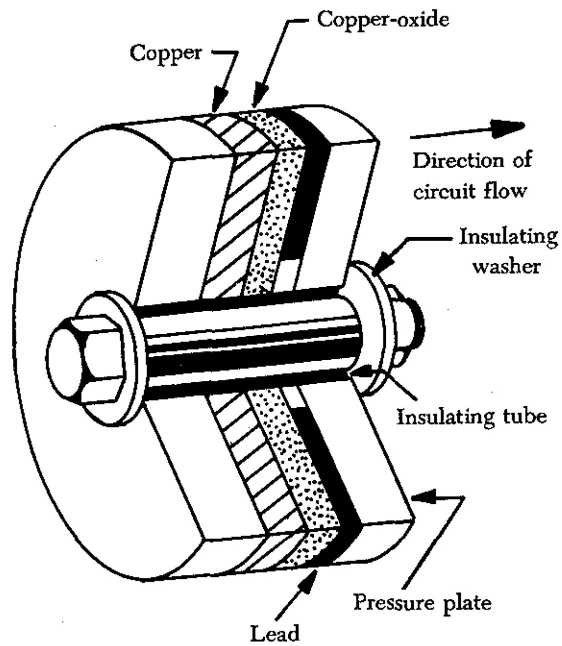


FIGURE 8–234. Copper-oxide dry-disk rectifier.

layer of copper sulfide. The disks are arranged similarly to the other types. Current flows from the magnesium to the copper sulfide.

Solid-State Rectifiers

In the study of transistors it was pointed out that the solid-state diode is manufactured from semiconductor material. It consists of N-type and P-type material joined in a single crystal. The point, or junction, where the two materials are in contact is called a P–N junction. This type of semiconductor, regardless of rating or size, is called a junction diode. The first type of semiconductor used was called the point-contact diode. It utilized a single type of semiconductor material, against which a tungsten or phosphor-bronze wire, called a "cat whisker," was pressed or fused. The point-contact diode has been largely replaced by the junction diode because of its limited current-carrying capabilities. The most common semiconductor materials are germanium and silicon. A typical junction diode is shown in figure 8–235.

In figure 8–236, the positive terminal of the battery is connected to the P-type semiconductor material, and the negative terminal is connected to the N-type. This arrangement constitutes forward bias. The holes in the P-type material are repelled from the positive terminal and move toward the junction. The electrons in the N-type

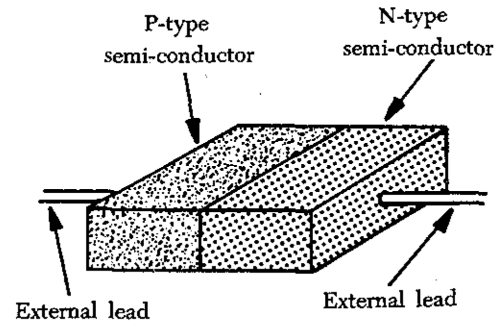


FIGURE 8–235. Junction diode.

material are repelled from the negative terminal and likewise move toward the junction. This decreases the space charge existing at the junction, and electron current flow is maintained through the external circuit. The current in the P-type material is in the form of holes, and in the N-type material it is in the form of electrons. If the forward bias is increased, current flow will increase. If the forward bias is increased excessively, it will cause excessive current. The excessive current will increase thermal agitation and the crystal structure will break down. One important fact worth remembering is that all solid-state devices are sensitive to heat and will be destroyed if the heat becomes too intense.

If the battery connections shown in figure 8–236 are reversed, the junction diode is reverse-biased. Now the holes are attracted toward the negative terminal and away from the junction. The electrons are attracted toward the positive terminal, also away from the junction. This widens the depletion region, increases the space charge, and reduces current to a minimum condition. It is possible to apply too high a reverse bias. When this happens, the crystal structure will break down.

The symbol for the semiconductor diode is shown in figure 8–237. Note that this is the same

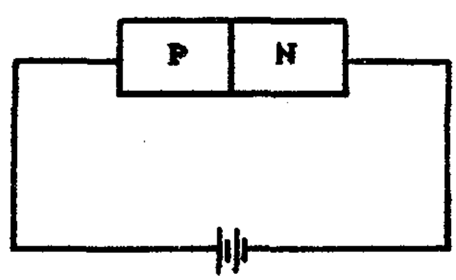


FIGURE 8–236. Forward bias on a junction diode.

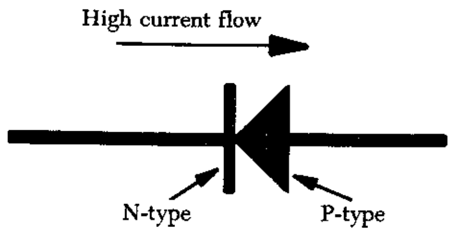


FIGURE 8–237. Semiconductor diode symbol.

symbol used for other types of diodes, such as the copper-oxide and selenium dry-disk rectifiers. The forward-bias, or high-current, direction is always against the arrow of the symbol.

Figure 8–238 shows a typical characteristic curve for a junction diode. As forward bias is increased a small amount, current flow is increased a considerable amount. For this reason, solid-state devices are said to be current-operated devices, since it is easier to measure the relatively large changes in current flow as compared to the small changes in applied voltage. With forward bias applied, the diode displays a low-resistance characteristic. On the other hand, with reverse bias applied, a high-resistance state exists. The most important characteristic of a diode is that it allows current to flow in one direction only. This permits solid-state devices to be used in rectifier circuits.

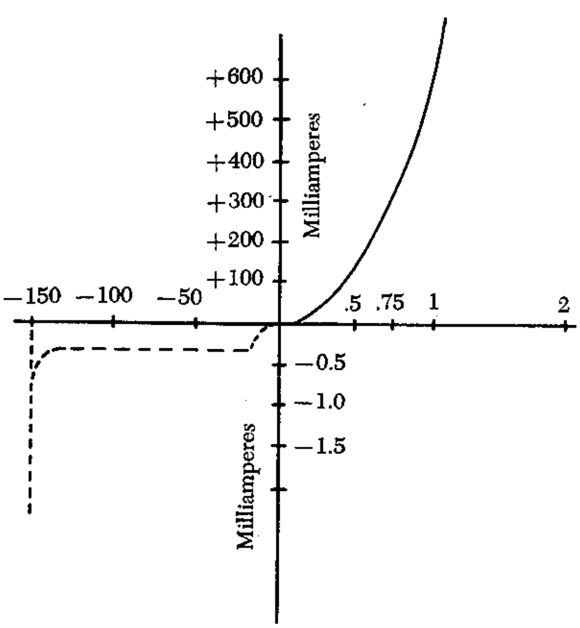


FIGURE 8–238. Typical junction diode characteristic curve.

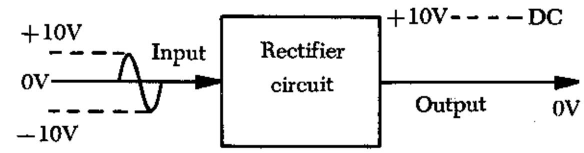


FIGURE 8–239. Rectification process.

Rectification

Rectification is the process of changing alternating current to direct current. When a semiconductor rectifier, such as a junction diode, is connected to an a.c. voltage source, it is alternately biased forward and reverse, in step with the a.c. voltage, as shown in figure 8–239.

In figure 8–240 a diode is placed in series with a source of a.c. power and a load resistor. This is called a half-wave rectifier circuit.

The transformer provides the a.c. input to the circuit; the diode provides the rectification of the a.c.; and the load resistor serves two purposes: (1) It limits the amount of current flow in the circuit to a safe level, and (2) it develops an output signal due to the current flow through it.

Assume, in figure 8–241, that the top of the transformer secondary is positive and the bottom negative. With this polarity, the diode is forward-biased, resistance of the diode is very low, and current flows through the circuit in the direction of the arrows. The output (voltage drop) across the load resistor follows the waveshape of the positive half of the a.c. input. When the a.c. input goes in a negative direction, the top of the transformer secondary becomes negative and the diode becomes reverse-biased.

With reverse bias applied to the diode, the resistance of the diode becomes very great, and current flow through the diode and load resistor becomes zero. (Remember that a very small current will flow through the diode.) The output,

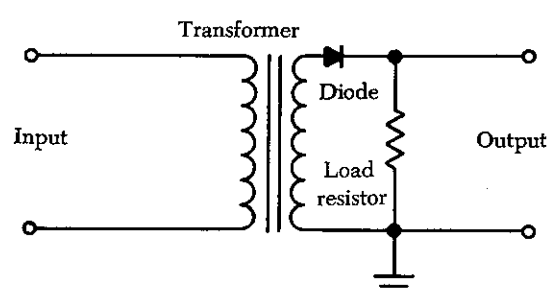


FIGURE 8–240. Half-wave rectifier circuit.

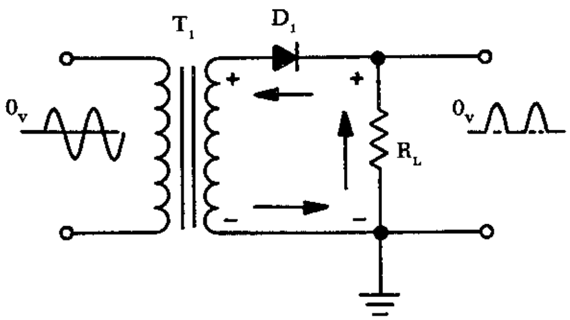


FIGURE 8–241. Output of a half-wave rectifier.

taken across the load resistor, will be zero. If the position of the diode were reversed, the output would be negative pulses.

In a half-wave rectifier, a half cycle of power is produced across the load resistor for each full cycle of input power. To increase the output power, a full-wave rectifier can be used. Figure 8–242 shows a full-wave rectifier, which is, in effect, two half-wave rectifiers combined into one circuit. In this circuit a load resistor is used to limit current flow and develop an output voltage, two diodes to provide rectification, and a transformer to provide an a.c. input to the circuit. The transformer, used in full-wave rectifier circuits, must be center tapped to complete the path for current flow through the load resistor.

Assuming the polarities shown on the transformer, diode D_1 will be forward-biased and current will flow from ground through the load resistor, through diode D_1, to the top of the transformer.

When the a.c. input changes direction, the transformer secondary will assume an opposite polarity.

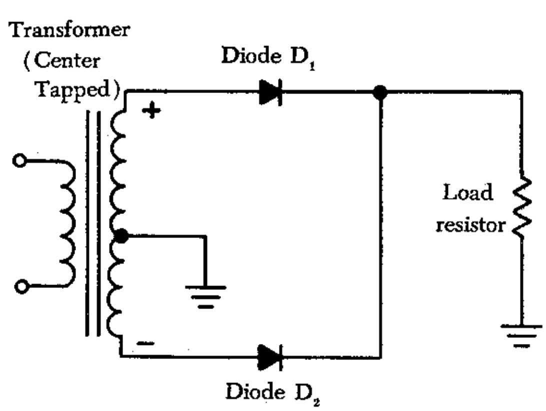


FIGURE 8–242. Full-wave rectifier.

Diode D_2 is now forward-biased and current will flow in the opposite direction, from ground through the load resistor, through diode D_2, to the bottom half of the transformer.

When one diode is forward-biased, the other is reverse-biased. No matter which diode is forward biased, current will flow through the load resistor in the same direction; so the output will be a series of pulses of the same polarity. By reversing both diodes, the output polarity will be reversed.

The voltage which is felt across a rectifier when reverse bias is being applied is often referred to as "the inverse peak voltage." By definition, this is the peak value of the instantaneous voltage across the rectifier during the half-cycle in which current does not flow or that reverse bias is applied. If an inverse voltage is applied that is too large, the rectifier will be destroyed. The term "breakdown voltage" is often used instead of the term "inverse peak voltage rating," but both terms have the same meaning. Breakdown voltage is the maximum voltage that the rectifier can stand while it is not conducting (reverse-biased); the inverse peak voltage is the voltage actually being applied to the rectifier. As long as the inverse peak voltage is lower than breakdown voltage, there will be no problem of rectifier destruction.

Diode Bridge Rectifier Circuit

An advantageous modification of the full-wave diode rectifier is the bridge rectifier. The bridge rectifier differs from the full-wave rectifier in that a bridge rectifier does not require a center-tapped transformer, but does require two additional diodes.

To illustrate how a bridge rectifier performs, consider a sine wave input which is on its positive alternation as denoted on the schematic of figure 8–243. With the secondary of T_1 functioning as the bridge rectifier's power supply, point A is the most positive point of the bridge, while B is the most negative. Current flow will be from B to A through the forward-biased diodes. As an aid in finding the path of electron flow, consider the redrawn bridge circuit in figure 8–244. The forward-biased diodes, CR_3 and CR_4 are easily recognized. Voltage is dropped across each voltage loop as indicated. Thus, on the positive half-cycle input CR_3 and CR_4 are both forward-biased and CR_1 and CR_2 are reverse-biased.

As long as diode breakdown voltage is not exceeded, current flow will be from point B up and

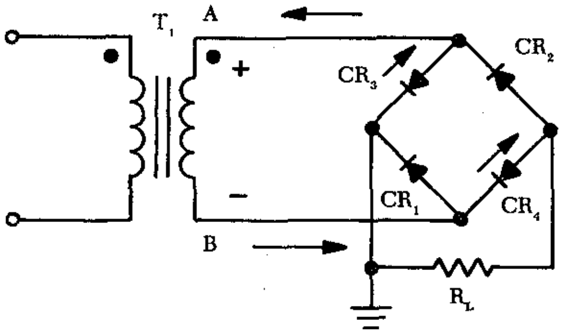


FIGURE 8–243. Diode bridge rectifier.

across CR_4 down and to the left across R_L. After current crosses R_L, it will flow to point A through CR_3. Notice that current flow across R_L is from right to left, or in respect to polarity, a negative half-cycle output for positive half-cycle input.

Remember that, when tracing current flow for the negative half-cycle, electron flow through a diode is against the symbolic arrow and from negative to a less negative or positive point. Therefore, no confusion should arise when tracing electron flow up to and away from the common point between CR_3 and CR_1. Although it may appear that CR_1 as well as CR_4 is forward-biased, such is not the case. The collector of CR_1 is more negative than its emitter; therefore, it is reverse-biased.

Since, on the negative half-cycle, CR_1 and CR_2 are forward-biased, the output signal on the negative half-cycle is negative.

Since both half-cycles of the input signal result in negative output pulses, the bridge rectifier has accomplished the same goal as the full-wave diode rectifier.

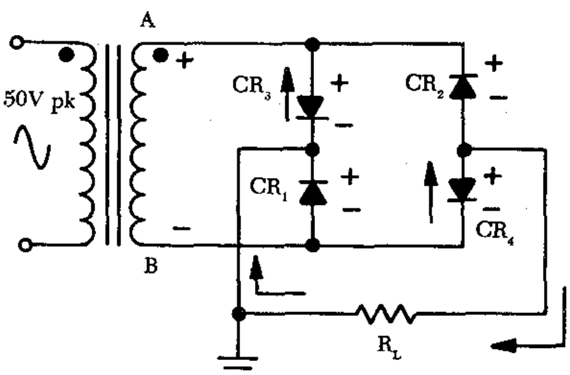


FIGURE 8–244. Redrawn bridge rectifier circuit.

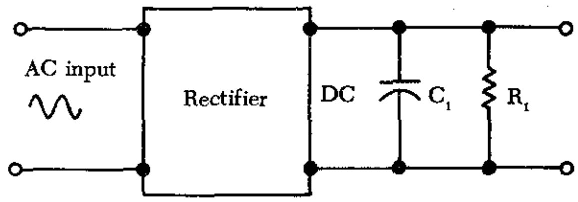


FIGURE 8–245. A capacitor used as a filter.

FILTERING

That part of the rectification process which involves the converting of an a.c. voltage into pulses of d.c. voltage has been treated in the discussion of vacuum tube, dry-disk, and semiconductor diodes. To complete the rectification process so that the pulses of voltage are changed to an acceptable approximation of smooth d.c. involves a process called filtering.

Any reactance which opposes a change in voltage (or current) by storing energy and then releasing this energy back to the circuit may be used as a filter.

In the study of capacitors, it was demonstrated that a capacitance opposes a voltage change across its terminal by storing energy in its electrostatic field. Whenever the voltage tends to rise, the capacitor converts this voltage change to stored energy. When the voltage tends to fall, the capacitor converts this stored energy back to voltage. The use of a capacitor for filtering the output of a rectifier is illustrated in figure 8–245. The rectifier is shown as a block, and the capacitor C_1 is connected in parallel with the load R_1.

The capacitor C_1 is chosen to offer very low impedance to the a.c. ripple frequency and very high impedance to the d.c. component. The ripple voltage is therefore bypassed to ground through the low-impedance path, while the d.c. voltage is applied unchanged to the load. The effect of the capacitor on the output of the rectifier can be seen in the waveshapes shown in figure 8–246. Dotted lines show the rectifier output; solid lines show the effect of the capacitor. Full-wave rectifier outputs are shown. The capacitor C_1 charges when the rectifier voltage output tends to increase and discharges when the voltage output tends to decrease. In this manner, the voltage across the load R_1 is kept fairly constant.

An inductance may be used as a filter, because it opposes a change in current through it by storing energy in its electromagnetic field when-

FIGURE 8–246. Half-wave and full-wave rectifier outputs using capacitor filter.

ever current tends to increase. When the current through the inductor tends to decrease, the inductor supplies the energy to maintain the flow of current. The use of an inductor for filtering the output of a rectifier is shown in figure 8–247. Note that the inductor L_1 is in series with the load R_1.

The inductance L_1 is chosen to offer high impedance to the a.c. ripple voltage and low impedance to the d.c. component. Therefore, for the a.c. ripple, a very large voltage drop occurs across the inductor and a very small voltage drop across the load R_1. For the d.c. component, however, a very small voltage drop occurs across the inductor and a very large voltage drop across the load. The effect of an inductor on the output of a full-wave rectifier in the output waveshape is shown in figure 8–248. Note that the ripple has been attenuated (reduced) in the output voltage.

Capacitors and inductors are combined in various ways to provide more satisfactory filtering than can be obtained with a single capacitor or inductor. These are referred to collectively as "LC filters." Several combinations are shown schematically in figure 8–249. Note that the L-, or inverted L-type, and the T-type filter sections resemble schematically the corresponding letters of the alphabet. The pi-type filter section resembles the Greek letter pi (π) schematically.

All the filter sections shown are similar in that

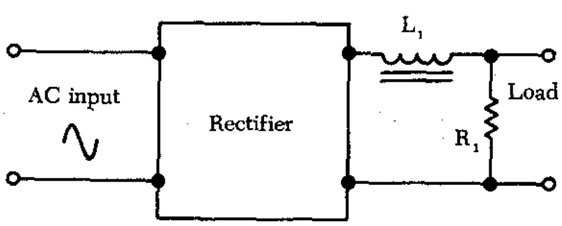


FIGURE 8–247. An inductor used as a filter.

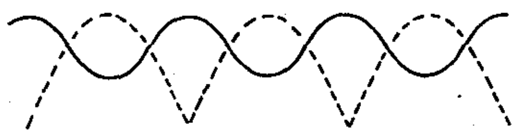


FIGURE 8–248. Output of an inductor filter rectifier.

the inductances are in series and the capacitances are in parallel with the load. The inductances must, therefore, offer a very high impedance and the capacitors a very low impedance to the ripple frequency. Since the ripple frequency is comparatively low, the inductances are iron-core coils having large values of inductance (several henries). Because they offer such high impedance to the ripple frequency, these coils are called chokes. The capacitors must also be large (several microfarads) to offer very little opposition to the ripple frequency. Because the voltage across the capacitor is d.c., electrolytic capacitors are frequently used as filter capacitors. The correct polarity in connecting electrolytic capacitors should always be observed.

Additional filter sections may be combined to improve the filtering action.

LC filters are also classified according to the position of the capacitor and inductor. A capacitor-input filter is one in which the capacitor is connected directly across the output terminals of the rectifier. A choke-input filter is one in which a choke precedes the filter capacitor.

If it is necessary to increase the applied voltage to more than a single rectifier can tolerate, the usual solution is to stack them. These rectifiers are similar to resistors added in series. Each resistor will drop a portion of the applied voltage rather than the total voltage. The same theory applies to rectifiers added in series, or stacked. Series stacking increases the voltage rating. If, for example, a rectifier will be destroyed with an applied voltage exceeding 50 volts, and it is to be used in a circuit with an applied voltage of 150 volts, stacking of diodes can be employed. The result is shown in figure 8–250.

Identification of Semiconductor Diodes

There are many types of semiconductor diodes in existence today and several methods are used to identify the emitter and collector. The following are the three most common methods used to identify the emitter and collector.

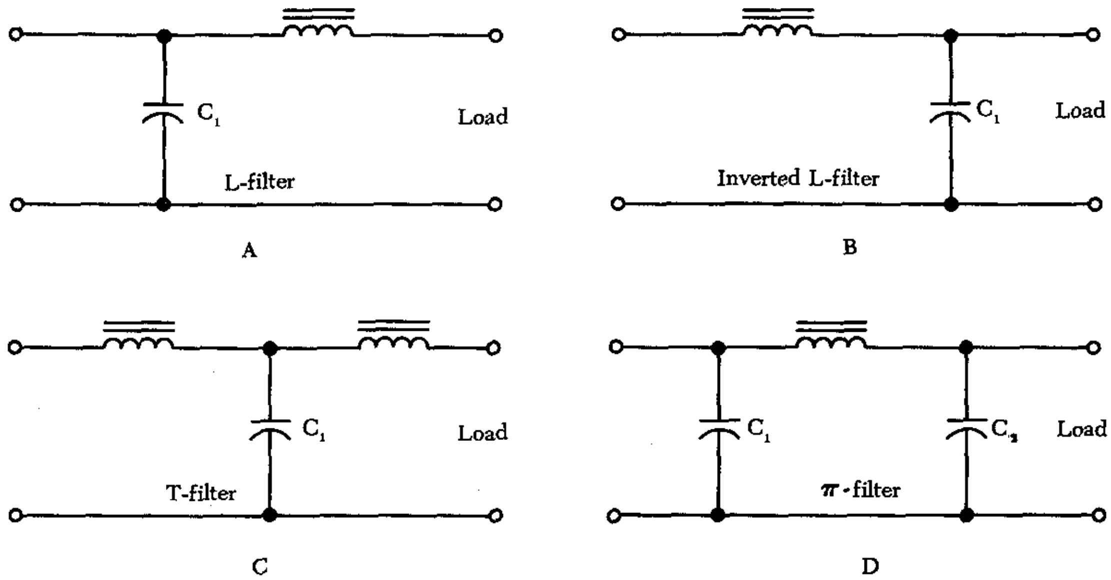


FIGURE 8–249. LC filters.

One method places a small dot near the emitter lead (A of figure 8–251). A second method stamps the rectifier symbol on the diode case (B of figure 8–251). The third method used quite frequently is the color code method (C of figure 8–251). Frequently the color code used is the same as the color code used for resistors.

One very common diode is the 1N538. The "1N" indicates that there is only one PN junction, or that the device is a diode; the numbers that follow normally indicate manufacturing sequence; that is, a 1N537 was developed before the 1N538, which may be an improved model of the 1N537 or may be an entirely different diode altogether.

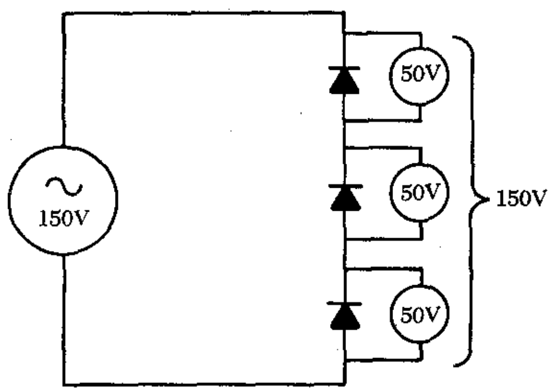


FIGURE 8–250. Stacking diodes in a circuit.

A. C. MEASURING INSTRUMENTS

A d.c. meter, such as an ammeter, connected in an a.c. circuit will indicate zero, because the moving ammeter coil that carries the current to be measured is located in a permanent magnet

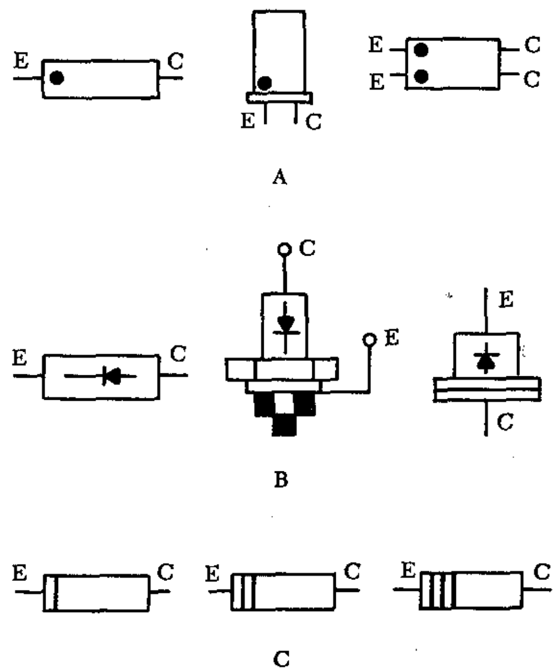


FIGURE 8–251. Diode identification.

field. Since the field of a permanent magnet remains constant and in the same direction at all times, the moving coil follows the polarity of the current. The coil attempts to move in one direction during half of the a.c. cycle and in the reverse direction during the other half when the current reverses.

The current reverses direction too rapidly for the coil to follow, causing the coil to assume an average position. Since the current is equal and opposite during each half of the a.c. cycle, the direct current meter indicates zero, which is the average value. Thus, a meter with a permanent magnet cannot be used to measure alternating voltage and current. However, the permanent magnet D'Arsonval meter may be used to measure alternating current or voltage if the current that passes through the meter is first rectified—that is, changed from alternating current to direct current.

Rectifier A. C. Meters

Copper-oxide rectifiers are generally used with D'Arsonval d.c. meter movements to measure alternating currents and voltages; however, there are many types of rectifiers which may be used, some of which are included in the discussion of alternator systems.

A copper-oxide rectifier allows current to flow through a meter in only one direction. As shown in figure 8–252, the copper-oxide rectifier consists of copper-oxide disks separated alternately by copper disks and fastened together as a single unit. Current flows more readily from copper to copper oxide than from copper oxide to copper. When a.c. is applied, therefore, current flows in only one direction, yielding a pulsating d.c. output as shown by the output wave shapes in figure 8–253. This current can then be measured as it flows through the meter movement.

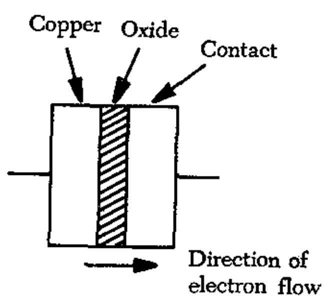


FIGURE 8–252. Copper-oxide rectifier.

In some a.c. meters, selenium or vacuum tube rectifiers are used in place of the copper-oxide rectifier. The principle of operation, however, is the same in all meters employing rectifiers.

Electrodynamometer Meter Movement

The electrodynamometer meter can be used to measure alternating or direct voltage and current. It operates on the same principles as the permanent magnet moving-coil meter, except that the permanent magnet is replaced by an air-core electromagnet. The field of the electrodynamometer meter is developed by the same current that flows through the moving coil (see figure 8–254).

In the electrodynamometer meter, two stationary field coils are connected in series with the movable coil. The movable coil is attached to the central shaft and rotates inside the two stationary field coils. The spiral springs provide the restraining force for the meter and also a means of introducing current to the movable coil.

When current flows through field coils A and B and movable coil C, coil C rotates in opposition to the springs and places itself parallel to the field coils. The more current flowing through the coils, the more the moving coil overcomes the opposition of the springs and the farther the pointer moves across the scale. If the scale is properly calibrated and the proper shunts or multipliers are used, the dynamometer movement will indicate current or voltage.

Although electrodynamometer meters are very accurate, they do not have the sensitivity of D'Arsonval meters and, for this reason, are not widely used outside the laboratory.

Electrodynamometer Ammeter

In the electrodynamometer ammeter, low resistance coils produce only a small voltage drop in the circuit measured. An inductive shunt is connected in series with the field coils. This shunt, similar to the resistor shunt used in d.c. ammeters, permits only part of the current being measured to flow through the coils. As in the d.c. ammeter, most of the current in the circuit flows through the shunt; but the scale is calibrated accordingly, and the meter reads the total current. An a.c. ammeter, like a d.c. ammeter, is connected in series with the circuit in which current is measured. Effective values are indicated by the

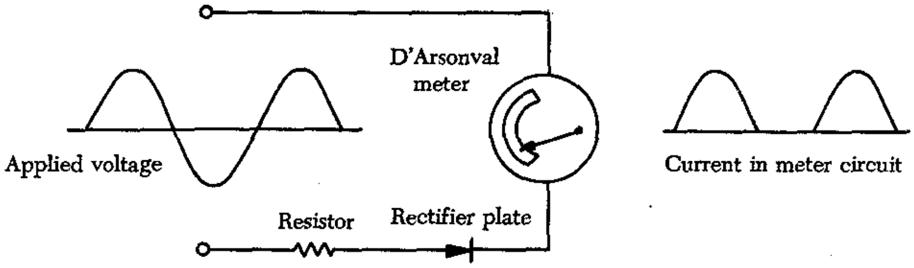


FIGURE 8–253. A half-wave rectifier circuit.

meter. A schematic diagram of an electrodynamometer ammeter circuit is shown in figure 8–255.

Electrodynamometer Voltmeter

In the electrodynamometer voltmeter, field coils are wound with many turns of small wire. Approximately 0.01 ampere of current flow through both coils is required to operate the meter. Resistors of a noninductive material, connected in series with the coils, provide for different voltage ranges. Voltmeters are connected in parallel across the unit in which voltage is to be measured. The values of voltages indicated are effective values. A schematic diagram of an electrodynamometer voltmeter is shown in figure 8–256.

Moving Iron-Vane Meter

The moving iron-vane meter is another basic type of meter. It can be used to measure either a.c. or d.c. Unlike the D'Arsonval meter, which employs permanent magnets, it depends on induced magnetism for its operation. It utilizes the principle of repulsion between two concentric iron vanes, one fixed and one movable, placed inside a solenoid, as shown in figure 8–257. A pointer is attached to the movable vane.

When current flows through the coil, the two iron vanes become magnetized with north poles at their upper ends and south poles at their lower ends for one direction of current through the coil. Because like poles repel, the unbalanced component of force, tangent to the movable element, causes it to turn against the force exerted by the springs.

The movable vane is rectangular in shape and the fixed vane is tapered. This design permits the use of a relatively uniform scale.

When no current flows through the coil, the movable vane is positioned so that it is opposite the larger portion of the tapered fixed vane, and the scale reading is zero. The amount of magnetization of the vanes depends on the strength of the field, which, in turn, depends on the amount of current flowing through the coil. The force of

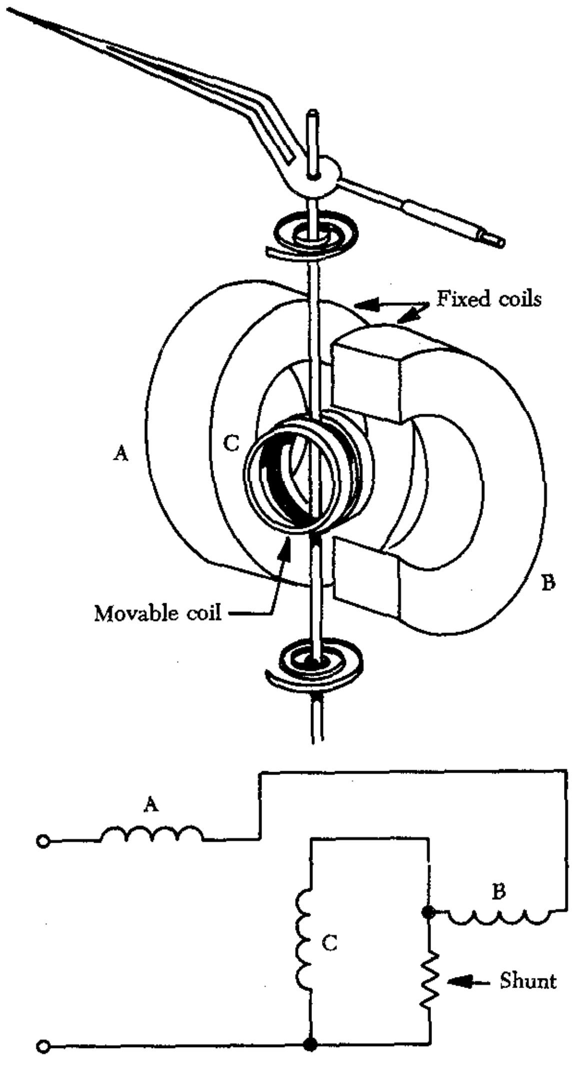


FIGURE 8–254. Simplified diagram of an electrodynamometer movement.

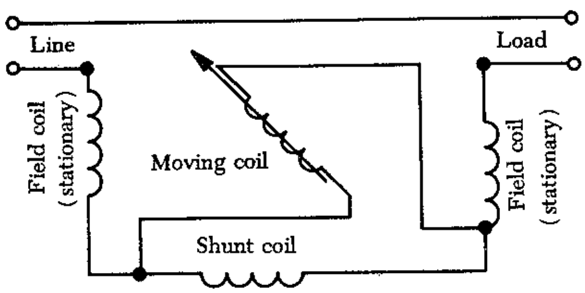


FIGURE 8–255. Electrodynamometer ammeter circuit.

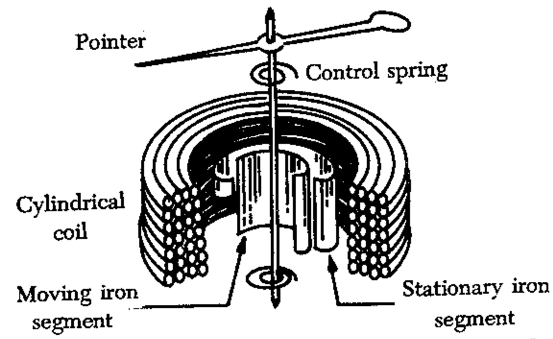


FIGURE 8–257. Moving iron-vane meter.

repulsion is greater opposite the larger end of the fixed vane than it is nearer the smaller end. Therefore, the movable vane moves toward the smaller end through an angle that is proportional to the magnitude of the coil current. The movement ceases when the force of repulsion is balanced by the restraining force of the spring.

Because the repulsion is always in the same direction (toward the smaller end of the fixed vane), regardless of the direction of current flow through the coil, the moving iron-vane instrument operates on either d.c. or a.c. circuits.

Mechanical damping in this type of instrument can be obtained by the use of an aluminum vane attached to the shaft so that, as the shaft moves, the vane moves in a restricted air space.

When the moving iron-vane meter is designed to be used as an ammeter, the coil is wound with relatively few turns of large wire in order to carry the rated current.

When the moving iron-vane meter is designed to be used as a voltmeter, the solenoid is wound with many turns of small wire. Portable voltmeters are made with self-contained series resistance for ranges up to 750 volts. Higher ranges

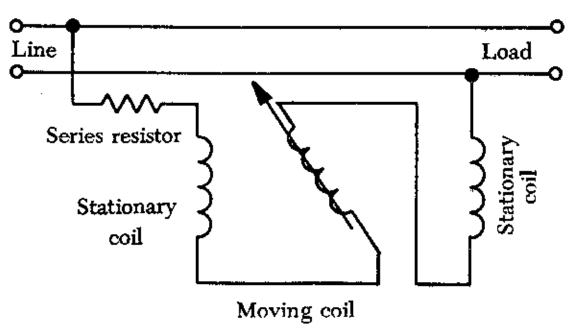


FIGURE 8–256. Electrodynamometer voltmeter circuit.

are obtained by the use of additional external multipliers.

The moving iron-vane instrument may be used to measure direct current but has an error due to residual magnetism in the vanes. The error may be minimized by reversing the meter connections and averaging the readings. When used on a.c. circuits the instrument has an accuracy of 0.5 percent. Because of its simplicity, its relatively low cost, and the fact that no current is conducted to the moving element, this type of movement is used extensively to measure current and voltage in a.c. power circuits. However, because the reluctance of the magnetic circuit is high, the moving iron-vane meter requires much more power to produce full-scale deflection than is required by a D'Arsonval meter of the same range. Therefore, the moving iron-vane meter is seldom used in high-resistance low-power circuits.

Inclined-Coil Iron-Vane Meter

The principle of the moving iron-vane mechanism is applied to the inclined-coil type of meter, which can be used to measure both a.c. and d.c. The inclined-coil, iron-vane meter has a coil mounted at an angle to the shaft. Attached obliquely to the shaft, and located inside the coil, are two soft-iron vanes. When no current flows through the coil, a control spring holds the pointer at zero, and the iron vanes lie in planes parallel to the plane of the coil. When current flows through the coil, the vanes tend to line up with magnetic lines passing through the center of the coil at right angles to the plane of the coil. Thus, the vanes rotate against the spring action to move the pointer over the scale.

The iron vanes tend to line up with the magnetic lines regardless of the direction of current

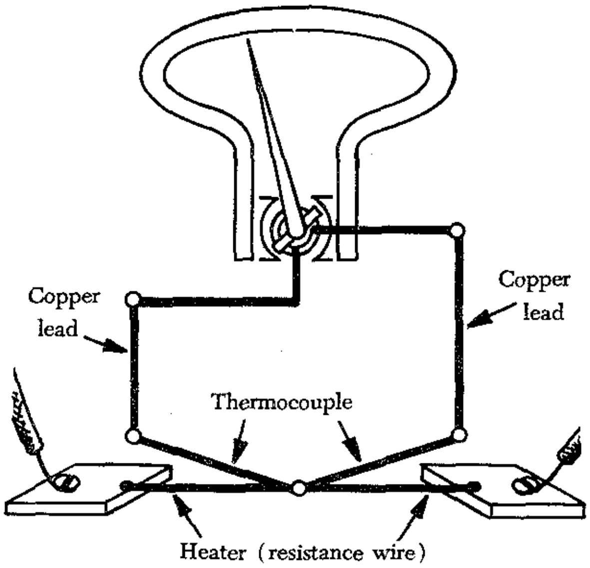


FIGURE 8–258. Simplified diagram of a thermocouple meter.

flow through the coil. Therefore, the inclined-coil, iron-vane meter can be used to measure either alternating current or direct current. The aluminum disk and the drag magnets provide electromagnetic damping.

Like the moving iron-vane meter, the inclined-coil type requires a relatively large amount of current for full-scale deflection and is seldom used in high-resistance low-power circuits.

As in the moving iron-vane instruments, the inclined-coil instrument is wound with few turns of relatively large wire when used as an ammeter and with many turns of small wire when used as a voltmeter.

Thermocouple Meter

If the ends of two dissimilar metals are welded together and this junction is heated, a d.c. voltage is developed across the two open ends. The voltage developed depends on the material of which the wires are made and on the difference in temperature between the heated junction and the open ends.

In one type of instrument, the junction is heated electrically by the flow of current through a heater element. It does not matter whether the current is alternating or direct because the heating effect is independent of current direction. The maximum current that can be measured depends on the current rating of the heater, the heat that the thermocouple can stand without being damaged, and on the current rating of the meter used with the thermocouple. Voltage can also be measured if a suitable resistor is placed in series with the heater. In meter applications, a D'Arsonval meter is used with a resistance wire heater, as shown in figure 8–258.

As current flows through the resistance wire, the heat developed is transferred to the contact point and develops an e.m.f. which causes current to flow through the meter. The coil rotates and causes the pointer to move over a calibrated scale. The amount of coil movement is dependent on the amount of heat, which varies as the square of the current. Thermocouple meters are used extensively in a.c. measurements.

Varmeters

Multiplying the volts by the amperes in an a.c. circuit gives the apparent power: the combination of the true power which does the work and the reactive power which does no work and is returned to the line. Reactive power is measured in units of vars (volt-amperes reactive) or kilovars (kilovolt-amperes reactive, abbreviated KVAR). When properly connected, wattmeters measure the reactive power. As such, they are called varmeters. The illustration in figure 8–259 shows a varmeter connected in an a.c. circuit.

Wattmeter

Electric power is measured by means of a wattmeter. Because electric power is the product of current and voltage, a wattmeter must have two elements, one for current and the other for voltage, as indicated in figure 8–260. For this reason, wattmeters are usually of the electrodynamometer type.

The movable coil with a series resistance forms the voltage element, and the stationary coils constitute the current element. The strength of

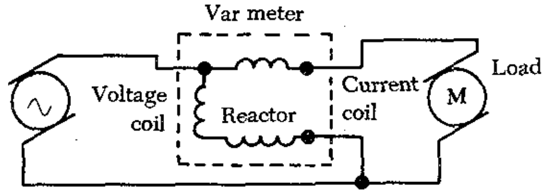


FIGURE 8–259. A varmeter connected in an a.c. circuit.

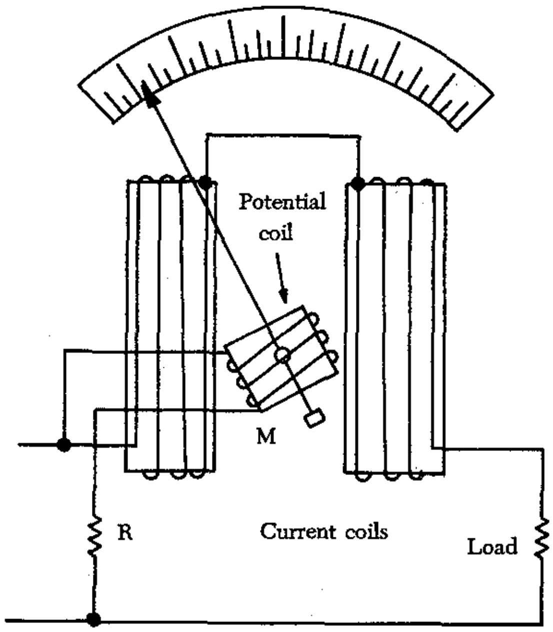


FIGURE 8–260. Simplified electrodynamometer wattmeter circuit.

the field around the potential coil depends on the amount of current that flows through it. The current, in turn, depends on the load voltage applied across the coil and the high resistance in series with it. The strength of the field around the current coils depends on the amount of current flowing through the load. Thus, the meter deflection is proportional to the product of the voltage across the potential coil and the current through the current coils. The effect is almost the same (if the scale is properly calibrated) as if the voltage applied across the load and the current through the load were multiplied together.

If the current in the line is reversed, the direction of current in both coils and the potential coil is reversed, the net result is that the pointer continues to read up-scale. Therefore, this type of wattmeter can be used to measure either a.c. or d.c. power.

FREQUENCY METERS

Alternating-current electrical equipment is designed to operate within a given frequency range. In some instances the equipment is designed to operate at one particular frequency, as are electric clocks and time switches. For example, electric clocks are commonly designed to operate at 60 c.p.s. If the supply frequency is reduced to 59 c.p.s., the clock will lose one minute every hour.

Transformers and a.c. machinery are designed to operate at a specified frequency. If the supply frequency falls more than 10 percent from the rated value, the equipment may draw excessive current, and dangerous overheating will result. It is, therefore, necessary to control the frequency of electric power systems. Frequency meters are employed to indicate the frequency so that corrective measures can be taken if the frequency varies beyond the prescribed limits.

Frequency meters are designed so that they will not be affected by changes in voltage. Because a.c. systems are designed to operate normally at one particular frequency, the range of the frequency meter may be restricted to a few cycles on either side of the normal frequency. There are several types of frequency meters, including the vibrating-reed type, the fixed-coil and moving-coil type, the fixed-coil and moving-disk type, and the resonant-circuit type. Of these types, the vibrating-reed frequency meter is used most often in aircraft systems, and is discussed in some detail.

Vibrating-Reed Frequency Meter

The vibrating-reed type of frequency meter is one of the simplest devices for indicating the frequency of an a.c. source. A simplified diagram of one type of vibrating-reed frequency meter is shown in figure 8–261.

The current whose frequency is to be measured flows through the coil and exerts maximum attraction on the soft-iron armature twice during each cycle (A of figure 8–261). The armature is attached to the bar, which is mounted on a flexible support. Reeds of suitable dimensions to have natural vibration frequencies of 110, 112, 114, and so forth up to 130 c.p.s. are mounted on the bar (B of figure 8–261). The reed having a frequency of 110 c.p.s. is marked "55" cycles; the one having a frequency of 130 c.p.s. is marked "65" c.p.s.; the one having a frequency of 120 c.p.s. is marked "60" c.p.s., and so forth.

In some instruments the reeds are the same lengths, but are weighted by different amounts at the top so that they will have different natural rates of vibration.

When the coil is energized with a current having a frequency between 55 and 65 c.p.s., all the reeds are vibrated slightly; but the reed having a

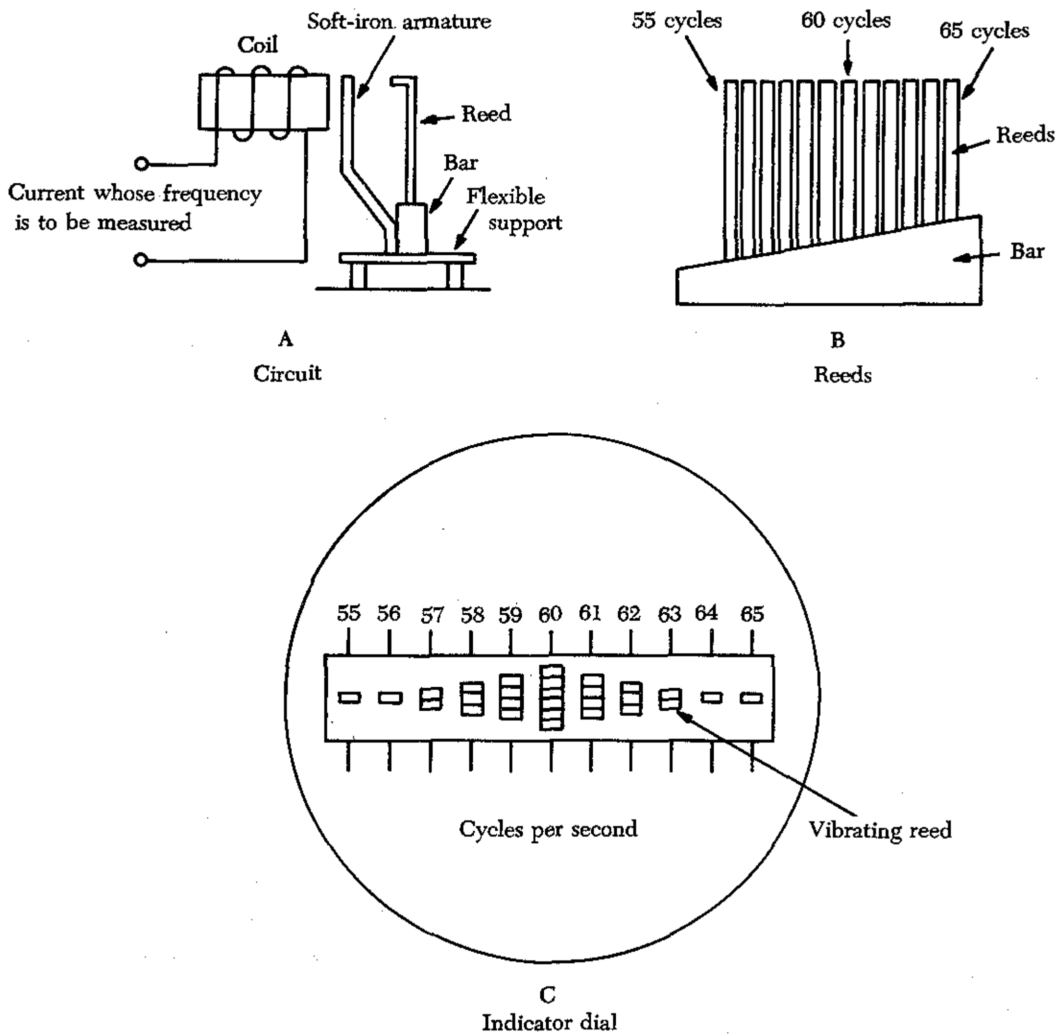


FIGURE 8–261. Simplified diagram of a vibrating-reed frequency meter.

natural frequency closest to that of the energizing current (whose frequency is to be measured) vibrates through a larger amplitude. The frequency is read from the scale value opposite the reed having the greatest amplitude of vibration.

An end view of the reeds is shown in the indicator dial (C of figure 8–261). If the energizing current has a frequency of 60 c.p.s., the reed marked "60" c.p.s. will vibrate the greatest amount, as shown.