# Section 15

# Electrical and Electronics Engineering

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### by C. James Erickson
### revised by Charles D. Potts

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# 15.1 ELECTRICAL ENGINEERING

### by C. James Erickson
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REFERENCES: Knowlton, ''Standard Handbook for Electrical Engineers,'' McGraw-Hill. Pender and Del Mar, ''Electrical Engineers' Handbook,'' Wiley. Dawes, ''Course in Electrical Engineering,'' Vols. I and II, McGraw-Hill. Gray, ''Principles and Practice of Electrical Engineering,'' McGraw-Hill. Laws, ''Electrical Measurements,'' McGraw-Hill. Karapetoff-Dennison, ''Experimental Electrical Engineering and Manual for Electrical Testing,'' Wiley. Langsdorf, ''Principles of Direct-current Machines,'' McGraw-Hill. Hehre and Harness, ''Electric Circuits and Machinery,'' Vols. I and II, Wiley. Timbie-Higbie, ''Alternating Current Electricity and Its Application to Industry,'' Wiley. Lawrence, ''Principles of Alternating-current Machinery,'' McGraw-Hill. Puchstein and Lloyd, ''Alternating-current Machinery,'' Wiley. Lovell, ''Generating Stations,'' McGraw-Hill. Underhill, ''Coils and Magnet Wire'' and ''Magnets,'' McGraw-Hill. Abbott, ''National Electrical Code Handbook,'' McGraw-Hill. Dyke, ''Automobile and Gasoline Engine Encyclopedia,'' The Goodheart-Wilcox Co., Inc. Fink and Carrol, ''Standard Handbook for Electrical Engineers,'' McGraw-Hill.

## ELECTRICAL AND MAGNETIC UNITS

**System of Units** The International System of Units **(SI)** is being adopted universally. The SI system has its roots in the metre, kilogram, second (mks) system of units. Since a centimeter, gram, second **(cgs)** system has been widely used, and will still be used in some instances, Tables 15.1.1 and 15.1.2 are provided for conversion between the two systems. Basic SI units are metre, kilogram (mass), second, ampere, kelvin, mole (quantity), and candela (luminous intensity). Other SI units are derived from these basic units.

### Electrical Units

(See Table 15.1.1.)

**Current** ($I$, $i$) The SI unit of current is the **ampere,** which is equal to one-tenth the absolute unit of current **(abampere).** The abampere of current is defined as follows: if 0.01 metre (1 centimetre) of a circuit is bent into an arc of 0.01 metre (1 centimetre) radius, the current is 1 abampere if the magnetic field intensity at the center is 0.01257 ampere per metre (1 oersted), provided the remainder of the circuit produces no magnetic effect at the center of the arc. One **international ampere** (9.99835 amperes) (dc) will deposit 0.001118 gram per second of silver from a standard silver solution.

**Quantity** ($Q$) The **coulomb** is the quantity of electricity transported in one second by a current of one ampere.

**Potential Difference or Electromotive Force** ($V$, $E$, emf) The **volt** is the difference of electric potential between two points of a conductor carrying a constant current of one ampere, when the power dissipated between these points is equal to one watt.

**Resistance** ($R$, $r$) The **ohm** is the electrical resistance between two points of a conductor when a constant difference of potential of one volt, applied between these two points, produces in this conductor a current of one ampere, this conductor not being the source of any electromotive force.

**Resistivity** ($\rho$) The resistivity of a material is the dc resistance between the opposite parallel faces of a portion of the material having unit length and unit cross section.

**Conductance** ($G$, $g$) The **siemens** is the electrical conductance of a conductor in which a current of one ampere is produced by an electric potential difference of one volt. One siemens is the reciprocal of one ohm.

**Conductivity** ($\gamma$) The conductivity of a material is the dc conductance between the opposite parallel faces of a portion of the material having unit length and unit cross section.

**Capacitance** ($C$) is that property of a system of conductors and dielectrics which permits the storage of electricity when potential difference exists between the conductors. Its value is expressed as a ratio of a quantity of electricity to a potential difference. A capacitance value is always positive. The farad is the capacitance of a capacitor between the plates of which there appears a difference of potential of one volt when it is charged by a quantity of electricity equal to one coulomb.

**Permittivity or dielectric constant** ($\varepsilon_0$) is the electrostatic energy stored per unit volume of a vacuum for unit potential gradient. The permittivity of a vacuum or free space is $8.85 \times 10^{-12}$ farads per metre.

**Relative Permittivity or Dielectric Constant** ($\varepsilon_r$) is the ratio of electrostatic energy stored per unit volume of a dielectric for a unit potential gradient to the permittivity ($\varepsilon_0$) of a vacuum. The relative permittivity is a number.

**Self-inductance** ($L$) is the property of an electric circuit which determines, for a given rate of change of current in the circuit, the emf induced in the same circuit. Thus $e_1 = -L\,di_1/dt$, where $e_1$ and $i_1$ are in the same circuit and $L$ is the coefficient of self-inductance.

The **henry** is the inductance of a closed circuit in which an electromotive force of one volt is produced when the electric current varies uniformly at a rate of one ampere per second.

**Mutual inductance** ($M$) is the common property of two associated electric circuits which determines, for a given rate of change of current in one of the circuits, the emf induced in the other. Thus $e_1 = -M\,di_2/dt$ and $e_2 = -M\,di_1/dt$, where $e_1$ and $i_1$ are in circuit 1; $e_2$ and $i_2$ are in circuit 2; and $M$ is the mutual inductance.

The **henry** is the mutual inductance of two separate circuits in which an electromotive force of one volt is produced in one circuit when the electric current in the other circuit varies uniformly at a rate of one ampere per second.

If $M$ is the mutual inductance of two circuits and $k$ is the coefficient of coupling, i.e., the proportion of flux produced by one circuit which links the other, then $M = k(L_1L_2)^{1/2}$, where $L_1$ and $L_2$ are the respective **self-inductances** of the two circuits.

**Energy** ($J$) in a system is measured by the amount of work which a system is capable of doing. The **joule** is the work done when the point of application of a force of one newton is displaced a distance of one metre in the direction of the force.

**Power** ($W$) is the time rate of transferring or transforming energy. The **watt** is the power which gives rise to the production of energy at the rate of one joule per second.

**Active power** ($P$) at the points of entry of a single-phase, two-wire circuit or of a polyphase circuit is the time average of the values of the instantaneous power at the points of entry, the average being taken over a complete cycle of the alternating current. The value of active power is given in **watts** when the rms currents are in amperes and the rms potential differences are in volts. For sinusoidal emf and current, $P = EI \cos\theta$, where $E$ and $I$ are the rms values of volts and currents, and $\theta$ is the phase difference of $E$ and $I$.

**Reactive power** ($Q$) at the points of entry of a single-phase, two-wire circuit, or for the special case of a sinusoidal current and sinusoidal potential difference of the same frequency, is equal to the product obtained by multiplying the rms value of the current by the rms value of the potential difference and by the sine of the angular phase difference by which the current leads or lags the potential difference. $Q = EI \sin\theta$. The unit of $Q$ is the **var** (volt-ampere-reactive). One kilovar $= 10^3$ var.

**Apparent power** ($EI$) at the points of entry of a single-phase, two-wire circuit is equal to the product of the rms current in one conductor multiplied by the rms potential difference between the two points of entry. Apparent power $= EI$.

**Power factor** (pf) is the ratio of power to apparent power. pf $= P/EI =$

**Table 15.1.1 Electrical Units**

| Quantity | Symbol | Equation | SI unit | SI unit symbol | CGS unit | Ratio of magnitude of SI to cgs unit |
|---|---|---|---|---|---|---|
| Current | $I, i$ | $I = E/R$; $I = E/Z$; $I = Q/t$ | Ampere | A | Abampere | $10^{-1}$ |
| Quantity | $Q, q$ | $Q = it$; $Q = CE$ | Coulomb | C | Abcoulomb | $10^{-1}$ |
| Electromotive force | $E, e$ | $E = IR$; $E = W/Q$ | Volt | V | Abvolt | $10^{8}$ |
| Resistance | $R, r$ | $R = E/I$; $R = \rho l/A$ | Ohm | $\Omega$ | Abohm | $10^{9}$ |
| Resistivity | $\rho$ | $\rho = RA/l$ | Ohm-metre | $\Omega \cdot \mathrm{m}$ | Abohm-cm | $10^{11}$ |
| Conductance | $G, g$ | $G = \gamma A/l$; $G = A/\rho l$ | Siemens | S | Abmho | $10^{-9}$ |
| Conductivity | $\gamma$ | $\gamma = 1/\rho$; $\gamma = l/RA$ | Siemens/meter | S/m | Abmho/cm | $10^{-11}$ |
| Capacitance | $C$ | $C = Q/E$ | Farad | F | Abfarad* | $10^{-9}$ |
| Permittivity | $\varepsilon$ | | Farads/meter | F/m | Stat farad*/cm | $8.85 \times 10^{-12}$ |
| Relative permittivity | $\varepsilon_r$ | $\varepsilon_r = \varepsilon/\varepsilon_0$ | Numerical | | Numerical | 1 |
| Self-inductance | $L$ | $L = -N(d\phi/dt)$ | Henry | H | Abhenry | $10^{9}$ |
| Mutual inductance | $M$ | $M = K(L_1L_2)^{1/2}$ | Henry | H | Abhenry | $10^{9}$ |
| Energy | $J$ | $J = eit$ | Joule | J | Erg | $10^{7}$ |
| | kWh | kWh $=$ kW/3600; 3.6 M$J$ | Kilowatthour | kWh | | $36 \times 10^{12}$ |
| Active power | $W$ | $W = J/t$; $W = EI \cos \theta$ | Watt | W | Abwatt | $10^{7}$ |
| Reactive power | $jQ$ | $Q = EI \sin \theta$ | Var | var | Abvar | $10^{7}$ |
| Apparent power | $VA$ | $VA = EI$ | Volt-ampere | VA | | |
| Power factor | pf | pf $= W/VA$; pf $= W/(W + jQ)$ | | | | 1 |
| Reactance, inductive | $X_L$ | $X_L = 2\pi fL$ | Ohm | $\Omega$ | Abohm | $10^{9}$ |
| Reactance, capacitive | $X_C$ | $X_C = 1/(2\pi fC)$ | Ohm | $\Omega$ | Abohm | $10^{9}$ |
| Impedence | $Z$ | $Z = E/I$; $Z = R + j(X_L - X_C)$ | Ohm | $\Omega$ | Abohm | $10^{9}$ |
| Conductance | $G$ | $G = R/Z^2$ | Siemens | S | Abmho | $10^{-9}$ |
| Susceptance | $B$ | $B = X/Z^2$ | Siemens | S | Abmho | $10^{-9}$ |
| Admittance | $Y$ | $Y = I/E$; $Y = G + jB$ | Siemens | S | Abmho | $10^{-9}$ |
| Frequency | $f$ | $f = 1/T$ | Hertz | Hz | Cps, Hz | 1 |
| Period | $T$ | $T = 1/f$ | Second | s | Second | 1 |
| Time constant | $T$ | $L/R$; $RC$ | Second | s | Second | 1 |
| Angular velocity | $\omega$ | $\omega = 2\pi f$ | Radians/second | rad/s | Radians/second | 1 |

* 1 Abfarad (EMU Units) $= 9 \times 10^{-20}$ stat farads (ESU units).

$\cos \theta$, where $\theta$ is the phase difference between $E$ and $I$, both assumed to be sinusoidal.

The **reactance** ($X$) of a portion of a circuit for a sinusoidal current and potential difference of the same frequency is the product of the sine of the angular phase difference between the current and potential difference times the ratio of the rms potential difference to the rms current, there being no source of power in the portion of the circuit under consideration. $X = (E/I) \sin \theta = 2\pi fL$ ohms, where $f$ is the frequency, and $L$ the inductance in henries; or $X = 1/2\pi fC$ ohms, where $C$ is the capacitance in farads.

The **impedance** ($Z$) of a portion of an electric circuit to a completely specified periodic current and potential difference is the ratio of the rms value of the potential difference between the terminals to the rms value of the current, there being no source of power in the portion under consideration. $Z = E/I$ ohms.

**Admittance** ($Y$) is the reciprocal of impedance. $Y = I/E$ siemens.

The **susceptance** ($B$) of a portion of a circuit for a sinusoidal current and potential difference of the same frequency is the product of the sine of the angular phase difference between the current and the potential difference times the ratio of the rms current to the rms potential difference, there being no source of power in the portion of the circuit under consideration. $B = (I/E) \sin \theta$.

### Magnetic Units

(See Table 15.1.2.)

**Magnetic flux** ($\Phi$, $\phi$) is the magnetic flow that exists in any magnetic circuit.

The **weber** is the magnetic flux which, linking a circuit of one turn, produces in it an electromotive force of one volt as it is reduced to zero at a uniform rate in one second.

**Magnetic flux density** ($\beta$) is the ratio of the flux in any cross section to the area of that cross section, the cross section being taken normal to the direction of flux.

The **tesla** is the magnetic flux density given by a magnetic flux of one weber per square metre.

**Unit magnetic pole,** when concentrated at a point and placed one metre apart in a vacuum from a second unit magnetic pole, will repel or attract the second unit pole with a force of one **newton.**

The **weber** is the magnetic flux produced by a unit pole.

**Table 15.1.2 Magnetic Units**

| Quantity | Symbol | Equation* | SI unit | SI unit symbol | CGS unit | Ratio of magnitude of SI to cgs unit |
|---|---|---|---|---|---|---|
| Magnetic flux | $\Phi, \phi$ | $\phi = F/R$ | Weber | wb | Maxwell | $10^{8}$ |
| Magnetic flux density | $\beta$ | $\beta = \phi/A$ | Tesla | T | Gauss | $10^{4}$ |
| Pole strength | $Q_m$ | $Q_m = F/\beta$; $Q_m = Fl/NI\mu_0\mu_r$ | Ampere-turns-metre | $\mathrm{A \cdot m}$ | | |
| | | | Unit pole | | Unit pole | $0.7958 \times 10^{7}$ |
| Magnetomotive force | $\mathscr{F}$ | $\mathscr{F} = NI$ | Ampere-turns | A | Gilbert | 1.257 |
| Magnetic field intensity | $H$ | $H = \mathscr{F}/l$ | Ampere-turns per metre | A/m | Oersted | 0.01257 |
| Permeability air | $\mu_0$ | $\mu_0 = \beta/H$ | Henry per metre | H/m | Gilbert per oersted | $1.257 \times 10^{-6}$ |
| Relative permeability | $\mu_r$ | $\mu_r = \mu/\mu_0$ | Numeric | | Numeric | 1 |
| Reluctivity | $\gamma$ | $\gamma = 1/\mu_r$ | Numeric | | Numeric | 1 |
| Permeance | $P$ | $P = \mu_0\mu_r A/l$ | Henry | H | | $7.96 \times 10^{7}$ |
| Reluctance | $R$ | $R = l/\mu_0\mu_r A$ | 1/Henry | 1/H | | $1.257 \times 10^{-8}$ |

* $l$ = length in metres; $A$ = area in square metres; $F$ = force in newtons; $N$ = number of turns.

**Magnetomotive force** ($\mathcal{F}$, mmf) produces magnetic flux and corresponds to electromotive force in an electric circuit.

The **ampere** (turn) is the unit of mmf.

**Magnetic field intensity** ($H$) at a point is the vector quantity which is measured by a mechanical force which is exerted on a unit pole placed at the point in a vacuum.

An **ampere per metre** is the unit of field intensity.

**Permeability** ($\mu$) is the ratio of unit magnetic flux density to unit magnetic field intensity in air ($B/H$). The permeability of air is $1.257 \times 10^{-6}$ **henry per metre.**

**Relative permeability** ($\mu_r$) is the ratio of the magnetic flux in any element of a medium to the flux that would exist if that element were replaced with air, the magnetomotive force (mmf) acting on the element remaining unchanged ($\mu_r = \mu/\mu_0$).

The relative permeability is a number.

**Permeance** ($P$) of a portion of a magnetic circuit bounded by two equipotential surfaces, and by a third surface at every point of which there is a tangent having the direction of the magnetic induction, is the ratio of the flux through any cross section to the magnetic potential difference between the surfaces when taken within the portion under consideration. The equation for the permeance of the medium as defined above is $P = \mu_0 \mu_r A/l$. Permeance is the **reciprocal of reluctance.**

**Reluctivity** ($\gamma$) of a medium is the reciprocal of its permeability.

**Reluctance** ($R$) is the **reciprocal of permeance.** It is the resistance to magnetic flow. In a homogeneous medium of uniform cross section, reluctance is equal to the length divided by the product of the area and permeability, the length and area being expressed in metre units. $R = l/A\mu_0\mu_r$, where $\mu_0 = 1.257 \times 10^{-6}$.

## CONDUCTORS AND RESISTANCE

**Resistivity,** or **specific resistance,** is the resistance of a sample of the material having both a length and cross section of unity. The two most common resistivity samples are the centimetre cube and the cir mil · ft. If $l$ is the length of a conductor of uniform cross section $a$, then its resistance is

$$R = \rho l/a \tag{15.1.1}$$

where $\rho$ is the resistivity. With a cir mil · ft $\rho$ is the resistance of a cir mil · ft and $a$ is the cross section, cir mils. Since $v = la$ is the volume of a conductor,

$$R = \rho l^2/v = \rho v/a^2 \tag{15.1.2}$$

A **circular mil** is a unit of area equal to that of a circle whose diameter is 1 mil (0.001 in). It is the unit of area which is used almost entirely in this country for wires and cables. To obtain the cir mils of a solid cylindrical conductor, square its diameter expressed in mils. For example, the diameter of 000 AWG solid copper wire is 410 mils and its cross section is $(410)^2 = 168{,}100$ cir mils. The diameter in mils of a solid cylindrical conductor is the square root of its cross section expressed in cir mils.

A **cir mil · ft** is a conductor having a length of 1 ft and a uniform cross section of 1 cir mil. In terms of the copper standard the resistance of a cir mil · ft of copper at 20°C is 10.371 Ω. As a first approximation 10 Ω may frequently be used.

At 60°C a cir mil · in of copper has a resistance of 1.0 Ω. This is a very convenient unit of resistivity for magnet coils since the resistance is merely the length of copper in inches divided by its cross section in cir mils.

**Temperature Coefficient of Resistance** The resistance of the pure metals increases with temperature. The resistance at any temperature $t$°C is

$$R = R_0(1 + \alpha t) \tag{15.1.3}$$

where $R_0$ is the resistance at 20°C and $\alpha$ is the **temperature coefficient of resistance.** For copper, $\alpha = 0.00393$.

With any initial temperature $t_1$, the resistance at temperature $t$°C is

$$R = R_1[1 + \alpha_1(t - t_1)] \tag{15.1.4}$$

**Table 15.1.3 Properties of Metals and Alloys**
(See Table 15.1.27 for properties of resistor alloys)

| Metals | Resistivity, 20°C |  | Temperature coefficient of resistance at 20°C |
|---|---|---|---|
|  | μΩ · cm | Ω · cir mil/ft |  |
| Aluminum | 2.828 | 17.01 | 0.00403 |
| Antimony | 42.1 | 251.0 | 0.0036 |
| Bismuth | 111.0 | 668.0 | 0.004 |
| Brass | 6.21 | 37.0 | 0.0015 |
| Carbon: amorphous | 3,800–4,100 | ........... | (−) |
| Retort (graphite) | 720–812* | ........... | (−) |
| Copper (drawn) | 1.724 | 10.37 | 0.00393 |
| Gold | 2.44 | 14.7 | 0.0034 |
| Iron: electrolytic | 10.1 | 59.9 | 0.0064 |
| Cast | 75.2–98.8 | 448–588 |  |
| Wire | 97.8 | 588 |  |
| Lead | 22.0 | 132 | 0.00387 |
| Molybdenum | 5.78 | 34.8 |  |
| Monel metal | 43.5 | 262 | 0.0019 |
| Mercury | 96.8 | 576 | 0.00089 |
| Nickel | 8.54 | 50.8 | 0.0041 |
| Platinum | 10.72 | 63.8 | 0.003 |
| Platinum silver, 2Ag + 1Pt | 24.6† | 148.0 | 0.00031 |
| Silver | 1.628 | 9.8 | 0.0038 |
| Steel: soft | 15.9 | 95.8 | 0.0016 |
| Glass hard | 45.7 | 275 |  |
| Silicon (4 percent) | 51.18 | 308 |  |
| Transformer | 11.09 | 66.7 |  |
| Trolley wire | 12.7 | 76.4 |  |
| Tin | 11.63 | 70 | 0.0042 |
| Tungsten | 5.51 | 33.2 | 0.005 |
| Zinc | 5.97 | 35.58 | 0.0037 |

NOTE: Max working temperature: Cu, 260°C; Ni, 600°C; Pt, 1,500°C.
* Furnace electrodes, 3,000°C.
† 0°C.

where $R_1$ is the resistance at temperature $t_1$°C and $\alpha_1$ is the temperature coefficient of resistance at temperature $t_1$ [see Eq. (15.1.5)].

For any initial temperature $t_1$ the value of $\alpha_1$ is

$$\alpha_1 = 1/(234.5 + t_1) \qquad (15.1.5)$$

**Inferred Absolute Zero** Between 100 and 0°C the resistance of copper decreases at a rate which is practically uniform and which if continued would give a resistance of zero at −234.5°C (an easy number to remember). If the resistance at $t_1$°C is $R_1$ and the resistance at $t_2$°C is $R_2$, then

$$R_2/R_1 = (234.5 + t_2)/(234.5 + t_1) \qquad (15.1.6)$$

EXAMPLE. The resistance of a copper coil at 25°C is 4.26 Ω. Determine its resistance at 45°C. Using Eq. (15.1.4) and $\alpha_1 = 1/(234.5 + 25) = 0.00385$, $R = 4.26[1 + 0.00385(45 - 25)] = 4.59\ \Omega$. Using Eq. (15.1.6) $R = 4.26(234.5 + 45)/(234.5 + 25) = 4.26 \times 1.077 = 4.59\ \Omega$.

The inferred absolute zero for aluminum is −228°C.

**Materials** The materials generally used for the transmission and distribution of electrical energy are copper, aluminum, and sometimes iron and steel. For resistors and heaters, iron, steel, commercial alloys, and carbon are most used.

**Copper** is the most widely used electrical conductor. It has high conductivity, relatively low cost, good resistance to oxidation, is readily soldered, and has good mechanical characteristics such as tensile strength, toughness, and ductility. Its tensile strength together with its low linear temperature coefficient of expansion are desirable characteristics in its use for overhead transmission lines. The international copper standard for 100 percent conductivity annealed copper is a density of 8.89 g/cm$^3$ (0.321 lb/in$^3$) and resistivity is given in Table 15.1.3. ASTM specifications for minimum conductivities of copper wire are as follows:

| Conductor diam, in | Soft or annealed | Medium hard drawn | Hard drawn |
|---|---|---|---|
| 0.040–0.324 | 98.16% | 96.60% | 96.16% |
| 0.325–0.460 | 98.16% | 97.66% | 97.16% |

**Table 15.1.4 Working Table, Standard Annealed Copper Wire, Solid**
[American Wire Gage (B & S)]

| Gage no. | Diam, mils | Cross section | | Ω per 1,000 ft | | Ω/mi at 25°C (=77°F) | Weight per 1,000 ft, lb |
|---|---|---|---|---|---|---|---|
| | | cir mils | in$^2$ | 25°C (=77°F) | 65°C (=149°F) | | |
| 0000 | 460.0 | 212,000 | 0.166 | 0.0500 | 0.0577 | 0.264 | 641.0 |
| 000 | 410.0 | 168,000 | 0.132 | 0.0630 | 0.0727 | 0.333 | 508.0 |
| 00 | 365.0 | 133,000 | 0.105 | 0.0795 | 0.0917 | 0.420 | 403.0 |
| 0 | 325.0 | 106,000 | 0.0829 | 0.100 | 0.116 | 0.528 | 319.0 |
| 1 | 289.0 | 83,700 | 0.0657 | 0.126 | 0.146 | 0.665 | 253.0 |
| 2 | 258.0 | 66,400 | 0.0521 | 0.159 | 0.184 | 0.839 | 201.0 |
| 3 | 229.0 | 52,600 | 0.0413 | 0.201 | 0.232 | 1.061 | 159.0 |
| 4 | 204.0 | 41,700 | 0.0328 | 0.253 | 0.292 | 1.335 | 126.0 |
| 5 | 182.0 | 33,100 | 0.0260 | 0.319 | 0.369 | 1.685 | 100.0 |
| 6 | 162.0 | 26,300 | 0.0206 | 0.403 | 0.465 | 2.13 | 79.5 |
| 7 | 144.0 | 20,800 | 0.0164 | 0.508 | 0.586 | 2.68 | 63.0 |
| 8 | 128.0 | 16,500 | 0.0130 | 0.641 | 0.739 | 3.38 | 50.0 |
| 9 | 114.0 | 13,100 | 0.0103 | 0.808 | 0.932 | 4.27 | 39.6 |
| 10 | 102.0 | 10,400 | 0.00815 | 1.02 | 1.18 | 5.38 | 31.4 |
| 11 | 91.0 | 8,230 | 0.00647 | 1.28 | 1.48 | 6.75 | 24.9 |
| 12 | 81.0 | 6,530 | 0.00513 | 1.62 | 1.87 | 8.55 | 19.8 |
| 13 | 72.0 | 5,180 | 0.00407 | 2.04 | 2.36 | 10.77 | 15.7 |
| 14 | 64.0 | 4,110 | 0.00323 | 2.58 | 2.97 | 13.62 | 12.4 |
| 15 | 57.0 | 3,260 | 0.00256 | 3.25 | 3.75 | 17.16 | 9.86 |
| 16 | 51.0 | 2,580 | 0.00203 | 4.09 | 4.73 | 21.6 | 7.82 |
| 17 | 45.0 | 2,050 | 0.00161 | 5.16 | 5.96 | 27.2 | 6.20 |
| 18 | 40.0 | 1,620 | 0.00128 | 6.51 | 7.51 | 34.4 | 4.92 |
| 19 | 36.0 | 1,290 | 0.00101 | 8.21 | 9.48 | 43.3 | 3.90 |
| 20 | 32.0 | 1,020 | 0.000802 | 10.4 | 11.9 | 54.9 | 3.09 |
| 21 | 28.5 | 810 | 0.000636 | 13.1 | 15.1 | 69.1 | 2.45 |
| 22 | 25.3 | 642 | 0.000505 | 16.5 | 19.0 | 87.1 | 1.94 |
| 23 | 22.6 | 509 | 0.000400 | 20.8 | 24.0 | 109.8 | 1.54 |
| 24 | 20.1 | 404 | 0.000317 | 26.2 | 30.2 | 138.3 | 1.22 |
| 25 | 17.9 | 320 | 0.000252 | 33.0 | 38.1 | 174.1 | 0.970 |
| 26 | 15.9 | 254 | 0.000200 | 41.6 | 48.0 | 220 | 0.769 |
| 27 | 14.2 | 202 | 0.000158 | 52.5 | 60.6 | 277 | 0.610 |
| 28 | 12.6 | 160 | 0.000126 | 66.2 | 76.4 | 350 | 0.484 |
| 29 | 11.3 | 127 | 0.0000995 | 83.4 | 96.3 | 440 | 0.384 |
| 30 | 10.0 | 101 | 0.0000789 | 105 | 121 | 554 | 0.304 |
| 31 | 8.9 | 79.7 | 0.0000626 | 133 | 153 | 702 | 0.241 |
| 32 | 8.0 | 63.2 | 0.0000496 | 167 | 193 | 882 | 0.191 |
| 33 | 7.1 | 50.1 | 0.0000394 | 211 | 243 | 1,114 | 0.152 |
| 34 | 6.3 | 39.8 | 0.0000312 | 266 | 307 | 1,404 | 0.120 |
| 35 | 5.6 | 31.5 | 0.0000248 | 335 | 387 | 1,769 | 0.0954 |
| 36 | 5.0 | 25.0 | 0.0000196 | 423 | 488 | 2,230 | 0.0757 |
| 37 | 4.5 | 19.8 | 0.0000156 | 533 | 616 | 2,810 | 0.0600 |
| 38 | 4.0 | 15.7 | 0.0000123 | 673 | 776 | 3,550 | 0.0476 |
| 39 | 3.5 | 12.5 | 0.0000098 | 848 | 979 | 4,480 | 0.0377 |
| 40 | 3.1 | 9.9 | 0.0000078 | 1,070 | 1,230 | 5,650 | 0.0200 |

**Aluminum** is used to considerable extent for high-voltage transmission lines, because its weight is one-half that of copper for the same conductance. Moreover, the greater diameter reduces corona loss. As it has 1.4 times the linear temperature coefficient of expansion, changes in sag with temperature are greater. Because of its lower melting point, spans may fail more readily with arc-overs. In aluminum cable steel-reinforced (ACSR), the center strand is a steel cable, which gives added tensile strength. Aluminum is used occasionally for bus bars because of its large heat-dissipating surface for a given conductance. The greater cross section for a given conductance requires a greater volume of insulation for a given voltage. When the ratio of the cost of aluminum to the cost of copper becomes economically favorable, aluminum is often used for insulated wires and cables. The international aluminum standard for 62 percent conductivity aluminum is a density of 2.70 g/cm$^3$ (0.0976 lb/in$^3$) and resistivity as given in Table 15.1.3.

**Steel,** either **galvanized** or **copper-covered** (''copperweld''), is used for high-voltage transmission spans where tensile strength is more important than high conductance. Steel is also used for third rails.

**Copper alloys** and **bronzes** are of increasing importance as electrical conductors. They have lower electrical conductivity but greater tensile strength and are resistant to corrosion. **Hitenso, Calsum bronzes, Signal bronze, Phono-electric,** and **Everdur** are bronzes containing phosphorus, silicon, manganese, or zinc. Their conductivities vary from 20 to 85 percent of 100 percent conductivity copper, and they have tensile strengths up to 130,000 lb/in$^2$, about twice that of hard-drawn copper. Such alloys were frequently used for trolley wires. Copper alloys having lower conductivity are usually classified as resistor materials.

In Table 15.1.3 are given the electrical properties of some of the pure metals and alloys.

**American Wire Gage (AWG)** The AWG (formerly Brown & Sharpe gage) is based on a constant ratio between diameters of successive gage numbers (Table 15.1.4). The ratio of any diameter to the next smaller is 1.123, and the corresponding ratio of cross sections is $(1.123)^2 = 1.261$, or 1¼ approximately. $(1.123)^6$ is 2.0050, so that diameters differing by 6 gage numbers have a ratio of approximately 2; cross sections differing by 3 gage numbers also have a ratio of approximately 2. The ratio of cross sections differing by 2 numbers is $(1.261)^2 = 1.590$, or 1.6 approximately. The ratio of cross sections differing by 10 numbers is approximately 10. The gage ordinarily extends from no. 40 to 0000 (4/0). Wires larger than 0000 must be stranded, and their cross section is given in cir mils.

The diameter of no. 10 wire is 102.0 mils. As an approximation this may be considered as being 100 mils; the cross section is 10,000 cir mils; the resistance is 1 Ω per 1,000 ft; and the weight of 1,000 ft is $31.4(10\pi)$ lb. Also the weight of 1,000 ft of no. 2 is 200 lb. These facts give many short cuts in estimating resistances and weights of various gage numbers.

**Lay Cables** In order to obtain sufficient flexibility, wires larger than 0000 are stranded, and they are designated by their circular mils (Table 15.1.5). Smaller wires may be stranded also since sizes as small as no. 4 when insulated are usually too stiff for easy handling. Lay cables are made up geometrically as shown in Fig. 15.1.1. Six strands will just fit around the single central conductor; the number of strands in each succeeding layer increases by 6. The number of strands that can thus be laid up are 1, 7, 19, 37, 61, 91, 127, etc. In order to obtain sufficient flexibility with large cables, the strands themselves frequently consist of stranded cable.

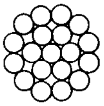


**Fig. 15.1.1** Makeup of a 19-strand cable.

The **resistance of cables** is readily computed from Eq. (15.1.1), using the cir mil ft as the unit of resistivity.

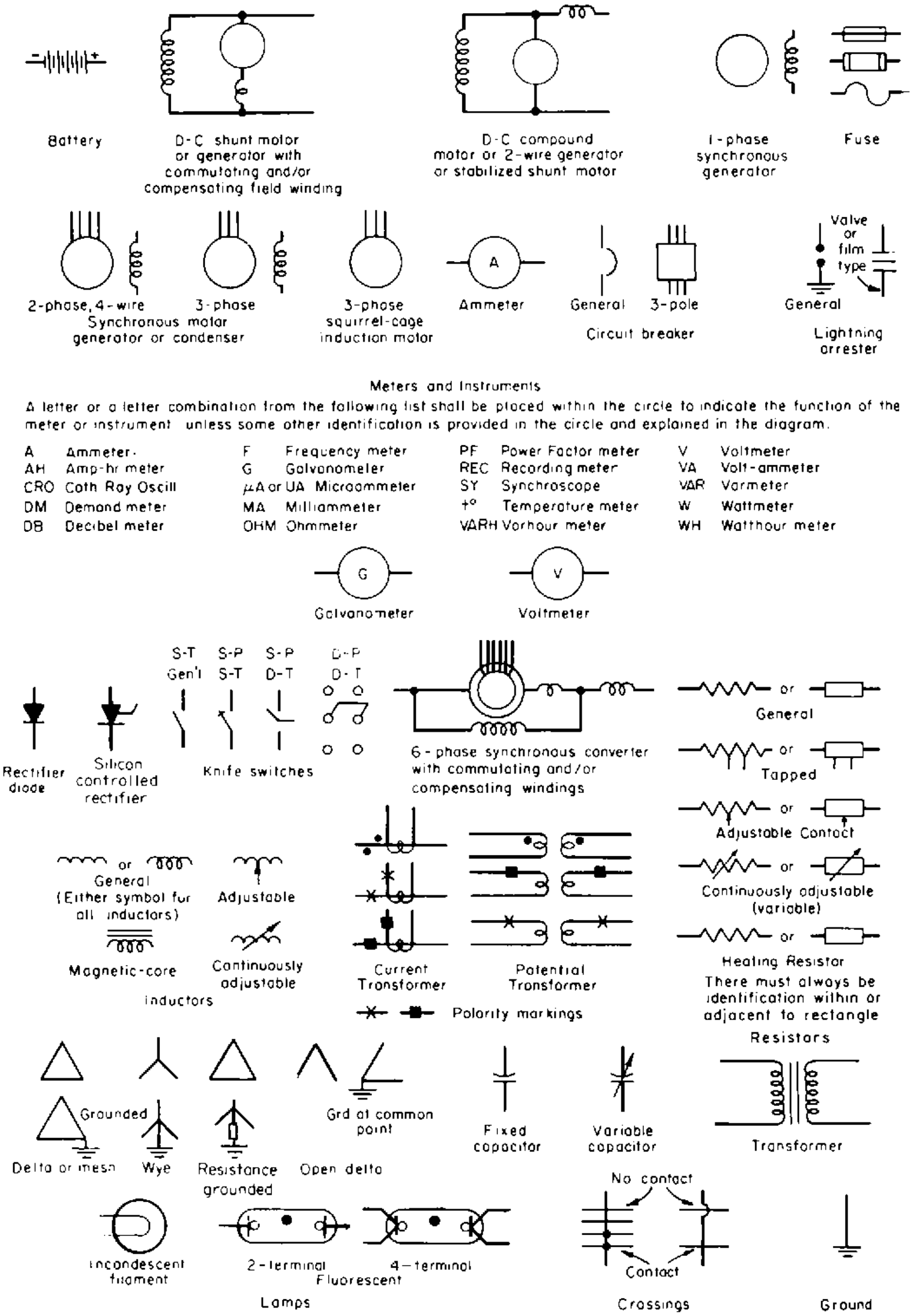
EXAMPLE. Determine the resistance of 3,500 ft of 800,000 cir mil cable at 20°C. *Answer:* $\rho$ (of a cir mil · ft) = 10.37. $R = 10.37 \times 3{,}500/800{,}000 = 0.0454\ \Omega$.

$\rho = 10\ \Omega$/cir mil · ft is often sufficiently accurate for practical purposes.

**Table 15.1.5 Bare Concentric Lay Cables of Standard Annealed Copper**

| | | Ω per 1,000 ft | | | Standard concentric standing | | |
|---|---|---|---|---|---|---|---|
| AWG no. | cir mils | 25°C (=77°F) | 65°C (=149°F) | Weight per 1,000 ft, lb | No. of wires | Diam of wires, mils | Outside diam, mils |
| | 2,000,000 | 0.00539 | 0.00622 | 6,180 | 127 | 125.5 | 1,631 |
| | 1,700,000 | 0.00634 | 0.00732 | 5,250 | 127 | 115.7 | 1,504 |
| | 1,500,000 | 0.00719 | 0.00830 | 4,630 | 91 | 128.4 | 1,412 |
| | 1,200,000 | 0.00899 | 0.0104 | 3,710 | 91 | 114.8 | 1,263 |
| | 1,000,000 | 0.0108 | 0.0124 | 3,090 | 61 | 128.0 | 1,152 |
| | 900,000 | 0.0120 | 0.0138 | 2,780 | 61 | 121.5 | 1,093 |
| | 850,000 | 0.0127 | 0.0146 | 2,620 | 61 | 118.0 | 1,062 |
| | 750,000 | 0.0144 | 0.0166 | 2,320 | 61 | 110.9 | 998 |
| | 650,000 | 0.0166 | 0.0192 | 2,010 | 61 | 103.2 | 929 |
| | 600,000 | 0.0180 | 0.0207 | 1,850 | 61 | 99.2 | 893 |
| | 550,000 | 0.0196 | 0.0226 | 1,700 | 61 | 95.0 | 855 |
| | 500,000 | 0.0216 | 0.0249 | 1,540 | 37 | 116.2 | 814 |
| | 450,000 | 0.0240 | 0.0277 | 1,390 | 37 | 110.3 | 772 |
| | 400,000 | 0.0270 | 0.0311 | 1,240 | 37 | 104.0 | 728 |
| | 350,000 | 0.0308 | 0.0356 | 1,080 | 37 | 97.3 | 681 |
| | 300,000 | 0.0360 | 0.0415 | 926 | 37 | 90.0 | 630 |
| | 250,000 | 0.0431 | 0.0498 | 772 | 37 | 82.2 | 575 |
| 0000 | 212,000 | 0.0509 | 0.0587 | 653 | 19 | 105.5 | 528 |
| 000 | 168,000 | 0.0642 | 0.0741 | 518 | 19 | 94.0 | 470 |
| 00 | 133,000 | 0.0811 | 0.0936 | 411 | 19 | 83.7 | 418 |
| 0 | 106,000 | 0.102 | 0.117 | 326 | 19 | 74.5 | 373 |
| 1 | 83,700 | 0.129 | 0.149 | 258 | 19 | 66.4 | 332 |
| 2 | 66,400 | 0.162 | 0.187 | 205 | 7 | 97.4 | 292 |
| 3 | 52,600 | 0.205 | 0.237 | 163 | 7 | 86.7 | 260 |
| 4 | 41,700 | 0.259 | 0.299 | 129 | 7 | 77.2 | 232 |

NOTE: See Table 15.1.21 for the carrying capacity of wires.
SOURCE: From *NBS Cir.* 31.



Meters and Instruments

A letter or a letter combination from the following list shall be placed within the circle to indicate the function of the meter or instrument unless some other identification is provided in the circle and explained in the diagram.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| A | Ammeter | F | Frequency meter | PF | Power Factor meter | V | Voltmeter |
| AH | Amp-hr meter | G | Galvanometer | REC | Recording meter | VA | Volt-ammeter |
| CRO | Cath Ray Oscill | $\mu$A or UA | Microammeter | SY | Synchroscope | VAR | Varmeter |
| DM | Demand meter | MA | Milliammeter | $+^\circ$ | Temperature meter | W | Wattmeter |
| DB | Decibel meter | OHM | Ohmmeter | VARH | Varhour meter | WH | Watthour meter |

**Fig. 15.1.2** Diagrammatic symbols for electrical machinery and apparatus. *(American Standard, "Graphic Symbols for Electrical and Electronic Diagrams," ANS/IEEE, 315, 1975.)*

## ELECTRICAL CIRCUITS

Figure 15.1.2 shows standard symbols for electrical circuit diagrams.

**Ohm's law** states that, with a steady current, the current in a circuit is **directly** proportional to the **total** emf acting in the circuit and is **inversely** proportional to the total resistance of the circuit. The law may be expressed by the following three equations:

$$I = E/R \tag{15.1.7}$$
$$E = IR \tag{15.1.8}$$
$$R = E/I \tag{15.1.9}$$

where $E$ is the emf, V; $R$ the resistance, Ω; and $I$ the current, A.

**Series Circuits** The combined resistance of a number of series-connected resistors is the sum of their separate resistances. When batteries or other sources of emf are connected in series, the total emf of the combination is the sum of the separate emfs. The open-circuit emf of a battery is the total generated emf and can be measured at the battery terminals only when no current is being delivered by the battery. The internal resistance is the resistance of the battery alone. The current in a circuit connected in series with a source of emf is $I = E/(R + r)$, where $E$ is the open-circuit emf, $R$ the external resistance, and $r$ the internal resistance of the source of emf.

**Parallel Circuits** The combined conductance of a number of parallel-connected resistors is the sum of their separate conductances.

$$G = G_1 + G_2 + G_3 + \cdots \tag{15.1.10}$$
$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots \tag{15.1.11}$$

The equivalent resistance for two parallel resistors having resistances $R_1$, $R_2$ is

$$R = R_1R_2/(R_1 + R_2) \tag{15.1.12}$$

The equivalent resistance for three parallel resistors having resistances $R_1$, $R_2$, $R_3$ is

$$R = \frac{R_1R_2R_3}{R_1R_2 + R_2R_3 + R_3R_1} \tag{15.1.13}$$

and for four parallel resistors having resistances $R_1$, $R_2$, $R_3$, $R_4$

$$R = \frac{R_1R_2R_3R_4}{R_1R_2R_3 + R_2R_3R_4 + R_3R_4R_1 + R_4R_1R_2} \tag{15.1.14}$$

To obtain the resistance of combined series and parallel resistors, the equivalent resistance of each parallel portion is obtained separately and then these equivalent resistances are added to the series resistances according to the principles stated above.

**Kirchhoff's laws** (derived from Ohm's law) make it possible to solve many circuit networks that would otherwise be difficult to solve. The first law states that: *In any branching network of wires the algebraic sum of the currents in all the wires that meet at a point is zero.* The second law states that: *The sum of all the electromotive forces acting around a complete circuit is equal to the sum of the resistances of its separate parts multiplied each by the strength of the current in it, or the total change of potential around any closed circuit is zero.*

In applying Kirchhoff's laws the following rules should be observed. Currents going toward a junction should be preceded by a plus sign. Currents going away from a junction should be preceded by a minus sign. A rise in potential should be preceded by a plus sign. (This occurs in going through a source of emf from the negative to the positive terminal, and in going through resistance in opposition to the direction of current.) A drop in potential should be preceded by a minus sign. (This occurs in going through a source of emf from the positive to the negative terminal and in going through resistance in conjunction with the current.)

The application of Kirchhoff's laws is illustrated by the following example.

EXAMPLE. Determine the three currents $I_1$, $I_2$, and $I_3$ in the circuit network (Fig. 15.1.3). The arrows show the assumed directions of the three currents.

Applying Kirchhoff's second law to circuit *abcdea*,

$$+4 + 0.2I_1 + 0.5I_1 - 3I_2 + 2 - 0.1I_2 + I_1 = 0$$

or

$$+6 + 1.7I_1 - 3.1I_2 = 0 \tag{I}$$

and for *edcfge.*

$$-2 + 0.1I_2 + 3I_2 + I_3 + 3 + 0.3I_3 = 0$$

or

$$+1 + 3.1I_2 + 1.3I_3 = 0 \tag{II}$$

Applying Kirchhoff's first law to junction *c*,

$$-I_1 - I_2 + I_3 = 0 \tag{III}$$

Solving (I), (II), and (III) simultaneously gives $I_1 = -2.56$, $I_2 = +0.53$, and $I_3 = -2.03$. The minus signs before $I_1$ and $I_3$ show that the actual directions of these two currents are opposite the assumed directions.

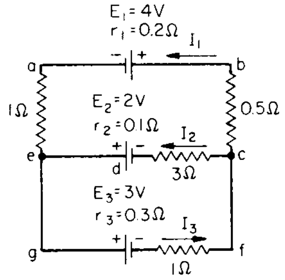


**Fig. 15.1.3** Electric network and Kirchhoff's laws.

**Electrical Power** With direct currents the electrical power is given by the product of the volts and amperes. That is,

$$P = EI \qquad \text{W} \tag{15.1.15}$$

Also, by substituting for $E$ and $I$ Eqs. (8) and (7),

$$P = I^2R \qquad \text{W} \tag{15.1.16}$$
$$P = E^2/R \qquad \text{W} \tag{15.1.17}$$

The watt is too small a unit for many purposes. Hence, the **kilowatt** (kW) is used. 746 watts = 1 hp = 0.746 kW; 1 kW = 1.340 hp. The **kilowatthour (kWh)** is the common engineering unit of electrical energy.

**Joule's Law** When an electric current flows through resistance, the number of heat units developed is proportional to the square of the current, directly proportional to the resistance, and directly proportional to the time that the current flows. $h = i^2rt$, where $h$ = number of joules; $i$ = current, A; $r$ = resistance, Ω; and $t$ = time, s. $h$ (in Btu) = $0.0009478i^2rt$.

## MAGNETISM

**Magnetic Circuit** The magnetic circuit is analogous to the electric circuit in that the flux $\Phi$ is proportional to the magnetomotive force $\mathcal{F}$ and inversely proportional to the reluctance $\mathcal{R}$ or magnetic resistance. Thus

$$\Phi = \mathcal{F}/\mathcal{R} \tag{15.1.18}$$

Compare with Eq. (15.1.7). $\Phi$ is in webers, where the weber is the SI unit of flux, $\mathcal{F}$ in ampere-turns, and $\mathcal{R}$ in SI reluctance units. In the cgs system, $\phi$ is in maxwells, $\mathcal{F}$ is in gilberts, and $\mathcal{R}$ is in cgs reluctance units.

$$\mathcal{R} = l/\mu_r\mu_v A \tag{15.1.19}$$

where $\mu_r$ is **relative permeability** (commonly called permeability, $\mu$), a property of the magnetic material, and $\mu_v$ is the permeability of evacuated space $= 4\pi \times 10^{-7}$, and $A$ is in square metres. In the cgs system $\mu_v = 1$

$$\mathcal{R} = \frac{l}{\mu_r(4\pi \times 10^{-7})A} = \frac{l}{\mu_r(1.257 \times 10^{-6})A} \tag{15.1.20}$$

$l$ is in metres and $A$ in square metres.

The unit of **flux density** in the SI system is the tesla, which is equal to the number of webers per square metre taken perpendicular to their direction. One ampere-turn between opposite faces of a metre cube of a magnetic medium produces $\mu_r$ tesla. For air, $\mu_r = 4\pi \times 10^{-7}$. In the cgs system the unit of flux density is gauss $= 10^4$T (see Table 15.1.2).

Magnetic-circuit calculations cannot be made with the same degree of accuracy as electric-circuit calculations because of several factors. The cross-sectional dimensions of the magnetic circuit are large relative to its length; magnetic paths are irregular, and their geometry can only be approximated as with the air gap of electric machines, which usually have slots on one or both sides of the gap.

Magnetic flux cannot be confined to definite magnetic paths, but a considerable proportion usually takes paths external to the circuit giving magnetic leakage (see Fig. 15.1.7). The relative permeability of iron varies over wide ranges with the flux density and with the previous magnetic condition (see Fig. 15.1.5). These variations of relative permeability cannot be expressed by any simple equation. Although the foregoing factors prevent the obtaining of extremely high accuracy in magnetic calculations, yet, with experience, it is possible to design magnetic circuits with a precision that is satisfactory for all practical purposes.

The **magnetomotive force** $\mathscr{F}$ in Eq. (15.1.18) is expressed in ampere-turns $= NI$, where $N$ is the number of turns linked with the circuit and $I$ is the current, A. The unit of reluctance is the reluctance of a 1-m cube of air. The total reluctance is proportional to the length and inversely proportional to the cross-sectional area of the magnetic circuit, which is analogous to electrical resistance. Hence the reluctance of any given path of uniform cross section $A$ is $l/A\mu$, where $l$ = length of path, cm; $A$ = its cross section, cm$^2$; and $\mu$ = permeability. Reluctances in series are added to obtain their combined reluctance. Ohm's law of the magnetic circuit becomes

$$\Phi = \frac{NI}{l_1/A_1\mu_1 + l_2/A_2\mu_2 + l_3/A_3\mu_3 \cdots}\ \text{Mx} \qquad (15.1.21)$$

where $l_1$, $A_1$, $\mu_1$, etc., are the lengths, cross sections, and relative permeabilities of each series part of the circuit.

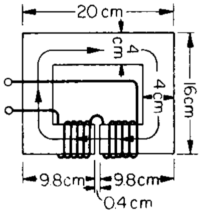


**Fig. 15.1.4** Magnetic circuit.

EXAMPLE. In Fig. 15.1.4 is shown a magnetic circuit of cast steel with a 0.4-cm air gap. The cross section of the core is 4 cm square. There are 425 turns wound on the core and the current is 10 A. The relative permeability of the steel at the operating flux density is 1,100. Assume that the path of the flux is as shown, the average path at the corners being quarter circles. Neglect fringing at the air gap and any leakage. Determine the flux and the flux density.

Using the SI system, the length of the iron is 0.522 m, the length of the air gap is 0.004 m, and the cross section of the iron and air gap is 0.0016 m$^2$.

$$\Phi = \frac{425 \times 10}{\dfrac{0.522}{1{,}100 \times 4\pi \times 10^{-7} \times 0.0016} + \dfrac{0.004}{4\pi \times 10^{-7} \times 0.0016}}$$

$$= 0.00191 \text{ Wb}$$

Using the cgs system, the length of the magnetic path in the iron $= 12 + 8 + 8 + 5.8 + 5.8 + 4\pi = 52.2$ cm. From Eq. (15.1.21),

$$\Phi = \frac{0.4\pi \times 425 \times 10}{[52.2/(16 \times 1{,}100)] + (0.4/16)} = 191{,}000 \text{ Mx}$$

$$B = \frac{191{,}000}{16} = 11{,}940 \text{ G}$$

**Magnetization and Permeability Curves** The magnetic permeability of air is a constant and is taken as unity. The relative permeability of iron and other magnetic substances varies with the flux density. In Fig. 15.1.5 is shown a magnetization curve for cast steel in which the flux density $B$ in tesla is plotted as a function of the field intensity, amperes per metre, $H$. Also the relative permeability $\mu_r = B/H$ is plotted as a function of the flux density $B$. Note the wide range over which the relative permeability varies. No satisfactory equation has been found to express the relation between magnetizing force and flux density and between relative permeability and flux density. If an attempt is made to solve Eq. (15.1.21) for flux, the factors $\mu_1$, $\mu_2$, etc., are unknown since they are functions of the flux density, which is being determined. The simplest method is one of trial and error, i.e., a value of flux, and the corresponding permeability, is first assumed, the equation solved for the flux, and if the computed flux differs widely from the assumed flux, a second approximation is made, etc. In nearly all magnetic designs either the flux or flux density is the independent variable, and it is required to find the necessary ampere-turns to produce them. Let the flux $\Phi = BA$ where $B$ is the flux density, G. Then

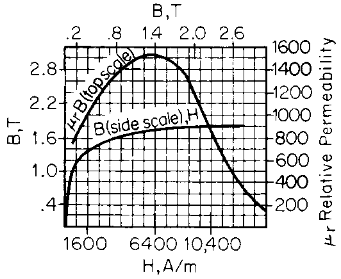


**Fig. 15.1.5** Magnetization and relative-permeability curves for cast steel.

$$\Phi = BA = 0.4\pi NI(l/A\mu_r)$$

$$\text{and} \qquad NI = Bl/\mu_0\mu_r = 0.796Bl/\mu_r \times 10^6 \qquad (15.1.22)$$

Equation (15.1.22) shows that the necessary ampere-turns are proportional to the **flux density** and the length of path and are inversely proportional to the relative permeability.

With air and nonmagnetic substances $\mu_r$ [Eq. (15.1.22)] becomes unity, and

$$NI = 0.796Bl \times 10^6 \qquad (15.1.23)$$

in metre units. With inch units

$$NI = 0.313B'l' \qquad (15.1.24)$$

where $B'$ is the flux density, Mx/in$^2$; and $l'$ the length of the magnetic path, in.

EXAMPLE. The average flux density in the air gap of a generator is 40,000 Mx/in$^2$, and the effective length of the gap is 0.2 in. How many ampere-turns per pole are necessary for the gap?

$$NI = 0.313 \times 40{,}000 \times 0.2 = 2{,}500$$

Since the relation of $\mu_r$ to flux density $B$ in Eq. (15.1.22) is not simple, the relation of ampere-turns per unit length of magnetic circuit to flux density is ordinarily shown graphically. Typical curves of this character are shown in Fig. 15.1.6, inch units being used although scales of tesla, and ampere turns per metre are also given. To determine the number of ampere-turns necessary to produce a given total flux in a magnetic circuit composed of several parts in series having various lengths, cross sections, and relative permeabilities, determine the flux density if the cross section is fixed, or otherwise choose a cross section to give a suitable flux density. From the magnetization curve obtain the ampere-turns necessary to drive this **flux density** through a unit length of the portion of the circuit considered and multiply by the length. Add together the ampere-turns required for each series part of the magnetic circuit to obtain the total ampere-turns necessary to give the assumed flux.

It is desirable to operate magnetic circuits at as high flux densities as is practicable in order to reduce the amount of iron and copper. The air gaps of dynamos are operated at average densities of 40,000 to 50,000 Mx/in$^2$. Higher densities increase the exciting ampere-turns and tooth losses. At 45,000 Mx/in$^2$ the flux density in the teeth may be as high as 120,000 to 130,000 Mx/in$^2$. The flux densities in transformer cores are limited as a rule by the permissible losses. At 60 Hz and with silicon steel the maximum density is 60,000 to 70,000 Mx/in$^2$, at 25 Hz the density may run as high as 75,000 to 90,000 Mx/in$^2$. With laminated cores, the net iron is approximately 0.9 the gross cross section.

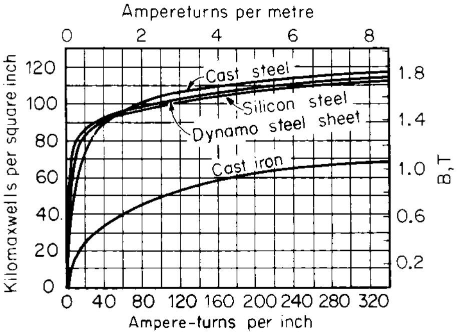


**Fig. 15.1.6** Typical magnetization curves.

**Magnetic Leakage** It is impossible to confine all magnetic flux to any desired path since there is no known insulator of magnetic flux. Figure 15.1.7 shows the magnetic circuit of a modern four-pole dynamo. A considerable proportion of the useful magnetic flux leaks between the pole shoes and cores, rather than across the air gap. The ratio of the maximum flux, which exists in the field cores, to the useful flux, i.e., the flux that crosses the air gap, is the **coefficient of leakage.** This coefficient must always be greater than unity and in carefully designed dynamos may be as low as 1.15. It is frequently as high as 1.30. Although the geometry of the leakage-flux paths is not simple, the leakage flux may be determined by approximations with a fair degree of accuracy.

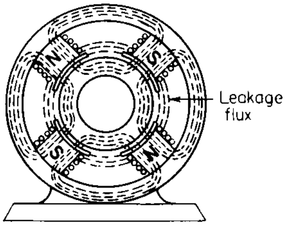


**Fig. 15.1.7** Magnetic circuit of a four-pole dynamo with leakage flux.

**Magnetic Hysteresis** The magnetization curves shown in Figs. 15.1.5 and 15.1.6 are called **normal curves.** They are taken with the magnetizing force continuously increased from zero. If at any point the magnetizing force be decreased, a greater value of flux density for any given magnetizing force will result. The effect of carrying iron through a complete cycle of magnetization, both positive and negative, is shown in Fig. 15.1.8.

The curve *OKB*, taken with increasing values of magnetizing force per centimeter *H*, is the **normal induction** curve. If after the magnetizing force has reached the value *OA*, it is decreased, the magnetic flux density *B* will decrease in accordance with curve *BCD*, between *A* and *O* the values being much greater than those given by the normal curve, i.e., the flux density lags the magnetizing force. At zero magnetizing force, the flux density is *OC*, call the **remanence.** A negative magnetizing force *OD*, called the **coercive force,** is required to bring the flux density to zero. If the magnetizing force is increased negatively to *OA′*, the flux density will be given by the curve *DE*. If the magnetizing force is increased positively from *A′* to *A*, the flux density will be given by the curve *EFGB*, which is similar to the curve *BCDE*. *OF* is the negative remanence and *OG* again is the coercive force. The complete curve is called a **hysteresis loop.** When the normal curve reaches the point *K*, if the magnetizing force is then decreased, another hysteresis loop, a portion of which is shown at *KL*, will be obtained. It is seen that the flux density lags the magnetizing force throughout.

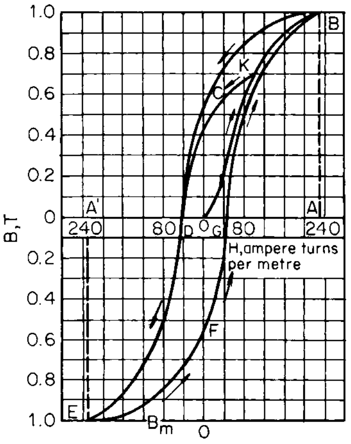


**Fig. 15.1.8** Hysteresis loop for dynamo steel.

The energy dissipated per cycle is proportional to the area of the loop and is equal to $(1/4\pi)\int H\,dB$ ergs/(Hz)(cm$^3$). For moderately high densities the energy loss per cycle varies according to the **Steinmetz law**

$$W = 10\eta B_m^{1.6} \qquad \mathrm{W \cdot s/m^3} \tag{15.1.25}$$

where $B_m$ is the maximum value of the flux density, T (Fig. 15.1.8). Table 15.1.6 gives values of the Steinmetz coefficient $\eta$ for common magnetic steels.

**Table 15.1.6 Steinmetz Coefficients**

| | | | |
|---|---|---|---|
| Hard tungsten steel | 0.058 | Ordinary sheet iron | 0.004 |
| Hard cast steel | 0.025 | Pure iron | 0.003 |
| Forged steel | 0.020 | Annealed iron sheet | 0.002 |
| Cast iron | 0.013 | Best annealed sheet | 0.001 |
| Electrolytic iron | 0.009 | Silicon steel sheet | 0.00046 |
| Soft machine steel | 0.009 | Permalloy | 0.0001 |
| Annealed cast steel | 0.008 | | |

A permanent increase in the hysteresis constant occurs if the temperature of operation remains for some time above 80°C. This phenomenon is known as **aging** and may be much reduced by proper annealing of the iron. Silicon steels containing about 3 percent silicon have a lower hysteresis loss, somewhat larger eddy-current loss, and are practically nonaging.

**Eddy-current losses,** also known as Foucault-current losses, occur in iron subjected to cyclic magnetization. Eddy-current losses are reduced by laminating the iron, which subdivides the emf and increases greatly the length of path of the parasitic currents. Eddy currents also have a screening effect, which tends to prevent the flux penetrating the iron. Hence laminating also allows the full cross section of the iron to be utilized unless the frequency is too high.

Eddy-current loss in sheets is given by

$$P_e = (\pi t f B_m)^2/6\rho 10^{16} \qquad \mathrm{W/cm^3} \tag{15.1.26}$$

where $t$ = thickness, cm; $f$ = frequency, Hz; $B_m$ = the maximum flux density, G; $\rho$ = the resistivity, $\Omega \cdot$ cm.

**Relations of Direction of Magnetic Flux to Current Direction** The direction of the magnetizing force of a current is at right angles to its direction of flow. Magnetic lines about a cylindrical conductor carrying current exist in circular planes concentric with and normal to the conductor. This is illustrated in Fig. 15.1.9*a*. The $\oplus$ sign, corresponding to the feathered end of the arrow, indicates a direction of current away from the observer; a $\odot$ sign, corresponding to the tip of an arrow, indicates a direction of current toward the observer.

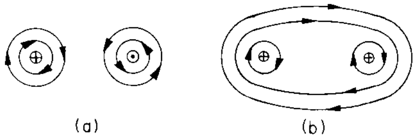


**Fig. 15.1.9** Currents in (*a*) opposite directions, (*b*) in the same direction.

**Corkscrew Rule** The direction of the current and that of the resulting magnetic field are related to each other as the forward travel of a corkscrew and the direction in which it is rotated.

**Hand Rule** Grasp the conductor in the right hand with the thumb pointing in the direction of the current. The fingers will then point in the direction of the lines of flux.

The applications of these rules are illustrated in Fig. 15.1.9. If the currents in parallel conductors are in opposite directions (Fig. 15.1.9*a*), the conductors tend to move apart; if the currents in parallel conductors are in the same direction (Fig. 15.1.9*b*), the conductors tend to come together. The magnetic lines act like stretched rubber bands and, in attempting to contract, tend to pull the two conductors together.

The relation of the direction of current in a solenoid helix to the direction of flux is shown in Fig. 15.1.10. Figure 15.1.11 shows the effect on a uniform field of placing a conductor carrying current in that field and normal to it. In (*a*) the direction of the current is toward the observer. By applying the corkscrew rule it is seen that the current weakens the field immediately above it and strengthens the field immediately below it. The reverse is true in (*b*), where the direction of the current is away from the observer.

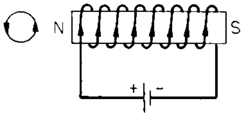


**Fig. 15.1.10** Direction of current and poles in a solenoid.

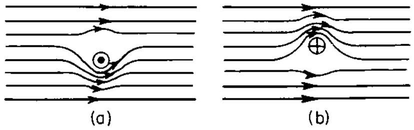


**Fig. 15.1.11** Effect of a current on a uniform magnetic field.

Figure 15.1.11 is illustrative of the force developed on a conductor carrying current in a magnetic field. In (*a*) the conductor will tend to move upward owing to the stretching of the magnetic lines beneath it. Similarly, the conductor in (*b*) will tend to move downward. This principle is the basis of motor action. (See also ‘‘Magnets.’’)

## BATTERIES

In an **electric cell,** or **battery,** chemical energy is converted into electrical energy. The word *battery* may be used for a single cell or for an assembly of cells connected in series or parallel. A battery utilizes the potential difference which exists between different elements. When two different elements are immersed in electrolyte an emf exists tending to send current within the cell from the negative pole, which is the more highly electropositive, to the positive pole. The **poles,** or **electrodes** of a battery form the junction with the external circuit.

If the external circuit is closed, current flows from the battery at the **positive electrode,** or **anode,** and enters the battery at the **negative electrode,** or **cathode.**

In a **primary battery** the chemically reacting parts **require renewal;** in a **secondary battery,** the electrochemical processes **are reversible** to a high degree and the chemically reacting parts are restored after partial or complete discharge by reversing the direction of current through the battery. See Table 15.1.7 for a summary of battery types and applications.

**Electromotive force** of a battery is the total potential difference existing between the electrodes on open circuit. When current flows, the potential difference across the terminal drops because of the resistance drop within the cell and because of **polarization.**

**Polarization** When current flows in a battery, hydrogen is deposited on the cathode. This produces two effects, both of which reduce the terminal voltage of the battery. The hydrogen in contact with the cathode constitutes a hydrogen battery which opposes the emf of the battery; the hydrogen bubbles reduce the contact area of the electrolyte with the cathode, thus increasing the battery resistance. The most satisfactory method of reducing polarization is to have present at the cathode some compound that supplies negative ions to combine with the positive hydrogen ions at the plate. In the Leclanché cell, manganese peroxide in contact with the carbon cathode serves as a depolarizer, its oxygen ion combining with the hydrogen ion to form water.

If $E$ is the emf of the cell, $E_p$ the emf of polarization, $r$ the internal resistance, $V$ the terminal voltage, when current $I$ flows, then

$$V = (E - E_p) - Ir \tag{15.1.27}$$

### Primary Batteries

**Dry Cells** A dry cell is one in which the electrolyte exists in the form of a jelly, is absorbed in a porous medium, or is otherwise restrained from flowing from its intended position, such a cell being completely portable and the electrolyte nonspillable. The Leclanché cell consists of a cylindrical zinc container which serves as the negative electrode and is lined with specially prepared paper, or some similar absorbent material, to prevent the mixture of carbon and manganese dioxide, which is tamped tightly around the positive carbon electrode, from coming in contact with the zinc. The absorbent lining and the mixture are moistened with a solution of zinc chloride and sal ammoniac. In smaller cells (Fig. 15.1.12) the manganese-carbon mixture is often molded into a cylinder around the carbon electrode, the whole is then set into the zinc cup, and the space between the molded mixture and the zinc is filled with electrolyte made into a paste in such a manner that it can be solidified by either standing or heating. The top of the cell is closed with a sealing compound, and the cell is placed in a cardboard container. The emf of a dry cell when new is 1.4 to 1.6 V.

In **block assembly** the dry cells, especially in the smaller sizes, are assembled in series and sealed in blocks of insulating compound with only two terminals and, sometimes, intermediate taps brought out. This type of battery is used for radio B and C batteries. Another construction is to build the battery up of layers in somewhat the manner of the old voltaic pile. Each cell consists of a layer of zinc, a layer of treated paper, and a flat cake of the manganese-carbon mixture. The cells are separated by layers of a special material which conducts electricity but which is impervious to electrolyte. A sufficient number of such cells are built up to give the required voltage and the whole battery is sealed into the carton.

**Leclanché cells** are generally available in sizes ranging from small, thin penlight batteries to large assemblies of cells in series or parallel for special high-voltage or high-current applications.

The **efficiency** of a standard-size dry battery depends on the rate at which it is discharged. Up to a certain rate the lower the discharge rate, the greater the efficiency. Above this rate the efficiency decreases (see *Natl. Bur. Stand. Circ.* 79, p. 39).

When used efficiently, a 6-in dry cell will give over 30 A · h of ser-

**Table 15.1.7 Battery Types and Applications**

| Battery type | Cell type | Nominal cell voltage | Capacity, wH/kg | Applications |
|---|---|---|---|---|
| | | Primary | | |
| Leclanché (zinc-carbon) | Dry | 1.5 | 22–44 | Flashlights, emergency lights, radios |
| Zinc-mercury (Ruben) | Dry | 1.34 | 90–110 | Medical, marine, space, laboratory, and emergency devices |
| Zinc-alkaline-manganese dioxide | Dry | 1.5 | 66 | Models, cameras, shavers, lights |
| Silver or cuprous chloride-magnesium | Wet | | 55–120 | Disposable devices: torpedoes, rescue beacons, meteorological balloons |
| | | Secondary | | |
| Lead-acid | Wet | 2 | | Automotive, industrial trucks, railway, station service |
| Lead-calcium | Wet | 2 | | Standby |
| Edison (nickel-iron) | Wet | 1.2 | | Industrial trucks; boat and train lights |
| Nickel-cadmium | Wet | 1.2 | 28 | Engine starting, emergency lighting, station service |
| Silver oxide-cadmium | Wet | 1.4 | 45–65 | Space |
| Silver-zinc | Wet | 1.55 | 90–155 | Models, photographic equipment, missiles |

vice. As ordinarily used, however, the dry cell give no more than 8 to 10 A · h of service and at times even less. The 1¼ by 2¼ in flashlight battery is usually employed with a lamp taking 0.25 to 0.35 A. Under these conditions 3 A · h or thereabouts may be expected if the battery is used for not more than an hour or so a day. The so-called ''heavy-duty'' radio battery will give about 8 to 10 A · h when efficiently used.

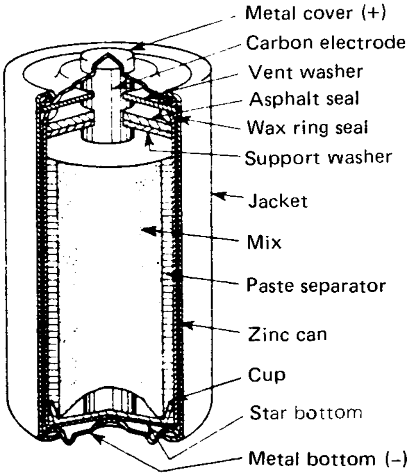


**Fig. 15.1.12** Cross section of a standard round zinc-carbon cell. *(From ''Standard Handbook for Electrical Engineers,'' Fink and Carrol, McGraw-Hill, NY, copyright 1968.)*

For the best results 6-in dry cells should not be used for current drains of over 0.5 A except for very short periods of time. Flashlight batteries should not be used for higher than the preceding current drain, and heavy-duty radio batteries will give best results if the current drain is kept below 25 mA.

Dry cells should be stored in a cool, dry place. Extreme heat during storage will shorten their life. The cell will not be injured by being frozen but will be as good as new after being brought back to normal temperature. In extreme cold weather dry cells may not give more than half of their normal service. At a temperature of about − 30°F they freeze solid and give neither voltage nor current.

The amperage of a dry cell by definition is the current that it will give when it is short-circuited (at about 70°F) through an ammeter which with its leads has a resistance of 0.01 Ω.

The **Ruben cell** (Ruben, Balanced Alkaline Dry Cells, *Trans. Electrochem. Soc.*, **92**, 1947) was developed jointly by the Ruben Laboratories and P. R. Mallory & Company during World War II for the operation of radar equipment and other electronic devices which require a high ratio of ampere-hour capacity to the volume of the cell at higher current densities than were considered practicable for the Leclanché type. The anode is of amalgamated zinc, and the cathode is a mercuric oxide depolarizing material intimately mixed with graphite in order to reduce its electrical resistivity. The electrolyte is a solution of potassium hydroxide (KOH) containing potassium zincate. The cell is made in three forms as shown in Fig. 15.1.13, the wound-anode type (*a*), the button type (*b*), and the cylindrical type (*c*).

The no-load emf of the cell is 1.34 V and remains essentially constant irrespective of time and temperature. Advantages of the cell are long shelf life, which enables them to be stored indefinitely; long service life, about four times that of the Leclanché dry cell of equivalent volume; small weight; a flat voltage characteristic which is advantageous for electronic uses in which the characteristics of tubes vary widely with voltage; adaptability to operating at high temperatures without deterioration; high resistance to shock.

The **zinc-alkaline-manganese dioxide cell** is a cell especially useful in applications that require a dry cell with relatively heavy or continuous drain. The anode is of amalgamated zinc, and the cathode is a manganese dioxide depolarizing material mixed with graphite for conductivity. The electrolyte is a solution of highly alkaline potassium hydroxide immobilized in cellulosic-type separators. These cells are available in standard-size cylindrical construction and wafer (flat) construction for cassette and tape recorder applications.

**Wet Cells** The **silver** or **cuprous chloride-magnesium cell** is a one-shot battery with a life of days after the electrolyte is added. A wet cell may be stored for years in a dry state. The cathode is either compacted copper chloride and graphite or sheet silver chloride, while the cathode is a thin magnesium sheet. The electrolyte is a solution of sodium chloride. The silver chloride cells are more expensive and are available in more and larger ratings.

The **Weston cell** is a primary cell used as a standard of emf. It consists of a glass H tube in the bottom of one leg of which is mercury which forms the cathode; in the bottom of the other leg is cadmium amalgam forming the anode. The electrolytes consist of mercurous sulfate and cadmium sulfate. There are two forms of the Weston cell: the saturated or normal cell, and the unsaturated cell. In the normal cell the electrolyte is saturated. This is the official standard since it is more permanent than the unsaturated type and can be reproduced with far greater accuracy. When carefully made, the emfs of cells agree within a few parts per million. There is, however, a small temperature coefficient. Although the unsaturated cell is not so reliable as the normal cell and must be standardized, it has a negligible temperature coefficient and is more convenient for general use. The manufacturers recommend that the temperature be not less than 4°C and not more than 40°C and the current

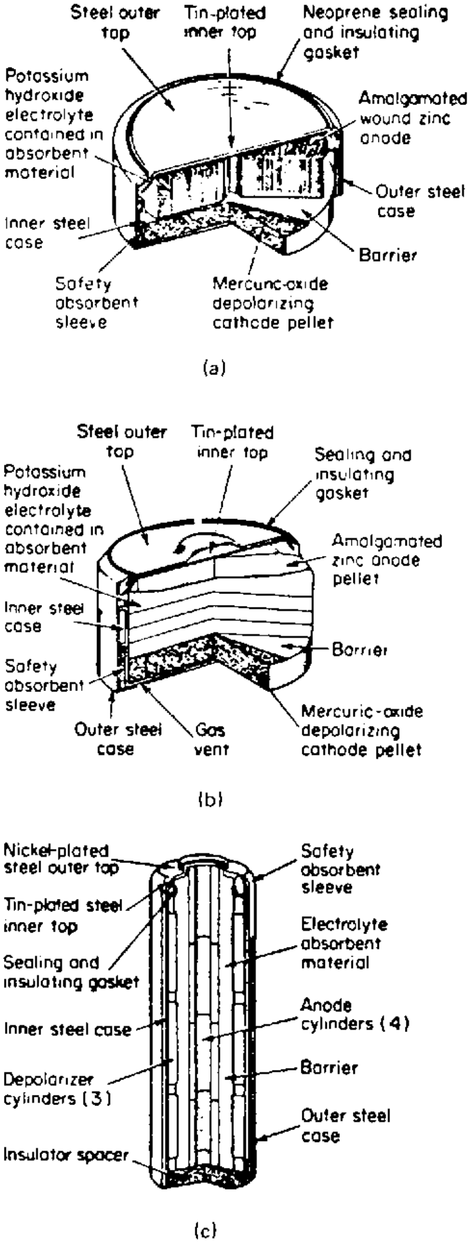


**Fig. 15.1.13** Ruben cells. (*a*) Wound-anode; (*b*) button; (*c*) cylindrical. *(From ''Standard Handbook for Electrical Engineers,'' Fink and Carrol, McGraw-Hill, NY, copyright 1968.)*

should not exceed 0.0001 A. The emf is between 1.0185 and 1.0190 V. Since no appreciable current can be taken from the cell, a null method must be used to utilize its emf.

### Storage (Secondary) Batteries

In a **storage battery** the electrolytic action must be **reversible** to a high degree. There are three types of storage batteries; the lead-lead-acid type, the nickel-iron-alkaline type (**Edison** battery), and the nickel-cadmium-alkali type (**Nicad**). In addition, there are various specialized types of cells for scientific and military purposes, and there is continuous development work in the search for higher capacities.

In the manufacture of the **lead-lead-acid cells** there are three general types of plates, or electrodes. In the **Planté type** the active material is electrically formed of pure lead by repeated reversals of the charging current. In the **Faure,** or **pasted-plate,** type, the positive and negative plates are formed by applying a paste, largely of lead oxides ($PbO_2$, $Pb_3O_4$), to lead-antimony or lead calcium supporting grids. A current is passed through the plates while they are immersed in weak sulfuric acid, the positive plates being connected as anodes and the negative ones as cathodes. The paste on the positive plates is converted into lead peroxide while that on the negative plate is reduced to spongy lead. The **tubular plate** (iron-clad) type has lead-alloy rods surrounded by perforated dielectric tubes with powdered-lead oxides packed between the rod and tube for the positive plate.

In order to obtain high capacity per unit weight it is necessary to expose a large plate area to the action of the acid. This is done in the Planté plate by ''ploughing'' with sharp steel disks, and by using corrugated helical inserts as active positive material (Manchester plate). In the pasted plate a large area of the material is necessarily exposed to the action of the acid.

The chemical reactions in a lead cell may be expressed by the following equation, based on the double sulfation theory:

$$\underbrace{PbO_2}_{\substack{\text{positive}\\\text{plate}}} + \underbrace{Pb}_{\substack{\text{negative}\\\text{plate}}} + \underbrace{2H_2SO_4}_{\substack{\text{sulfuric}\\\text{acid}}} \underset{\xrightarrow[\text{discharge}]{}}{\overset{\xleftarrow{\text{charge}}}{=}} \underbrace{2PbSO_4}_{\substack{\text{positive and}\\\text{negative plates}}} + \underbrace{2H_2O}_{\text{water}}$$

Between the extremes of complete charge and discharge, complex combinations of lead and sulfate are formed. After complete discharge a hard insoluble sulfate forms slowly on the plates, and this is reducible only by slow charging. This sulfation is objectionable and should be avoided.

**Specific Gravity** Water is formed with discharge and sulfuric acid is formed on charge, consequently the specific gravity must decrease on discharge and increase on charge. The variation of the specific gravity for a stationary battery is shown in Fig. 15.1.14. With starting and vehicle batteries it is necessary to operate the electrolyte from between 1.280 to 1.300 when fully charged to as low as 1.100 when completely discharged. The condition of charge of a battery can be determined by its specific gravity.

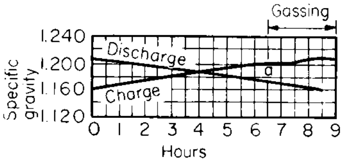


**Fig. 15.1.14** Variations of specific gravity in a stationary battery.

Battery electrolyte may be made from concentrated sulfuric acid (oil of vitriol, sp gr 1.84) by **pouring the acid into the water** in the following proportions:

**Parts Water to 1 Part Acid**

| | | | | |
|---|---|---|---|---|
| Specific gravity | 1.200 | 1.210 | 1.240 | 1.280 |
| Volume | 4.3 | 4.0 | 3.4 | 2.75 |
| Weight | 2.4 | 2.2 | 1.9 | 1.5 |

**Freezing Temperature of Sulfuric Acid and Water Mixtures**

| | | | | |
|---|---|---|---|---|
| Specific gravity | 1.180 | 1.200 | 1.240 | 1.280 |
| Freezing temp, °F | − 6 | − 16 | − 51 | − 90 |

**Voltage** The emf of a lead cell when fully charged and idle is 2.05 to 2.10 V. Discharge lowers the voltage in proportion to the current. When charging at constant current and normal rate, the terminal voltage gradually increases from 2.14 to 2.3 V, then increases rapidly to between 2.5

and 2.6 V (Fig. 15.1.15). This latter interval is known as the **gassing period.** When this period is reached, the charging rate should be reduced in order to avoid waste of power and unnecessary erosion of the plates.

Practically all batteries have a **normal rating** based on the 8-h rate of discharge. Thus a 320 A · h battery would have a normal rate of 40 A. The ampere-hour capacity of batteries falls off rapidly with increase in discharge rate.

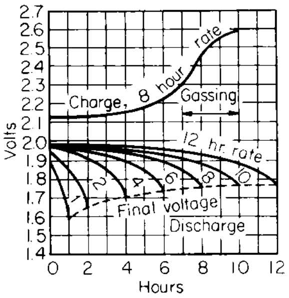


**Fig. 15.1.15** Voltage curves on charge and discharge for a lead cell.

**Effect of Discharge Rate on Battery Capacity**

| Discharge rate, h | 8 | 5 | 3 | 1 | ⅓ | ⅒ |
|---|---|---|---|---|---|---|
| Percentage of rated capacity, | | | | | | |
| Planté type | 100 | 88 | 75 | 55.8 | 37 | 19.5 |
| Pasted type | 100 | 93 | 83 | 63 | 41 | 25.5 |

The following rule may be observed in **charging a lead battery.** The charging rate in amperes should be less than the number of ampere-hours out of the battery. For example, if 200 A · h are out of a battery, a charging rate of 200 A may be used until the ampere-hours out of the battery are reduced appreciably.

There are two common methods of charging: the **constant-current method** and the **constant-potential method.** Figure 15.1.16*a* shows a common method of charging with constant current, provided a low-voltage dc power supply is available. The resistor connected in series may be adjusted to give the required current. Several batteries may be connected in series. Figure 15.1.16*b* shows a more common method, using a copper oxide or silicon rectifier, since ac power supply is more common than dc. The rectifier disks, mounted in a stack, are bridge-connected, the directions of rectification being indicated. The polarity of the two wires can readily be determined by means of a dc voltmeter.

The constant-potential method is to be preferred since the rate automatically tapers off as the cell approaches the charged condition. Without resistance the terminal voltage should be 2.3 V per cell, but it is preferable to use 2.4 to 2.5 V per cell with low resistance in series.

When a battery is being charged, its terminal voltage

$$V = E + Ir \tag{15.1.28}$$

Compare with Eq. (15.1.27).

When a battery is fully charged, any rate will produce gassing, but the rate may be reduced to such a low value that gassing is practically harmless. This is called the **finishing rate.**

**Portable batteries** for automobile starting and lighting, airplanes, industrial trucks, electric locomotives, train lighting, and power boats employ the pasted-type plates because of their high discharge rates for a given weight and size. The separators are either of treated grooved wood; perforated hard rubber; glass-wool mats; perforated rubber, and grooved wood; ribbed microporous rubber. In low-priced short-lived batteries for automobiles, grooved wood alone is used; in the better types, the wood is reinforced with perforated hard rubber. Containers for the low-priced short-lived automobile-type starting batteries are of asphaltic compound; for other portable types they are usually of hard rubber.

The **Exide iron-clad** battery is a portable type designed for propelling electric vehicles. The positive plate consists of a lead-antimony frame supporting perforated hard-rubber tubes. An irregular lead-antimony core runs down the center of each tube, and the lead peroxide paste is packed into these tubes so that shedding of active material from the positive plate cannot occur. Pasted negative plates are used. The separators are flat microporous rubber.

**Stationary Batteries** The tanks of stationary batteries are made of hard rubber or plastics. When the battery is used for regulating or cycling duty, the positive plates may be of the Planté type because of their long life. However, in most modern installations thick pasted plates are used. Because of the tight fit of the plate assembly within the container and the resulting pressure of the separator against the plate surfaces, shedding of active material is reduced to a minimum and long life is obtained. Pasted negative plates are used in almost all batteries.

A lead storage battery **removed from service** for less than 9 months should be charged once a month if possible; if not, it should be given a heavy overcharge before discontinuing service. If removed for a longer period, siphon off acid (which may be used again) and fill with fresh water. Allow to stand 15 h and siphon off water. Remove and throw away the wood separators. The battery will now stand indefinitely. To put in service again, install new separators, fill with acid (sp gr 1.210) and charge at normal rate 35 h or until gravity has ceased to rise over a period of 5 h. Charge at a low rate a few hours longer.

The **ampere-hour efficiency** of lead batteries is 85 to 90 percent. The **watthour efficiency** obtained from full charge to discharge at the normal rate and at rated amp-hour is 75 to 80 percent. Batteries which do regulating duty only may have a much higher watthour efficiency.

The **Edison storage cell** when fully charged has a positive plate of nickel pencils filled with a higher nickel oxide and a negative plate of flat nickel-plated-steel stampings containing metallic iron in finely divided form. The active material for the positive plate is nickel hydrate and for the negative plate, iron oxide. The electrolyte is a 21 percent solution of potassium hydrate with lithium hydroxides. The initial emf is about 1.4 V and the average emf about 1.1 V throughout discharge. In

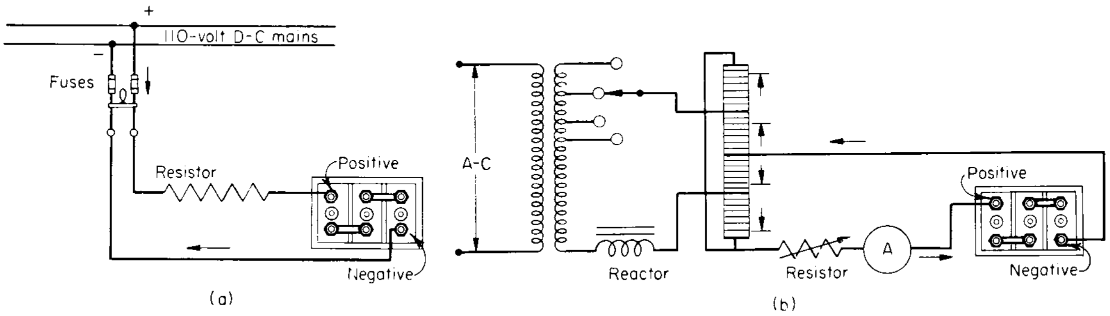


**Fig. 15.1.16** Connections for charging a storage battery from (*a*) 110-V dc mains, (*b*) copper oxide rectifier.

Fig. 15.1.17 are shown typical voltage characteristics on charge and discharge for an Edison cell. On account of the higher internal resistance of the cell the battery is not so efficient from the energy standpoint as the lead cell. The jar is welded nickel-plated steel. The battery is compact and extremely light and strong and for these reasons is particularly adapted for propelling electric vehicles and for boat- and train-lighting systems. The battery is rugged, and since there is no opportunity for the growth of active material on the plates or flaking of active material, the battery has long life.

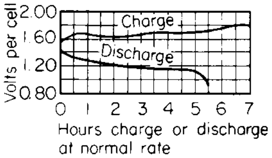


**Fig. 15.1.17** Voltage during charge and discharge of an Edison cell.

**Nickel-Cadmium-Alkali (Nicad) Battery** The positive active material is nickelic (black) hydroxide mixed with graphite to give it high conductivity. The negative active material is cadmium oxide. Both materials are used in powdered form and are contained within flat perforated steel pockets. These pockets are locked into steel plates, the positive and negative being alike in construction. All steel parts are nickel-plated. A complete plate group consists of a number of positive and negative plates assembled on bolts and terminal posts common to plates of the same polarity. The separators are thin strips of polystyrene, and all other battery insulation is also polystyrene. The entire plate assembly is contained within a welded-steel tank. The electrolyte is potassium hydroxide (KOH), specific gravity 1.210 at 72°F (22°C); it does not enter into any chemical reactions with the electrode materials, and its specific gravity remains constant during charge and discharge, neglecting any slight change due to the small amount of gassing. On charge, the voltage is 1.4 to 1.5 V until near the end when it rises to 1.8 V. On discharge, the voltage is nearly constant at 1.2 V.

Nicad batteries are strong mechanically and are not damaged by overcharge; they hold their charge over long periods of idleness, the active material cannot flake off, the internal resistance is low, there is no corrosion, and the battery has an indefinitely long life. It is a general-purpose battery.

In the **Sonotone** nickel-cadmium battery the positive plates are nickel oxide when the battery is charged, and the negative plates are metallic cadmium. On discharge the positive plates are reduced to a state of lower oxidation, and the negative plates regain oxygen. The electrolyte is a 30 percent solution of potassium hydroxide, the specific gravity of which is 1.29 at room temperature. The case is a transparent plastic. The terminal voltage at the normal discharge rate is 1.2 V per cell.

**Rechargeable batteries,** exemplified by Gould Nicad cells (Alkaline Battery Division, Gould National Batteries, Inc.), are hermetically sealed nickel-cadmium cells that contain no free alkaline electrolyte. Since there is no spillage or leakage, they can operate in any position, have long life, and require no maintenance or servicing, and their weight is small for their output. They are thus well adapted to power many types of cordless appliances such as tools, hedge shears, cameras, dictating equipment, electric razors, radios, and television sets. The electrodes consist of a plaque of microporous sintered nickel having an extremely high surface area. The electrochemical reactions differ from those of the conventional vented-type alkaline battery, a type which at the end of a charge liberates both oxygen and hydrogen gases as well as electrolytic fumes that must be vented through a valve in the top of the cell. In the sealed nickel-cadmium cell, the negative electrode (at the time that the cell is sealed) never becomes fully charged, and the evolution of hydrogen is completely suppressed. On charging, when the positive electrode has reached its full capacity, the oxygen which has evolved is channeled through the porous separator to the negative electrode and oxidizes the finely divided cadmium of the microporous plate to cadmium hydroxide, which at the same time is reduced to metallic cadmium. The cells are constructed in three different forms: the button type, the cylindrical type, and the prismatic type. Their ratings range from 20 mA · h to 23 A · h. Their average discharge voltage is 1.22 V, and they require 14 h of charge at the normal rate (one-tenth A · h rating), which for a 3.5 A · h cell is 0.35 A.

Precautions in the **care of storage batteries:** An ammeter should not be connected directly across the terminals to test the condition of a cell; a battery should not be left to stand in a discharged condition; a flame should not be brought in the vicinity of a battery that is being charged; the battery should not be allowed to become heated when charging; water should never be added to the concentrated acid—always acid to the water; acid should never be equalized except when the battery is in a charged condition; a battery should never be exposed to the influence of external heat; voltmeter tests should be made when the current is flowing; batteries should always be kept clean. To replace acid lost through slopping, use a solution of 2 parts concentrated sulfuric acid in 5 parts water by weight, unless a hydrometer is at hand to enable the solution to be made up according to the specifications of the makers of the cell.

## DIELECTRIC CIRCUITS

**Dynamic and Static Electricity** Electricity in motion such as an electric current is dynamic electricity; electricity at rest is static electricity. The two are identical physically. Since static electricity is frequently produced at high voltage and small quantity, the two are frequently considered as being two different types of electricity.

### Capacitors

**Capacitors (formerly condensers)** Two conducting bodies, or electrodes, separated by a dielectric constitute a capacitor. If a positive charge is placed on one electrode of a capacitor, an equal negative charge is induced on the other. The medium between the capacitor plates is called a **dielectric.** The dielectric properties of a medium relate to its ability to conduct **dielectric lines.** This is in distinction to its **insulating** properties which relate to its property to conduct **electric current.** For example, air is an excellent insulator but ruptures dielectrically at low voltage. It is not a good dielectric so far as breakdown strength is concerned.

With capacitors

$$Q = CE \tag{15.1.29}$$

$$C = Q/E \tag{15.1.30}$$

$$E = Q/C \tag{15.1.31}$$

where $Q$ = quantity, C; $C$ = capacitance, F; and $E$ = voltage. The unit of capacitance in the practical system is the **farad.** The farad is too large a unit for practical purposes, so that either the **microfarad** ($\mu$F) or the **picofarad** (pF) are used. However, in voltage, current, and energy relations the capacitance must be expressed in farads.

The energy stored in a capacitor is

$$W = ½QE = ½CE^2 = ½Q^2/C \qquad \text{J} \tag{15.1.32}$$

**Capacitance of Capacitors** The capacitance of a **parallel-electrode** capacitor (Fig. 15.1.18) is

$$C = \varepsilon_r A/(4\pi d \times 9 \times 10^3) \qquad \mu\text{F} \tag{15.1.33}$$

where $\varepsilon_r$ = relative capacitivity; $A$ = area of one electrode, m$^2$; and $d$ = distance between electrodes, m.

**Fig. 15.1.18** Parallel-electrode capacitor.

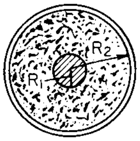


**Fig. 15.1.19** Coaxial-cylinder capacitor.

The capacitance of **coaxial cylindrical** capacitors (Fig. 15.1.19) is

$$C = 0.2171\varepsilon_r l/[9 \times 10^5 \log (R_2/R_1)] \qquad \mu\text{F} \tag{15.1.34}$$

where $\varepsilon_r$ is the relative capacitivity and $l$ the length, m. Also

$$C = 0.03882\varepsilon_r/\log (R_2/R_1) \qquad \mu\text{F/mi} \qquad (15.1.35)$$

Equation (15.1.35) is useful in that it is applicable to cables.

The capacitance of two **parallel cylindrical conductors** $D$ m between centers and having radii of $r$ m is

$$C = 0.01941/\log (D/r) \qquad \mu\text{F/mi} \qquad (15.1.36)$$

In practice, the capacitance to neutral or to an infinite conducting plane midway between the conductors and perpendicular to their plane is usually used. The capacitance to neutral is

$$C = 0.03882/\log (D/r) \qquad \mu\text{F/mi} \qquad (15.1.37)$$

Equations (15.1.36) and (15.1.37) are used for calculating the capacitance of overhead transmission lines. When computing charging current, use voltage between lines in (15.1.36) and to neutral in (15.1.37).

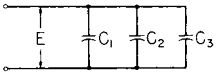


**Fig. 15.1.20** Capacitances in parallel.

**Capacitances in Parallel** The equivalent capacitance of capacitances in parallel (Fig. 15.1.20) is

$$C = C_1 + C_2 + C_3 \qquad (15.1.38)$$

Capacitances in parallel are all across the same voltage. If the voltage is $E$, then the total quantity $Q = CE$ and $Q_1 = C_1E$, etc.

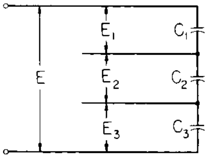


**Fig. 15.1.21** Capacitances in series.

**Capacitances in Series** The equivalent capacitance $C$ of capacitances in series (Fig. 15.1.21) is found as follows:

$$1/C = 1/C_1 + 1/C_2 + 1/C_3 \qquad (15.1.39)$$

If the capacitances are not leaky, the charge $Q$ is the same on each. $Q = CE$, $E_1 = Q/C_1$, $E_2 = Q/C_2$, etc.

**Insulators and Dielectrics** Insulating materials are applied to electric circuits to prevent the leakage of current. Insulating materials used with high voltage must not only have a high resistance to leakage current, but must also be able to resist dielectric puncture; i.e., in addition to being a good insulator, the material must be a good dielectric. Insulation resistance is usually expressed in M$\Omega$ and the resistivity given in M$\Omega \cdot$cm. The dielectric strength is usually given in terms of voltage gradient, common units being V/mil, V/mm, and kV/cm. Insulation resistance decreases very rapidly with increase in temperature. Absorbed moisture reduces the insulation resistance, and moisture and humidity have a large effect on surface leakage. In Table 15.1.8 are given the insulating and dielectric properties of several common insulating materials (see also Sec. 6). Dielectric heating of materials is described in Sec. 7.

## TRANSIENTS

**Induced EMF** If a flux $\phi$ webers linking $N$ turns of conductor changes, an emf

$$e = -N(d\phi/dt) \qquad \text{V} \qquad (15.1.40)$$

is induced.

**Self-inductance** Let a flux $\phi$ link $N$ turns. The linkages of the circuit are $N\phi$ weber-turns. If the permeability of the circuit is assumed constant, the number of these linkages per ampere is the **self-inductance** or **inductance** of the circuit. The unit of inductance is the **henry.** The inductance is

$$L = N\phi/(i) \qquad \text{H} \qquad (15.1.41)$$

If the permeability changes with the current

$$L = N(d\phi/di) \qquad \text{H} \qquad (15.1.42)$$

The energy stored in the magnetic field

$$W = \tfrac{1}{2}Li^2 \qquad \text{J} \qquad (15.1.43)$$

**EMF of Self-induction** If Eq. (15.1.41) is written $Li = N\phi$ and differentiated with respect to the time $t$, $L(di/dt) = N(d\phi/dt)$ and from Eq. (15.1.40)

$$e = -L(di/dt) \qquad \text{V} \qquad (15.1.44)$$

$e$ is the emf of self-induction. If a rate of change of current of 1 A/s induces an emf of 1 V, the inductance is then 1 H.

**Table 15.1.8 Electrical Properties of Insulating Materials**

| Material | Volume resistivity, M Ω · cm | Dielectric constant, 60Hz | Dielectric strength | |
|---|---|---|---|---|
| | | | V/mil | V/mm |
| Asbestos board (ebonized) | $10^7$ | | 55 | $2 \times 10^3$ |
| Bakelite | $5–30 \times 10^{11}$ | 4.5–5.5 | 450–1,400 | $(17–55) \times 10^3$ |
| Epoxy | $10^{14}$ | 3.5–5 | 300–400 | $(12–16) \times 10^3$ |
| Fluorocarbons: | | | | |
| Fluorinated ethylene propylene | $10^{18}$ | 2.1 | 500 | $20 \times 10^3$ |
| Polytetrafluoroethylene | $10^{18}$ | 2.1 | 400 | $16 \times 10^3$ |
| Glass | $17 \times 10^9$ | 5.4–9.9 | 760–3,800 | $(3–15) \times 10^4$ |
| Magnesium oxide | | 2.2 | 300–700 | $(12–27) \times 10^3$ |
| Mica | $10^{14}–10^{17}$ | 4.5–7.5 | 1,000–4,000 | $(4–16) \times 10^4$ |
| Nylon | $10^{14}–10^{17}$ | 4–7.6 | 300–400 | $(12–16) \times 10^3$ |
| Neoprene | | 7.5 | 600 | $23.5 \times 10^3$ |
| Oils: | | | | |
| Mineral | $21 \times 10^6$ | 2–4.7 | 300–400 | $(12–16) \times 10^3$ |
| Paraffin | $10^{15}$ | 2.41 | 410–550 | $(16–22) \times 10^3$ |
| Paper | | 1.7–2.6 | 110–230 | $(4–9) \times 10^3$ |
| Paper, treated | | 2.5–4 | 500–750 | $(20–30) \times 10^3$ |
| Phenolic (glass filled) | $10^{12}–10^{13}$ | 5–9 | 140–400 | $(5.5–16) \times 10^3$ |
| Polyethylene | $10^{15}–10^{18}$ | 2.3 | 450–1,000 | $(17–40) \times 10^3$ |
| Polyimide | $10^{16}–10^{17}$ | 3.5 | 400 | $16 \times 10^3$ |
| Polyvinyl chloride (flexible) | $10^{11}–10^{15}$ | 5–9 | 300–1,000 | $(12–40) \times 10^3$ |
| Porcelain | $3 \times 10^8$ | 5.7–6.8 | 240–300 | $(9.5–12) \times 10^3$ |
| Rubber | $10^{14}–10^{16}$ | 2–3.5 | 500–700 | $(20–27) \times 10^3$ |
| Rubber (butyl) | $10^{18}$ | 2.1 | | |

**Current in Inductive Circuit** If a circuit containing resistance $R$ and inductance $L$ in series is connected across a steady voltage $E$, the voltage $E$ must supply the $iR$ drop in the circuit and at the same time overcome the emf of self-induction. That is $E = Ri + L\,di/dt$. A solution of this differential equation gives

$$i = (E/R)\,(1 - e^{-Rt/L}) \qquad \text{A} \qquad (15.1.45)$$

where $e$ is the base of the natural system of logarithms.

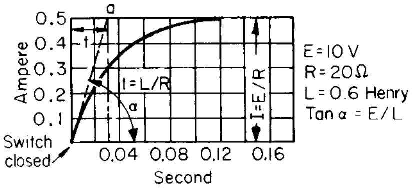


**Fig. 15.1.22** Rise of current in an inductive circuit.

Figure 15.1.22 shows this equation plotted when $E = 10$ V, $R = 20\ \Omega$, $L = 0.6$ H. It is to be noted that inductance causes the current to rise slowly to its Ohm's law value, $I_0 = E/R = 10/20 = 0.5$ A. When $t = L/R$, the current has reached 63.2 percent of its Ohm's law value. $L/R$ is the **time constant** of the circuit. In the foregoing circuit, the time constant $L/R = 0.6/20 = 0.03$ s. The initial rate of rise of current is tan $\alpha = E/L$. If current continued at this rate, it would reach $\alpha = E/R$ in $L/R$ s $[(E/L) \times (L/R) = E/R]$.

If a circuit containing inductance and resistance in series is short-circuited when the current is $I_0$, the equation of current becomes

$$i = I_0 e^{-Rt/L} \qquad \text{A} \qquad (15.1.46)$$

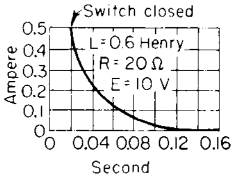


**Fig. 15.1.23** Decay of current in an inductive circuit.

Figure 15.1.23 shows this equation plotted when $I_0 = 0.5$ A, $R = 20\ \Omega$, $L = 0.6$ H. It is seen that inductance opposes the decay of current. Inductance always opposes change of current.

**Mutual Inductance** If two circuits having inductances $L_1$ and $L_2$ henrys are so related to each other geometrically that any portion of the flux produced by the current in one circuit links the other circuit, the two circuits possess **mutual inductance.** It follows that a change of current in one circuit causes an emf to be induced in the other. Let $\varepsilon_2$ be induced in circuit 2 by a change $di_1/dt$ in circuit 1. Then

$$e_2 = -M\,di_1/dt \qquad \text{V} \qquad (15.1.47)$$

$M$ is the mutual inductance of the two circuits.

$$M = k\sqrt{L_1 L_2} \qquad (15.1.48)$$

where $k$ is the **coefficient of coupling** of the two circuits, or the proportion of the flux in one circuit which links the other. Also a change of current $di_2/dt$ in circuit 2 induces an emf $e_1$ in circuit 1, $e_1 = -M\,di_2/dt$.

The stored energy is

$$W = ½L_1 I_1^2 + ½L_2 I_2^2 + MI_1 I_2 \qquad \text{J} \qquad (15.1.49)$$

where $I_1$ and $I_2$ are the currents in circuits 1 and 2.

**Current in Capacitive Circuit** If capacitance $C$ farads and resistance $R$ ohms are connected in series across the steady voltage $E$, the current is

$$i = (E/R)e^{-t/CR} \qquad \text{A} \qquad (15.1.50)$$

If a capacitor charged to voltage $E$ is discharged through resistance $R$, the current is

$$i = -(E/R)e^{-t/CR} \qquad \text{A} \qquad (15.1.51)$$

Except for sign, these two equations are identical and are of the same form as Eq. (15.1.46).

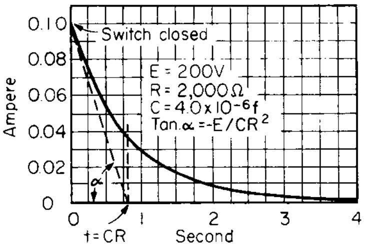


**Fig. 15.1.24** Transient current to a capacitor.

In Fig. 15.1.24 is shown the transient current to a capacitor in series with a resistor when $E = 200$ V, $C = 4.0\ \mu$F, $R = 2$ k$\Omega$. When $t = CR$, the current has reached $1/e = 0.368$ its initial value. $CR$ is the **time constant** of the circuit. The initial rate of decrease of current is tan $\alpha = -E/CR^2$. If the current continued at this rate it would reach zero when the time is $CR$ s. If, in its fully charged condition, the capacitor of Fig. 15.1.24 is discharged through the resistor $R$, the curve will be the negative of that shown in Fig. 15.1.24.

**Resistance, Inductance, and Capacitance in Series** If a circuit having resistance, inductance, and capacitance in series is connected across a source of steady voltage, a transient condition results. If $R > \sqrt{4L/C}$, the circuit is nonoscillatory or overdamped.

The current is

$$i = \frac{EC}{\sqrt{R^2C^2 - 4LC}}\left(e^{(-\alpha+\beta)t} - e^{(-\alpha-\beta)t}\right) \qquad \text{A} \qquad (15.1.52)$$

where $\alpha = R/2L$ and $\beta = (\sqrt{R^2C^2 - 4LC})/2LC$.

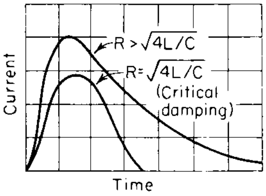


**Fig. 15.1.25** Transient current in nonoscillatory circuits.

In Fig. 15.1.25 is shown the curve corresponding to Eq. (15.1.52). When $R = \sqrt{4L/C}$, the system is **critically damped** and the transient dies out rapidly without oscillation. The current is

$$i = (E/L)te^{-Rt/2L} \qquad \text{A} \qquad (15.1.53)$$

Figure 15.1.25 shows also the curve corresponding to Eq. (15.1.53).

If $R < \sqrt{4L/C}$, the transient is oscillatory, being a logarithmically damped sine wave. The current is

$$i = \frac{2EC}{\sqrt{4LC - R^2C^2}}\, e^{-Rt/2L} \sin \frac{\sqrt{4LC - R^2C^2}}{2LC}\, t \qquad \text{A} \qquad (15.1.54)$$

The transient oscillates at a frequency very nearly equal to $1/(2\pi\sqrt{LC})$ Hz. This is the **natural frequency** of the circuit.

In Fig. 15.1.26 is shown the curve corresponding to Eq. (15.1.54). If the capacitor, after being charged to $E$ V, is discharged into the foregoing series circuits, the currents are given by Eqs. (15.1.52) to (15.1.54) multiplied by $-1$. Equations (15.1.52) to (15.1.54) are the same types obtained with dynamic mechanical systems with friction, mass, and elasticity.

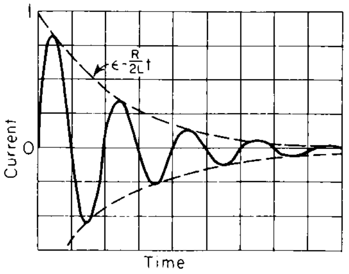


**Fig. 15.1.26** Transient current in an oscillatory circuit.

## ALTERNATING CURRENTS

**Sine Waves** In the following discussion of alternating currents, sine waves of voltage and current will be assumed. That is, $e = E_m \sin \omega t$ and $i = I_m \sin(\omega t - \theta)$, where $E_m$ and $I_m$ are maximum values of voltage and current; $\omega$, the angular velocity, in rad/s, is equal to $2\pi f$, where $f$ is the frequency; $\theta$ is the angle of phase difference.

**Cycle; Frequency** When any given armature coil has passed a pair of poles, the emf or current has gone through 360 electrical degrees, or 1 **cycle.** An **alternation** is one-half cycle. The **frequency** of a synchronous machine in cycles per second (hertz) is

$$f = NP/120 \qquad \text{Hz} \qquad (15.1.55)$$

where $N$ is the speed in r/min and $P$ the number of poles. In the United States and Canada the frequency of 60 Hz is almost universal for general lighting and power. For the ac power supply to dc transit systems, and for railroad electrification, a frequency of 25 Hz is used in many installations. In most of Europe and Latin America the frequency of 50 Hz is in general use. In aircraft the frequency of 400 Hz has become standard.

**Static inverters** make it possible to obtain high and variable frequencies to drive motors at greater than the 3,600 r/min limitation on 60-Hz circuits, and to vary speeds. The textile industry has small motors operating at 12,000 r/min (200 Hz), and larger motors have been run at 6,000 r/min (100 Hz). Many large mainframe computers have been powered at 400 Hz.

The **root-mean-square (rms),** or **effective, value of a current wave** produces the same heating in a given resistance as a direct current of the same ampere value. Since the heating effect of a current is proportional to $i^2r$, the rms value is obtained by squaring the ordinates, finding their average value, and extracting the square root, i.e., the rms value is

$$I = \sqrt{1/T \int_0^T i^2\,dt} \qquad \text{A} \qquad (15.1.56)$$

where $T$ is the time of a cycle. The rms value $I$ of a sine wave equals $(1/\sqrt{2})I_m = 0.707 I_m$.

**Average Value of a Wave** The average value of a sine wave over a complete cycle is zero. For a half cycle the average is $(2/\pi)I_m$, or $0.637\ I_m$, where $I_m$ is the maximum value of the sine wave. The average value is of importance only occasionally. A dc measuring instrument gives the average value of a pulsating wave. The average value is of use (1) when the effects of the current are proportional to the number of coulombs, as in electrolytic work and (2) when converting alternating to direct current.

**Form Factor** The form factor of a wave is the ratio of rms value to average value. For a sine wave this is $\pi/(2\sqrt{2}) = 1.11$. This factor is important in that it enters equations for induced emf.

**Inductive reactance,** $2\pi fL$ or $\omega L$, opposes an alternating current in inductance $L$. It is expressed in Ω. Reactance is usually denoted by the symbol $X$. Inductive reactance is denoted by $X_L$.

The **current** in an inductive reactance $X_L$ when connected across the voltage $E$ is

$$I = E/X_L = E/(2\pi fL) \qquad \text{A} \qquad (15.1.57)$$

This current lags the voltage by 90 electrical degrees. Inductance absorbs no energy. The energy stored in the magnetic field during each half cycle is returned to the source during the same half cycle.

**Capacitive reactance** is $1/(2\pi fC) = 1/\omega C$ and is denoted by $X_C$, where $C$ is in F. If $C$ is given in $\mu$F, $X_C = 10^6\, 2\pi fC$. The current in a capacitive reactance $X_C$ when connected across voltage $E$ is

$$I = E/X_C = 2\pi fCE \qquad \text{A} \qquad (15.1.58)$$

This current leads the voltage by 90 electrical degrees. Pure capacitance absorbs no energy. The energy stored in the dielectric field during each half cycle is returned to the source during the same half cycle.

**Impedance** opposes the flow of alternating current and is expressed in Ω. It is denoted by $Z$. With resistance and inductance in series

$$Z = \sqrt{R^2 + X_L^2} = \sqrt{R^2 + (2\pi fL)^2} \qquad \Omega \qquad (15.1.59)$$

With resistance and capacitance in series

$$Z = \sqrt{R^2 + X_C^2} = \sqrt{R^2 + [1/(2\pi fC)]^2} \qquad \Omega \qquad (15.1.60)$$

With resistance, inductance, and capacitance in series

$$\begin{aligned} Z &= \sqrt{R^2 + (X_L - X_C)^2} \\ &= \sqrt{R^2 + [2\pi fL - 1/(2\pi fC)]^2} \qquad \Omega \qquad (15.1.61) \end{aligned}$$

The current is

$$I = E/\sqrt{R^2 + [2\pi fL - 1/(2\pi fC)]^2} \qquad \text{A} \qquad (15.1.62)$$

**Phasor or Vector Representation** Sine waves of voltage and current can be represented by phasors, these phasors being proportional in magnitude to the waves that they represent. The angle between two phasors is also equal to the time angle existing between the two waves that they represent.

Phasors may be combined as forces are combined in mechanics. Both graphical methods and the methods of complex algebra are used. Impedances and also admittances may be similarly combined, either graphically or symbolically. The usual method is to resolve series impedances into their component resistances and reactances, then combine all resistances and all reactances, from which the resultant impedance is obtained. Thus $Z_1 + Z_2 = \sqrt{(r_1 + r_2)^2 + (x_1 + x_2)^2}$, where $r_1$ and $x_1$ are the components of $Z_1$, etc.

**Phase Difference** With resistance only in the circuit, the current and the voltage are in phase with each other; with inductance only in the circuit, the current lags the voltage by 90 electrical degrees; with capacitance only in the circuit, the current leads the voltage by 90 electrical degrees.

With resistance and inductance in series, the voltage leads the current by angle $\theta$ where $\tan\theta = X_L/R$. With resistance and capacitance in series, the voltage lags the current by angle $\theta$ where $\tan\theta = -X_C/R$.

With resistance, inductance, and capacitance in series, the voltage may lag, lead, or be in phase with the current.

$$\tan\theta = (X_L - X_C)/R = (2\pi fL - 1/2\pi fC)/R \qquad (15.1.63)$$

If $X_L > X_C$ the voltage leads; if $X_L < X_C$ the voltage lags; if $X_L = X_C$ the current and voltage are in phase and the circuit is in resonance.

**Power Factor** In ac circuits the power $P = I^2R$ where $I$ is the current and $R$ the effective resistance (see below). Also the power

$$P = EI\cos\theta \qquad \text{W} \qquad (15.1.64)$$

where $\theta$ is the phase angle between $E$ and $I$. Cos $\theta$ is the **power factor** (pf) of the circuit. It can never exceed unity and is usually less than unity.

$$\cos\theta = P/EI \qquad (15.1.65)$$

$P$ is often called the true power. The product $EI$ is the volt-amp (V · A) and is often called the apparent power.

**Active** or **energy** current is the projection of the total current on the voltage phasor. $I_e = I\cos\theta$. Power $= EI_e$.

**Reactive, quadrature,** or **wattless current** $I_q = I\sin\theta$ and is the component of the current that contributes no power but increases the $I^2R$ losses of the system. In power systems it should ordinarily be made low.

The **vars** (volt-amp-reactive) are equal to the product of the voltage and reactive current. **Vars** $= EI_q$. **Kilovars** $= EI_q/1{,}000$.

**Effective Resistance** When alternating current flows in a circuit, the losses are ordinarily greater than are given by the losses in the ohmic resistance alone. For example, alternating current tends to flow near the surface of conductors (skin effect). If iron is associated with the circuit, eddy-current and hysteresis losses result. These power losses may be accounted for by increasing the ohmic resistance to a value $R$, where $R$ is the **effective resistance,** $R = P/I^2$. Since the iron losses vary as $I^{1.8}$ to $I^2$, little error results from this assumption.

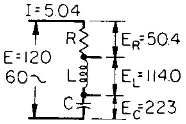


**Fig. 15.1.27** Resistor, inductor, and capacitor in series.

SOLUTION OF SERIES-CIRCUIT PROBLEM. Let a resistor $R$ of 10 Ω, an inductor $L$ of 0.06 H, and a capacitor $C$ of 60 μF be connected in series across 120-V 60-Hz mains (Fig. 15.1.27). Determine (1) the impedance, (2) the current, (3) the voltage across the resistance, the inductance, the capacitance, (4) the power factor, (5) the power, (6) the angle of phase difference.

(1) $\omega = 2\pi 60 = 377$. $X_L = 0.06 \times 377 = 22.6\ \Omega$; $X_C = 1/(377 \times 0.000060) = 44.2\ \Omega$; $Z = \sqrt{(10)^2 + (22.6 - 44.2)^2} = 23.8\ \Omega$; (2) $I = 120/23.8 = 5.04$ A; (3) $E_R = IR = 5.04 \times 10 = 50.4$ V; $E_L = IX_L = 5.04 \times 22.6 = 114.0$ V; $E_C = IX_C = 5.04 \times 44.2 = 223$ V; (4) $\tan\theta = (X_L - X_C)/R = -21.6/10 = -2.16$, $\theta = -65.2°$, $\cos\theta = \text{pf} = 0.420$; (5) $P = 120 \times 5.04 \times 0.420 = 254$ W; $P = I^2R = (5.04)^2 \times 10 = 254$ W (check); (6) From (4) $\theta = -65.2°$. Voltage lags. The phasor diagram to scale of this circuit is shown in Fig. 15.1.28. Since the current is common for all elements of the circuit, its phasor is laid horizontally along the axis of reference.

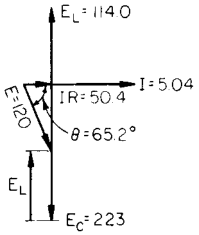


**Fig. 15.1.28** Phasor diagram for a series circuit.

**Resonance** If the voltage $E$ and the resistance $R$ [Eq. (15.1.62)] are fixed, the maximum value of current occurs when $2\pi fL - 1/2\pi fC = 0$. The circuit so far as its terminals are concerned behaves like a noninductive resistor. The current $I = E/R$, the power $P = EI$, and the power factor is unity.

The voltage across the inductor and the voltage across the capacitor are opposite and equal and may be many times greater than the circuit voltage. The frequency

$$f = 1/(2\pi\sqrt{LC}) \qquad \text{Hz} \tag{15.1.66}$$

is the **natural frequency** of the circuit and is the frequency at which it will oscillate if the circuit is not acted upon by some external frequency. This is the principle of radio sending and receiving circuits. Resonant conditions of this type should be avoided in power circuits, as the piling up of voltage may endanger apparatus and insulation.

EXAMPLE. For what value of the inductance in the circuit (Fig. 15.1.27) will the circuit be in resonance, and what is the voltage across the inductor and capacitor under these conditions?

From Eq. (15.1.66) $L = 1/(2\pi f)^2C = 0.1173$ H. $I = E/R = 120/10 = 12$ A. $L\omega I = I/C\omega = 0.1173 \times 377 \times 12 = 530$ V. This voltage is over four times the line voltage.

**Parallel Circuits** Parallel circuits are used for nearly all power distribution. With several series circuits in parallel it is merely necessary to find the current in each and add all the current phasors vectorially to find the total current. Parallel circuits may be solved analytically.

A series circuit has resistance $r_1$ and **inductive reactance** $x_1$. The **conductance** is

$$g_1 = r_1/(r_1^2 + x_1^2) = r_1/Z_1^2 \qquad \text{S} \tag{15.1.67}$$

and the **susceptance** is

$$b_1 = x_1/(r_1^2 + x_1^2) = x_1/Z_1^2 \qquad \text{S} \tag{15.1.68}$$

Conductance is not the reciprocal of resistance unless the reactance is zero; susceptance is not the reciprocal of reactance unless the resistance is zero. With inductive reactance the susceptance is **negative;** with capacitive reactance the susceptance is **positive.**

If a second circuit has resistance $r_2$ and **capacitive reactance** $x_2$ in series, $g_2 = r_2/(r_2^2 + x_2^2) = r_2/Z_2^2$; $b_2 = x_2/(r_2^2 + x_2^2) = x_2/Z_2^2$. The total conductance $G = g_1 + g_2$; the total susceptance $B = -b_1 + b_2$. The **admittance** is

$$Y = \sqrt{G^2 + B^2} = 1/Z \qquad \text{S} \tag{15.1.69}$$

The energy current is $EG$; the reactive current is $EB$; the power is

$$P = E^2G \qquad \text{W} \tag{15.1.70}$$

$$\text{vars} = E^2B \qquad \text{W} \tag{15.1.71}$$

The power factor is

$$pf = G/Y \tag{15.1.72}$$

Also the following relations hold:

$$r = g/(g^2 + b^2) = g/Y^2 \qquad \Omega \tag{15.1.73}$$

$$x = b/(g^2 + b^2) = b/Y^2 \qquad \Omega \tag{15.1.74}$$

SOLUTION OF A PARALLEL-CIRCUIT PROBLEM. In the parallel circuit of Fig. 15.1.29 it is desired to find the joint impedance, the total current, the power in each branch, the total power, and the power factor, when $E = 100$, $f = 60$, $R_1 = 2\ \Omega$, $R_2 = 4\ \Omega$, $L_1 = 0.00795$ H, $X_1 = 2\pi fL_1 = 3\ \Omega$, $C_2 = 1{,}326$ μF, $X_2 = 1/2\pi fC_2 = 2\ \Omega$, $Z_1 = \sqrt{2^2 + 3^2} = 3.6\ \Omega$, and $Y_1 = 1/3.6 = 0.278$ S.

*Solution:* $g_1 = R_1/(R_1^2 + X_1^2) = 2/13 = 0.154$; $b_1 = -3/13 = -0.231$; $Z_2 = \sqrt{16 + 4} = 4.47$; $Y_2 = 1/4.47 = 0.224$; $g_2 = R_2/(R_2^2 + X_2^2) = 4/(16 + 4) = 0.2$ S; $b_2 = 2/20 = 0.1$ S; $G = g_1 + g_2 = 0.154 + 0.2 = 0.354$ S; $B = b_1 + b_2 = -0.231 + 0.1 = -0.131$ S; $Y = \sqrt{G^2 + B^2} = \sqrt{0.354^2 + (-0.131)^2} = 0.377$ S, and joint impedance $Z = 1/0.377 = 2.65\ \Omega$. Phase angle $\theta = \tan^{-1}(-0.131/0.354) = -20.3°$. $I = EY = 100 \times 0.377 = 37.7$ A; $P_1 = E^2g_1 = 100^2 \times 0.154 = 1{,}540$ W; $P_2 = E^2g_2 = 100^2 \times 0.2 = 2{,}000$ W; total power $= E^2G = 100^2 \times 0.354 = 3{,}540$ W. Power factor $= \cos\theta = 3{,}540/(100 \times 37.7) = 93.8$ percent.

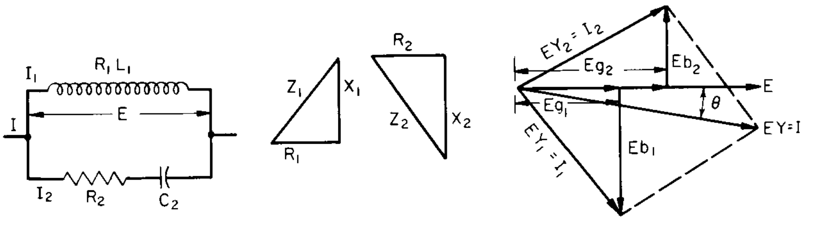


**Fig. 15.1.29** Parallel circuit and phasor diagrams.

With parallel circuits, unity power factor is obtained when the algebraic sum of the quadrature currents is zero. That is, $b_1 + b_2 + b_3 \cdots = 0$.

**Three-Phase Circuits** Ac generators are usually wound with three armature circuits which are spaced 120 electrical degrees apart on the armature. Hence these coils generate emfs 120 electrical degrees apart. The coils are connected either in Y (star) or in Δ (mesh) as shown in Fig. 15.1.30. Whether Y- or Δ-connected, with a balanced load, the three coil emfs $E_c$ and the three coil currents $I_c$ are equal. In the Y connection the line and coil currents are equal, but the line emfs $E_{AB}$, $E_{BC}$, $E_{CA}$ are $\sqrt{3}$ times in magnitude the coil emfs $E_{OA}$, $E_{OB}$, $E_{OC}$, since each is the phasor difference of two coil emfs. In the delta connection the line and coil emfs are equal, but $I$, the line current, is $\sqrt{3}\, I_c$, the coil current, i.e., it is the phasor difference of the currents in the two coils connected to the line. The power of a coil is $E_c I_c \cos\theta$, so that the total power is $3E_c I_c \cos\theta$. If $\theta$ is the angle between coil current and coil voltage, the angle between line current and line voltage will be $30° \pm \theta$. In terms of line current and emf, the power is $\sqrt{3}\, EI \cos\theta$. A fourth or neutral conductor connected to $O$ is frequently used with the Y connection. The neutral point $O$ is frequently grounded in transmission and distribution circuits. The coil emfs are assumed to be sine waves. Under these conditions they balance, so that in the delta connection the sum of the two coil emfs at each instant is balanced by the third coil emf. Even though the third, ninth, fifteenth . . . harmonics, $3(2n + 1)f$, where $n = 0$ or an integer, exist in the coil emfs, they cannot appear between the three external line conductors of the three-phase Y-connected circuit. In the delta circuit, the same harmonics $3(2n + 1)f$ cause local currents to circulate around the mesh. This may cause a very appreciable heating. In a three-phase system the power

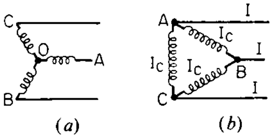


**Fig. 15.1.30** Three-phase connections. (*a*) Y connection; (*b*) Δ connection.

$$P = \sqrt{3}\, EI \cos\theta \qquad \text{W} \tag{15.1.75}$$

the power factor is

$$P/\sqrt{3}\, EI \tag{15.1.76}$$

and the kV·A

$$\sqrt{3}\, EI/1{,}000 \tag{15.1.77}$$

where $E$ and $I$ are line voltages and currents.

**Two-Phase Circuits** Two-phase generators have two windings spaced 90 electrical degrees apart on the armature. These windings generate emfs differing in time phase by 90°. The two windings may be independent and power transmitted to the receiver though the two single-phase circuits are entirely insulated from each other. The two circuits may be combined into a two-phase three-wire circuit such as is shown in Fig. 15.1.31, where $OA$ and $OB$ are the generator circuits (or transformer secondaries) and $A'O'$ and $B'O'$ are the load circuits. The wire $OO'$ is the common wire and under balanced conditions carries a current $\sqrt{2}$ times the current wires $AA'$ and $BB'$. For example, if $I_c$ is the coil current, $\sqrt{2}\, I_c$ will be the value of the current in the common conductor $OO'$. If $E_c$ is the voltage across $OA$ or $OB$, $\sqrt{2}\, E_c$ will be the voltage across $AB$. The power of a two-phase circuit is twice the power in either coil if the load is balanced. Normally, the voltages $OA$ and $OB$ are equal, and the current is the same in both coils. Owing to nonsymmetry and the high degree of unbalancing of this system even under balanced loads, it is not used at the present time for transmission and is little used for distribution.

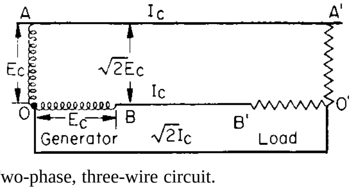


**Fig. 15.1.31** Two-phase, three-wire circuit.

**Four-Phase Circuit** A four-phase or quarter-phase circuit is shown in Fig. 15.1.32. The windings $AC$ and $BD$ may be independent or connected at $O$. The voltages $AC$ and $BD$ are 90 electrical degrees apart as in two-phase circuits. If a neutral wire $O$-$O'$ is added, three different voltages can be obtained. Let $E_1$ = voltage between $O$-$A$, $O$-$B$, $O$-$C$, $O$-$D$. Voltages between $A$-$B$, $B$-$C$, $C$-$D$, $D$-$A$ = $\sqrt{2}\, E_1$. Voltages between $A$-$C$, $B$-$D$ = $2E_1$. Because of this multiplicity of voltages and the fact that polyphase power apparatus and lamps may be connected at the same time, this system is still used to some extent in distribution.

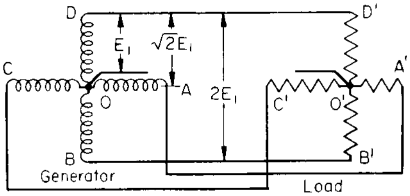


**Fig. 15.1.32** Four-phase or quarter-phase circuit.

**Advantages of Polyphase Power** The advantages of polyphase power over single-phase power are as follows. The output of synchronous generators and most other rotating machinery is from 60 to 90 percent greater when operated polyphase than when operated single phase; pulsating fluxes and corresponding iron losses which occur in many common types of machinery when operated single phase are negligible when operated polyphase; with balanced polyphase loads polyphase power is constant whereas with single phase the power fluctuates over wide limits during the cycle. Because of its minimum number of wires and the fact that it is not easily unbalanced, the three-phase system has for the most part superseded other polyphase systems.

## ELECTRICAL INSTRUMENTS AND MEASUREMENTS

Electrical measuring devices that merely indicate, such as ammeters and voltmeters, are called **instruments;** devices that totalize with time such as watthour meters and ampere-hour meters are called **meters.** (See also Sec. 16.) Most types of electrical instruments are available with digital read out.

**DC Instruments** Direct current and voltage are both measured with an indicating instrument based on the principle of the D'Arsonval galvanometer. A coil with steel pivots and turning in jewel bearings is mounted in a magnetic field produced by permanent magnets. The motion is restrained by two small flat coiled springs, which also serve to conduct the current to the coil. The deflections of the coil are read with a light aluminum pointer attached to the coil and moving over a graduated scale. The same instrument may be used for either current or voltage, but the method of connecting in circuit is different in the two cases. Usually, however, the coil of an instrument to be used as an ammeter is wound with fewer turns of coarser wire than an instrument to be used as a voltmeter and so has lower resistance. The instrument itself is frequently called a **millivoltmeter.** It cannot be used alone to measure voltage of any magnitude since its resistance is so low that it would be burned out if connected across the line. Hence a resistance $r'$ in series with the coil is necessary as indicated in Fig. 15.1.33*a* in which $r_c$ is the resistance of the coil. From 0.2 to 750 V this resistance is usually within the instrument. For higher voltages an external resistance $R$, called an extension coil or multiplier (Fig. 15.1.33*b*), is necessary. Let $e$ be the reading of the instrument, in volts (Fig. 15.1.33*b*), $r$ the internal resistance of the instrument, including $r'$ and $r_c$ in Eq. (15.1.33*a*), $R$ the resistance of the multiplier. Then the total voltage is

$$E = e(R + r)/r \tag{15.1.78}$$

It is clear that by using suitable values of $R$ a voltmeter can be made to have several scales.

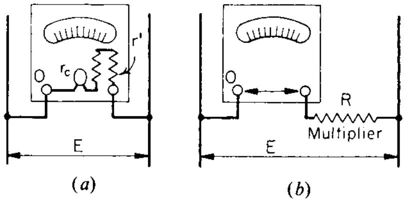


**Fig. 15.1.33** Voltmeters. (*a*) Internal resistance; (*b*) with multiplier.

Instruments themselves can only carry currents of the magnitudes of 0.01 to 0.06 A. To measure larger values of current the instrument is provided with a shunt $R$ (Fig. 15.1.34). The current divides inversely as the resistances $r$ and $R$ of the instrument and the shunt. A low resistance $r'$ within the instrument is connected in series with the coil. This permits some adjustment to the deflection so that the instrument can be adapted to its shunt. Usually most of the current flows through the shunt, and the current in the instrument is negligible in comparison. Up to 50 and 75 A the shunt can be incorporated within the instrument. For larger currents it is usually necessary to have the shunt external to the instrument and connect the instrument to the potential terminals of the shunt by means of leads. Any given instrument may have any number of ranges by providing it with a sufficient number of shunts. The range of the usual instrument of this type is approximately 50 mV. Although the same instrument may be used for voltmeters or ammeters, the moving coils of voltmeters are usually wound with more turns of finer wire. They take approximately 0.01 A so that their resistance is approximately 100 Ω/V. Instruments used as ammeters alone operate with 0.01 to 0.06 A.

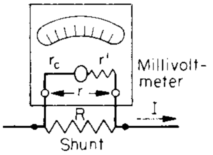


**Fig. 15.1.34** Millivoltmeter with shunt.

Permanent-magnet moving-coil instruments may be used to measure unidirectional pulsating currents or voltages and in such cases will indicate the average value of the periodically varying current or voltage.

**AC Instruments** Instruments generally used for alternating currents may be divided into five types: **electrodynamometer, iron-vane, thermocouple, rectifier,** and **electronic.** Instruments of the **electrodynamometer** type, the most precise, operate on the principle of one coil carrying current, turning in the magnetic field produced by a second coil carrying current taken from the same circuit. If these circuits or coils are connected in series, the torque exerted on the moving system for a given relative position of the coil system is proportional to the square of the current and is not dependent on the direction of the current. Consequently, the instrument will have a compressed scale at the lower end and will usually have only the upper two-thirds of the scale range useful for accurate measurement. Instruments of this type ordinarily require 0.04 to 0.08 A or more in the moving-coil circuit for full-scale deflection. They read the rms value of the alternating or pulsating current. The wattmeter operates on the electrodynamometer principle. The fixed coil, however, is energized by the current of the circuit, and the moving coil is connected across the potential in series with high resistance. Unless shielded magnetically the foregoing instruments will not, in general, indicate so accurately on direct as on alternating current because of the effects of external stray magnetic fields. Also reversed readings should be taken. **Iron vane** instruments consist of a fixed coil which actuates magnetically a light movable iron vane mounted on a spindle; they are rugged, inexpensive, and may be had in ranges of 30 to 750 V and 0.05 to 100 A. They measure rms values and tend to have compressed scales as in the case of electrodynamometer instruments.

The compressed part of the scale may, however, be extended by changing the shape of the vanes. Such instruments operate with direct current and are accurate to within 1 percent or so. AC instruments of the **induction type** (Westinghouse Electric Corp.) must be used on ac circuits of the frequency for which they have been designed. They are rugged and relatively inexpensive and are used principally for switchboards where a long-scale range and a strong deflecting torque are of particular advantage. **Thermocouple instruments** operate on the **Seebeck effect.** The current to be measured is conducted through a heater wire, and a thermojunction is either in thermal contact with the heater or is very close to it. The emf developed in the thermojunction is measured by a permanent-magnet dc type of instrument. By controlling the shape of the air gap, a nearly uniform scale is obtained. This type of instrument is well adapted to the measurement of high-frequency currents or voltages, and since it operates on the heating effect of current, it is convenient as a transfer instrument between direct current and alternating current.

In the **rectifier-type instrument** the ac voltage or current is rectified, usually by means of a small copper oxide or a selenium-type rectifier, connected in a bridge circuit to give full-wave rectification (Fig. 15.1.35). The rectified current is measured with a dc permanent-magnet-type instrument $M$. The instrument measures the **average** value of the half waves that have been rectified, and with the sine waves, the average value is 0.9 the rms value. The scale is calibrated to indicate rms values. With nonsinusoidal waves the ratio of average to rms may vary considerably from 0.9 so that the instrument may be in error up to ± 5 percent from this cause. This type of instrument is widely used in the measurement of high-frequency voltages and currents. **Electronic voltmeters** operate on the principle of the amplification which can be obtained with a transistor. Since the emf to be measured is applied to the base, the instruments take practically no current and hence are adapted to measure potential differences which would change radically were any appreciable current taken by the measuring device. This type of instrument can measure voltages from a few tenths of a volt to several hundred volts, and with a potential divider, up to thousands of volts. They are also adapted to frequencies up to 100 MHz.

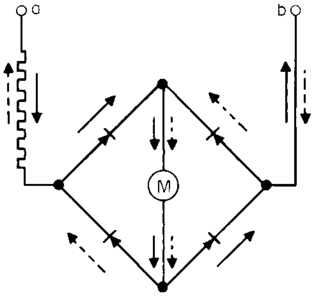


**Fig. 15.1.35** Rectifier-type instrument.

Particular care must be used in selecting instruments for measuring the nonsinusoidal waves of rectifier and controlled rectifier circuits. The **electrodynamic, iron vane,** and **thermocouple** instruments will read rms values. The **rectifier** instrument will read average values, while the **electronic** instrument may read either rms or average value, depending on the type.

**Power Measurement in Single-Phase Circuits** Wattmeters are not rated primarily in W, but in A and V. For example, with a low power factor the current and voltage coils may be overloaded and yet the needle be well on the scale. The current coil may be carrying several times its rated current, and yet the instrument reads zero because the potential circuit is not closed, etc. Hence it is desirable to use both an ammeter and a voltmeter in conjunction with a wattmeter when measuring power (Fig. 15.1.36*a*). The instruments themselves consume appreciable power, and correction is often necessary unless these losses are negligible compared with the power being measured. For example, in Fig. 15.1.36*a*, the wattmeter measures the $I^2 R$ loss in its own current coil and in the ammeter (1 to 2 W each), as well as the loss in the voltmeter ($= E^2/R$ where $R$ is the resistance of the voltmeter). The losses in the ammeter and voltmeter may be eliminated by short-circuiting the ammeter and disconnecting the voltmeter when reading the wattmeter. If the wattmeter is connected as shown in Fig. 15.1.36*b*, it measures the power taken by its own potential coil ($E^2/R_p$) which at 110 V is 5 to 7 W. ($R_p$ is the resistance of the potential circuit.) Frequently correction must be made for this power.

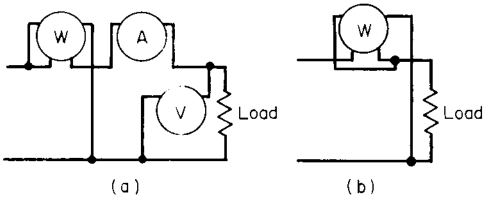


**Fig. 15.1.36** Connections of instruments to single-phase load.

**Power Measurement in Polyphase Circuits; Three-Wattmeter Method** Let *ao*, *bo*, and *co* be any Y-connected three-phase load (Fig. 15.1.37). Three wattmeters with their current coils in each line and their potential circuits connected to neutral measure the total power, since the power in each load is measured by one of the wattmeters. The connection *oo′* may, however, be broken, and the total power is still the sum of the three readings; i.e., the power $P = P_1 + P_2 + P_3$. This method is applicable to any system of *n* wires. The current coil of one wattmeter is connected in each of the *n* wires. The potential circuit of each wattmeter is connected between its own phase wire and a junction in common with all the other potential circuits. The wattmeters must be connected symmetrically, and the readings of any that read negative must be given the negative sign.

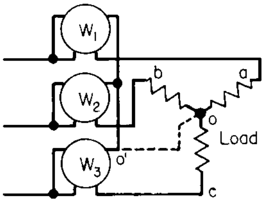


**Fig. 15.1.37** Three-wattmeter method.

In the general case any system of $n$ wires requires at least $n - 1$ wattmeters to measure the power correctly. The $n - 1$ wattmeters are connected in series with $n - 1$ wires. The potential circuit of each is connected between its own phase wire and the wire in which no wattmeter is connected (Fig. 15.1.38).

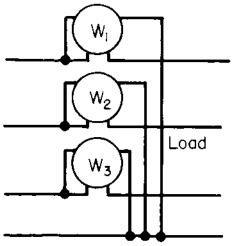


**Fig. 15.1.38** Power measurement in an *n*-wire system.

The thermal watt converter is also used to measure power. This instrument produces a dc voltage proportional to three-phase ac power.

**Three-Phase Systems** The three-wattmeter method (Fig. 15.1.37) is applicable to any three-phase system. It is commonly used with the three-phase four-wire system. If the loads are balanced, $P_1 = P_2 = P_3$ and the power $P = 3P_1$.

The **two-wattmeter** method is most commonly used with three-phase three-wire systems (Fig. 15.1.39). The current coils may be connected in *any* two wires, the potential circuits being connected to the third. It will be recognized that this is adapting the method of Fig. 15.1.38 to three wires. With balanced loads the readings of the wattmeters are $P_1 = Ei \cos(30° + \theta)$, $P_2 = Ei \cos(30° - \theta)$, and $P = P_2 \pm P_1$. $\theta$ is the angle of phase difference between coil voltage and current. Since

$$P_1/P_2 = \cos(30° + \theta)/\cos(30° - \theta) \qquad (15.1.79)$$

the power factor is a function of $P_1/P_2$. Table 15.1.9 gives values of power factor for different ratios of $P_1/P_2$.

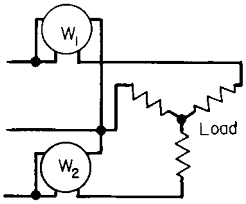


**Fig. 15.1.39** Two-wattmeter method.

$$P = P_2 + P_1 \text{ when } \theta < 60°.$$

When $\theta = 60°$, pf $= \cos 60° = 0.5$, $P_1 = \cos(30° + 60°) = 0$, $P = P_2$. When $\theta > 60°$, pf $< 0.5$, $P = P_2 - P_1$. Also,

$$\tan\theta = \sqrt{3}\,(P_2 - P_1)/(P_2 + P_1) \qquad (15.1.80)$$

In a **polyphase wattmeter** the two single-phase wattmeter elements are combined to act on a single spindle. Hence the adding and subtracting of the individual readings are done automatically. The total power is indicated on one scale. This type of instrument is almost always used on switchboards. The connections of a portable type are shown in Fig. 15.1.40.

In the foregoing instrument connections, Y-connected loads are shown. These methods are equally applicable to delta-connected loads. The two-wattmeter method (Fig. 15.1.39) is obviously adapted to the two-phase three-wire system (Fig. 15.1.31).

**Table 15.1.9 Ratio $P_1/P_2$ and Power Factor**

| $P_1/P_2$ | Power factor | $P_1/P_2$ | Power factor | $P_1/P_2$ | Power factor | $P_1/P_2$ | Power factor |
|---|---|---|---|---|---|---|---|
| +1.0 | 1.000 | +0.4 | 0.804 | −0.1 | 0.427 | −0.6 | 0.142 |
| +0.9 | 0.996 | +0.3 | 0.732 | −0.2 | 0.360 | −0.7 | 0.102 |
| +0.8 | 0.982 | +0.2 | 0.656 | −0.3 | 0.296 | −0.8 | 0.064 |
| +0.7 | 0.956 | +0.1 | 0.576 | −0.4 | 0.240 | −0.9 | 0.030 |
| +0.6 | 0.918 | 0.0 | 0.50 | −0.5 | 0.188 | −1.0 | 0.000 |
| +0.5 | 0.866 | | | | | | |

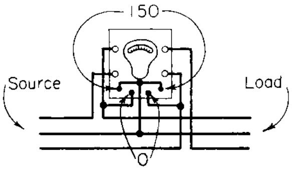


**Fig. 15.1.40** Connections for a polyphase wattmeter in a three-phase circuit.

### Measurement of Energy

**Watthour meters** record the energy taken by a circuit over some interval of time. Correct registration occurs if the angular velocity of the rotating element at every instant is proportional to the power. The method of accomplishing this with dc meters is illustrated in Fig. 15.1.41. The meter is in reality a small motor. The field coils *FF* are in series with the line. The armature *A* is connected across the line, usually in series with a resistor *R*. The movable field coil *F′* is in series with the armature *A* and serves to compensate for friction. *C* is a small commutator, either of copper or of silver, and the two small brushes are usually of silver. An aluminum disk, rotating between the poles of permanent magnets *M*, acts as a magnetic brake the retarding torque of which is proportional to the angular velocity of the disk. A small worm and the gears *G* actuate the recording dials.

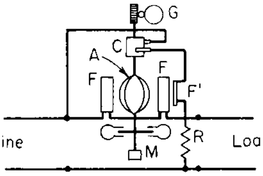


**Fig. 15.1.41** DC watthour meter.

The following relation, or an equivalent, holds with most types of meter. With each revolution of the disk, *K* Wh are recorded, where *K* is the **meter constant** found usually on the disk. It follows that the average watts *P* over any period of time *t* sec is

$$P = 3{,}600KN/t \tag{15.1.81}$$

where *N* is the revolutions of the disk during that period. Hence, the meter may be calibrated by connecting standardized instruments to measure the average power taken by the load and by counting the revolutions *N* for *t* s. Near full load, if the meter registers fast, the magnets *M* should be moved outward radially; if it registers slow, the magnets should be moved inward. If the meter registers fast at light (5 to 10 percent) load, the starting coil *F′* should be moved further away from the armature; if it registers slow, *F′* should be moved nearer the armature. A meter should not register more than 1.5 percent fast or slow, and with calibrated standards it can be made to register to within 1 percent of correct.

The **induction watthour meter** is used with alternating current. Although the dc meter registers correctly with alternating current, it is more expensive than the induction type, the commutator and brushes may cause trouble, and at low power factors compensation is necessary. In the induction watthour meter the driving torque is developed in the aluminum disk by the joint action of the alternating magnetic flux produced by the potential circuit and by the load current. The driving torque and the retarding torque are both developed in the same aluminum disk, hence no commutator and brushes are necessary. The rotating element is very light, and hence the friction torque is small. Equation (15.1.81) applies to this type of meter. When calibrating, the average power *W* for *t* s is determined with a calibrated wattmeter. The friction compensation is made at light loads by changing the position of a small hollow stamping with respect to the potential lug. The meter should also be adjusted at low power factor (0.5 is customary). If the meter is slow with lagging current, resistance should be cut out of the compensating circuit; if slow with leading current, resistance should be inserted.

**Power-Factor Measurement** The usual method of determining power factor is by the use of voltmeter, ammeter, and wattmeter. The wattmeter gives the watts of the circuit, and the product of the voltmeter reading and the ammeter reading gives the volt-amperes. The power factor is the ratio of the two [see Eqs. (15.1.65) and (15.1.76)]. Also single-phase and three-phase power-factor indicators, which can be connected directly in circuit, are on the market.

### Instrument Transformers

With voltages higher than 600 V, and even at 600 V, it becomes dangerous and inaccurate to connect instruments and meters directly into power lines. It is also difficult to make potential instruments for voltages in excess of 600 V and ammeters in excess of 60-A ratings. To insulate such instruments from high voltage and at the same time to permit the use of low-range instruments, instrument transformers are used. **Potential transformers** are identical with power transformers except that their volt-ampere rating is low, being 40 to 500 W. Their primaries are wound for line voltage and their secondaries for 110 V. **Current transformers** are designed to go in series with the line, and the rated secondary current is 5 A. The secondary of a current transformer **should always be closed** when current is flowing; it should never be allowed to become open circuited under these conditions. When open-circuited the voltage across the secondary becomes so high as to be dangerous and the flux becomes so large in magnitude that the transformer overheats. Semiconductors that break down at safe voltages and short current-transformer secondaries are available to ensure that the secondary is closed. The secondaries of both potential and current transformers should be well grounded at one point (Figs. 15.1.42 and 15.1.43). Instrument transformers introduce slight errors because of small variations in their ratio with load. Also there is slight phase displacement in both current and potential transformers. The readings of the instruments must be multiplied by the instrument transformer ratios. The scales of switchboard instruments are usually calibrated to take these ratios into account.

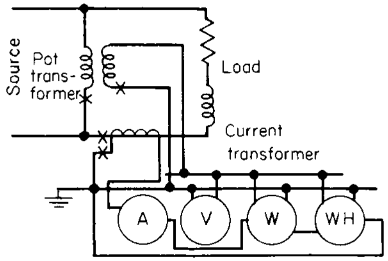


**Fig. 15.1.42** Single-phase connections of instruments with transformers.

Figure 15.1.42 shows the use of instrument transformers to measure the voltage, current, power, and kilowatthours of a single-phase load. Figure 15.1.43 shows the connections that would be used to measure the voltage, current, and power of a 26,400-V 600-A three-phase load.

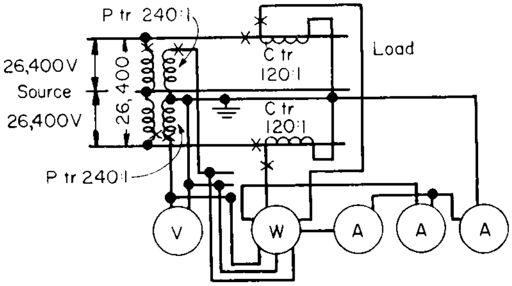


**Fig. 15.1.43** Three-phase connections of instruments and instrument transformers.

**Measurement of High Voltages** Potential transformers such as those shown in Figs. 15.1.42 and 15.1.43 may be used even for very high voltages, but for voltages above 132 kV they become so large and expensive that they are used only sparingly. A convenient method used with testing transformers is the employment of a voltmeter coil, which consists of a coil of a few turns interwoven in the high-voltage winding and insulated from it. The voltage ratio is the ratio of the turns in the high-voltage winding to those in the voltmeter coil. A capacitance voltage divider consists of two or more capacitors connected in series across the high voltage to be measured. A high-impedance voltmeter, such as an electronic one, is connected across the capacitor at the grounded end. The high voltage $V = V_m C_m / C$ V, where $V_m$ is the voltmeter reading, $C$ the capacitance (in $\mu$F) of the entire divider, and $C_m$ the equivalent capacitance (in $\mu$F) of the capacitor at the grounded end. A bushing potential device consists of a high-voltage-transformer bushing having a capacitance tap brought out from one of the metallic electrodes within the bushing which is near ground potential. This device is obviously a capacitance voltage divider. For testing, **sphere gaps** are used for the very high voltages. Calibration data for sphere gaps are given in the ANSI/IEEE Std. 4-1978 Standard Techniques for High Voltage Testing. Even when it is not being used for the measurement of voltage, it is frequently advisable to connect a sphere gap in parallel with the specimen being tested so as to prevent overvoltages. The gap is set to a slightly higher voltage than that which is desired.

### Measurement of Resistance

**Voltmeter-Ammeter Method** A common method of measuring resistance, known as the voltmeter-ammeter or fall-in-potential method, makes use of an ammeter and a voltmeter. In Fig. 15.1.44, the resistance to be measured is *R*. The current in the resistor *R* is *I* A, which is measured by the ammeter *A* in series. The drop in potential across the resistor *R* is measured by the voltmeter *V*. The current shunted by the voltmeter is so small that it may generally be neglected. A correction may be applied if necessary, for the resistance of the voltmeter is generally given with the instrument. The potential difference divided by the current gives the resistance included between the voltmeter leads. As a check, determinations are generally made with several values of current, which may be varied by means of the controlling resistor *r*. If the resistance to be measured is that of the armature of a dc machine and the voltmeter leads are placed on the brush holders, the resistance determined will include that of the brush contacts. To measure the resistance of the armature alone, the voltmeter leads should be placed directly on the commutator segments on which the brushes rest but not under the brushes.

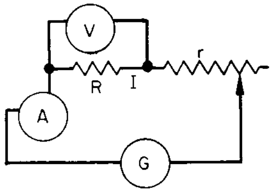


**Fig. 15.1.44** Voltmeter-ammeter method for resistance measurement.

**Insulation Resistance** Insulation resistance is so high that it is usually given in megohms ($10^6$ ohms, MΩ) rather than in ohms. Insulation resistance tests are important, for although they may not be conclusive they frequently reveal flaws in insulation, poor insulating material, presence of moisture, etc. Such tests are applied to the insulation of electrical machinery from the windings to the frame, to underground cables, to insulators, capacitors, etc.

For moderately low resistances, 1 to 10 MΩ, the voltmeter method given in Fig. 15.1.45, which shows insulation measurement to the frame of the field winding of a generator, may be used. To measure the current when a voltage *E* is impressed across the resistor *R*, a high-reading voltmeter *V* is connected in series with *R*. The current under this condition with the switch connecting *S* and *A* is *E*/(*R* + *r*), where *r* is the resistance of the voltmeter. A high-resistance voltmeter is necessary, since the method is in reality a comparison of the unknown insulation resistance *R* with the known resistance *r* of the voltmeter. Hence, the resistance of the voltmeter must be comparable with the unknown resistance, or the deflection of the instrument will be so small that the results will be inaccurate. To determine the impressed voltage *E*, the same voltmeter is used. The switch *S* connects *S* and *B* for this purpose. With these two readings, the unknown resistance is

$$R = r(E - e)/e \tag{15.1.82}$$

where *e* is the deflection of the voltmeter when in series with the resistance to be measured as when *S* is at *A*. If a special voltmeter, having a resistance of 100 kΩ per 150 V, is available, a resistance of the order of 2 to 3 MΩ may be measured very accurately.

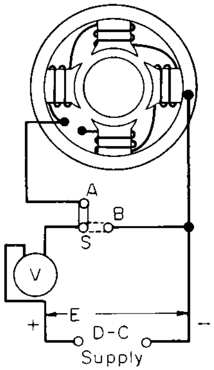


**Fig. 15.1.45** Voltmeter method for insulation resistance measurement.

When the insulation resistance is too high to be measured with a voltmeter, a sensitive galvanometer may be used. The connections for measuring the insulation resistance of a cable are shown in Fig. 15.1.46. The battery should have an emf of at least 100 V. Radio B batteries are convenient for this purpose. The method involves comparing the unknown resistance with a standard 0.1 MΩ. To calibrate the galvanometer the cable is short-circuited (dotted line) and the switch *S* is thrown to position (*a*). Let the galvanometer deflection be $D_1$ and the reading of the Ayrton shunt $S_1$. The short circuit is then removed. The 0.1 MΩ is left in circuit since it is usually negligible in comparison with the unknown resistance *X*. Let the reading of the galvanometer now be $D_2$ and the reading of the shunt $S_2$. Then

$$X = 0.1\, S_2 D_1 / S_1 D_2 \qquad \text{M}\Omega \tag{15.1.83}$$

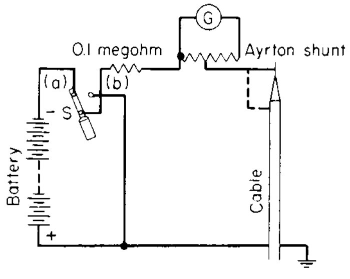


**Fig. 15.1.46** Measurement of insulation resistance with a galvanometer.

When the switch *S* is thrown to position (*b*), the cable is short-circuited through the 0.1 MΩ and becomes discharged.

The **Megger** insulation tester is an instrument that indicates insulation resistance directly on a scale. It consists of a small hand or motor-driven generator which generates 500 V, 1,000 V, 2,500 V, or 5,000 V. A clutch slips when the voltage exceeds the rated value. The current through the unknown resistance flows through a moving element consisting of two coils fastened rigidly together, but which move in different portions of the magnetic field. A pointer attached to the spindle of the moving element indicates the insulation resistance directly. These instruments have a range up to 10,000 MΩ and are very convenient where portability and convenience are desirable.

The insulation resistance of electrical machinery may be of doubtful significance as far as dielectric strength is concerned. It varies widely with temperature, humidity, and cleanliness of the parts. When the insulation resistance falls below the prescribed value, it can (in most cases of good design) be brought to the required standard by cleaning and drying the machine. Hence it may be useful in determining whether or not the insulation is in proper condition for a dielectric test. IEEE Std. 62-1978 specifies minimum values of insulation resistance in MΩ = (rated voltage)/(rating in kW + 1,000). If the operating voltage is higher than the rated voltage, the operating voltage should be used. The rule specifies that a dc voltage of 500 be used in testing. If not, the voltage should be specified.

**Wheatstone Bridge** Resistors from a fraction of an Ω to 100 kΩ and more may be measured with a high degree of precision with the Wheatstone bridge (Fig. 15.1.47). The bridge consists of four resistors *ABCX* connected as shown. *X* is the unknown resistance; *A* and *B* are ratio arms, the resistance units of which are in even decimal Ω as 1, 10, 100, etc. *C* is the rheostat arm. A battery or low-voltage source of direct current is connected across *ab*. A galvanometer *G* of moderate sensitivity is connected across *cd*. The values of *A* and *B* are so chosen that three or four significant figures in the value of *C* are obtained. As a first approximation it is well to make *A* and *B* equal. When the bridge is in balance,

$$X/C = A/B \tag{15.1.84}$$

The positions of the battery and galvanometer are interchangeable. There are many modifications of the bridge which adapt it to measurements of very low resistances and also to ac measurements.

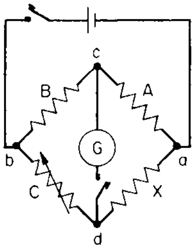


**Fig. 15.1.47** Wheatstone bridge.

**Kelvin Double Bridge** The simple Wheatstone bridge is not adapted to measuring very low resistances since the contact resistances of the test specimen become comparable with the specimen resistance. This error is avoided in the Kelvin double bridge, the diagram of which is shown in Fig. 15.1.48. The specimen *X*, which may be a short length of copper wire or bus bar, is connected in series with an adjustable calibrated resistor *R* whose resistance is comparable with that of the specimen. The arms *A* and *B* of the bridge are ratio arms usually with decimal values of 1, 10, 100 Ω. One terminal of the galvanometer is connected to *X* and *R* by means of two resistors *a* and *b*. If these resistors are set so that $a/b = A/B$, the contact resistance *r* between *X* and *R* is eliminated in the measurement. The contact resistances at *c* and *d* have no effect since at balance the galvanometer current is zero. The contact resistances at *f* and *e* need only be negligible compared with the resistances of arms *A* and *B* both of which are reasonably high. By means of the variable resistor *Rh* the value of current, as indicated by ammeter *A*, may be adjusted to give the necessary sensitivity. When the bridge is in balance,

$$X/R = A/B \tag{15.1.85}$$

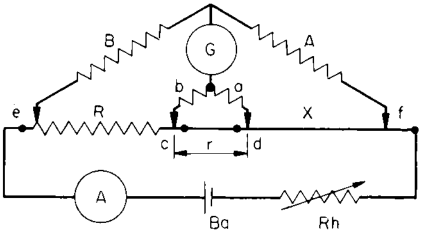


**Fig. 15.1.48** Kelvin double bridge.

**Potentiometer** The principle of the potentiometer is shown in Fig. 15.1.49. *ab* is a slide wire, and *bc* consists of a number of equal individual resistors between contacts. A battery *Ba* the emf of which is approximately 2 V supplies current to this wire through the adjustable rheostat *R*. A slider *m* makes contact with *ab*, and a contactor *m′* connects with the contacts in *bc*. A galvanometer *G* is in series with the wire connecting to *m*. By means of the double-throw double-pole switch *Sw*, either the standard cell or the unknown emf (*EMF*) may be connected to *mm′* through the galvanometer *G*. The potentiometer is standardized by throwing *Sw* to the standard-cell side, setting *mm′* so that their positions on *ab* and *bc* correspond to the emf of the standard cell. The rheostat *R* is then adjusted until *G* reads zero. (In commercial potentiometers a dial which may be set directly to the emf of the standard cell is usually provided.) The unknown emf is measured by throwing *Sw* to *EMF* and adjusting *m* and *m′* until *G* reads zero. The advantage of this method of measuring emf is that when the potentiometer is in balance no current is taken from either the standard cell or the source of emf. Potentiometers seldom exceed 1.6 V in range. To measure voltage in excess of this, a **volt box** which acts as a multiplier is used. To measure current, the voltage drop across a standard resistor of suitable value is measured with the potentiometer. For example, with 50 A a 0.01-Ω standard resistance gives a voltage drop of 0.5 V which is well within the range of the potentiometer.

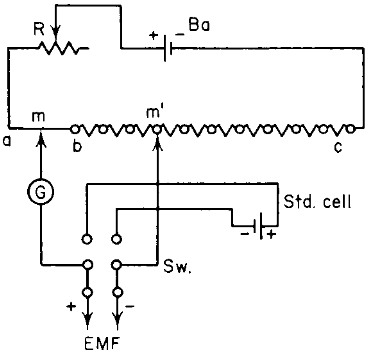


**Fig. 15.1.49** Potentiometer principle.

**Potentiometers of low range** are used extensively with thermocouple pyrometers. Figure 15.1.49 merely illustrates the principle of the potentiometer. There are many modifications, conveniences, etc., not shown in Fig. 15.1.49.

## DC GENERATORS

All electrical machines are comprised of a magnetic circuit of iron (or steel) and an electric circuit of copper. In a generator the armature conductors are rotated so that they cut the magnetic flux coming from and entering the field poles. In the dc generator (except the unipolar type) the emf induced in the individual conductors is alternating, but this is rectified by the commutator and brushes, so that the current to the external circuit is unidirectional.

The induced emf in a generator (or motor)

$$E = \phi ZNP/60P'10^8 \qquad \text{V} \tag{15.1.86}$$

where $\phi$ = flux in webers entering the armature from one north pole; $Z$ = total number of conductors on the armature; $N$ = speed, r/min; $P$ = number of poles; and $P'$ = number of parallel paths through the armature.

Since with a given generator, $Z$, $P$, $P'$ are fixed, the induced emf

$$E = K\phi N \qquad \text{V} \tag{15.1.87}$$

where $K$ is a constant. When the armature delivers current, the terminal volts are

$$V = E - I_a R_a \tag{15.1.88}$$

where $I_a$ is the armature current and $R_a$ the armature resistance including the brush and contact resistance, which vary somewhat.

There are three standard types of dc generators: the **shunt generator,** the **series generator,** and the **compound generator**.

**Shunt Generator** The field of the shunt generator in series with its rheostat is connected directly across the armature as shown in Fig. 15.1.50. This machine maintains approximately constant terminal voltage over its working range of load. An external characteristic of the generator is shown in Fig. 15.1.51. As load is applied the terminal voltage drops owing to the armature-resistance drop [Eq. (15.1.88)] and armature reaction which decreases the flux. The drop in terminal voltage reduces the field current which in turn reduces the flux, hence the induced emf, etc. At some point $B$, usually well above rated current, the foregoing reactions become cumulative and the generator starts to break down. The current reaches a maximum value and then decreases to nearly zero at short circuit. With large machines, point $B$ is well above rated current, the operating range being between $O$ and $A$. The voltage may be maintained constant by means of the field rheostat. Automatic regulators which operate through field resistance are frequently used to maintain constant voltage.

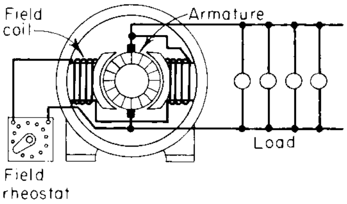


**Fig. 15.1.50** Shunt generator.

Shunt generators are used in systems which are all tied together where their stability when in parallel is an advantage. If a generator fails to build up, (1) the load may be connected; (2) the field resistance may be too high; (3) the field circuit may be open; (4) the residual magnetism may be insufficient; (5) the field connection may be reversed.

**Series Generator** In the series generator (Fig. 15.1.52) the entire load current flows through the field winding, which consists of relatively few turns of wire of sufficient size to carry the entire load current without undue heating. The field excitation, and hence the terminal voltage, depends on the magnitude of the load current. The generator supplies an essentially constant current and for years was used to supply series arc lamps for street lighting requiring direct current. Except for some special applications, the series generator is now obsolete.

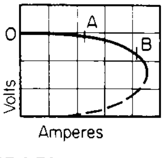


**Fig. 15.1.51** Shunt generator characteristic.

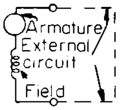


**Fig. 15.1.52** Series generator.

**Compound-Wound Generators** By the addition of a series winding to a shunt generator the terminal voltage may be automatically maintained very nearly constant, or, by properly proportioning the series turns, the terminal voltage may be made to increase with load to compensate for loss of voltage in the line, so that approximately constant voltage is maintained at the load. If the shunt field is connected outside the series field (Fig. 15.1.53), the machine is **long shunt;** if the shunt field is connected inside the series field, i.e., directly to the armature terminals, it is **short shunt**. So far as the operating characteristic is concerned, it makes little difference which way a machine is connected. Table 15.1.10 gives performance characteristics.

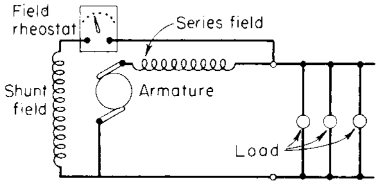


**Fig. 15.1.53** Compound-wound dc generator.

Compound-wound generators are chiefly used for small isolated plants and for generators supplying a purely motor load subject to rapid fluctuations such as in railway work. When first putting a compound generator in service, the shunt field must be so connected that the machine builds up. The series field is then connected so that it aids the shunt field. Figure 15.1.54 gives the characteristics of an overcompounded 200-kW 600-V compound-wound generator.

**Amplidynes** The amplidyne is a dc generator in which a small amount of power supplied to a control field controls the generator output, the response being nearly proportional to the control field input. The amplidyne is a dc amplifier which can supply large amounts of power. The amplifier operates on the principle of armature reaction. In Fig. 15.1.55, NN and SS are the conventional north and south poles of a dc generator with central cavities. BB are the usual brushes placed at right angles to the pole axes of NN and SS. A control winding CC of

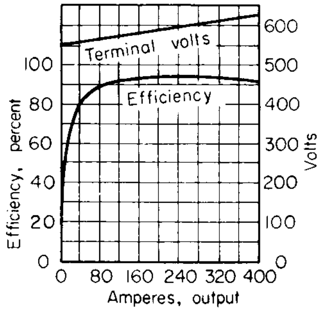


**Fig. 15.1.54** Characteristics of a 200-kW compound-wound dc generator.

**Table 15.1.10 Approximate Test Performance of Compound-Wound DC Generators with Commutating Poles**

| kW | Speed, r/min | Volts | Amperes | Efficiencies, percent ¼ load | ½ load | Full load |
|---|---|---|---|---|---|---|
| 5 | 1,750 | 125 | 40 | 77.0 | 80.5 | 82.0 |
| 10 | 1,750 | 125 | 80 | 80.0 | 83.0 | 85.0 |
| 25 | 1,750 | 125 | 200 | 84.0 | 86.5 | 88.0 |
| 50 | 1,750 | 125 | 400 | 83.0 | 86.0 | 88.0 |
| 100 | 1,750 | 125 | 800 | 87.0 | 88.5 | 90.0 |
| 200 | 1,750 | 125 | 1,600 | 88.0 | 90.5 | 91.0 |
| 400 | 1,750 | 250 | 1,600 | 91.7 | 91.9 | 91.7 |
| 1,000 | 1,750 | 250 | 4,000 | 92.1 | 92.6 | 92.1 |

SOURCE: Westinghouse Electric Corp.

small rating, as low as 100 W, is wound on the field poles. In Fig. 15.1.55, for simplicity, the control winding is shown as being wound on one pole only. The brushes BB are short-circuited, so that a small excitation mmf in the control field produces a large short-circuit current along the brush axis BB. This large short-circuit current produces a large armature-reaction flux AA along brush axis BB. The armature rotating in this field produces a large voltage along the brush axis B′B′. The load or working current is taken from brushes B′B′ as shown. In Fig. 15.1.55 the working current only is shown by the crosses and dots in the circles. The short-circuit current would be shown by crosses in the conductors to the left of brushes BB and by dots in the conductors to the right of brushes BB.

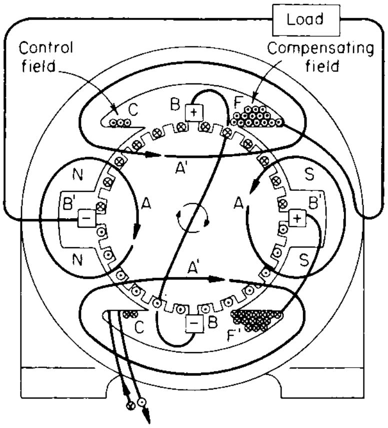


**Fig. 15.1.55** Amplidyne.

A small current in the control winding produces a high output voltage and current as a result of the large short-circuit current in brushes BB.

In order that the brushes B′B′ shall not be short-circuiting conductors which are cutting the flux of poles NN and SS, cavities are cut in these poles. Also the load current from brushes B′B′ produces an armature reaction mmf in opposition to flux A′A′ produced by the control field CC. Were this mmf not compensated, the flux A′A′ and the output of the machine would no longer be determined entirely by the control field. Hence there is a compensating field FF′ in series with the armature, which neutralizes the armature-reaction mmf which the load current produces. For simplicity the compensating field is shown on one field pole only.

The amplidyne is capable of controlling and regulating speed, voltage, current, and power with accurate and rapid response. The amplification is from 10,000 to 250,000 times in machines rated from 1 to 50 kW. Amplidynes are frequently used in connection with **selsyns** and are employed for gun and turret control and for accurate controls in many industrial power applications.

**Parallel Operation of Shunt Generators** It is desirable to operate generators in parallel so that the station capacity can be adapted to the load. Shunt generators, because of their drooping characteristics (Fig. 15.1.51), are inherently stable when in parallel. To connect shunt generators in parallel it is necessary that the switches be so connected that like poles are connected to the same bus bars when the switches are closed. Assume one generator to be in operation; to connect another generator in parallel with it, the incoming generator is first brought up to speed and its terminal voltage adjusted to a value slightly greater than the bus-bar voltage. This generator may then be connected in parallel with the other without difficulty. The proper division of load between them is adjusted by means of the field rheostats and is maintained automatically if the machines have similar voltage-regulation characteristics.

**Parallel Operation of Compound Generators** As a rule, compound generators have either flat or rising voltage characteristics. Therefore, when connected in parallel, they are inherently unstable. Stability may, however, be obtained by using an equalizer connection, Fig. 15.1.56, which connects the terminals of the generator at the junctions of the series fields. This connection is of low resistance so that any increase of current divides proportionately between the series fields of the two machines. The equalizer switch (E.S.) should be closed first and opened last, if possible. In practice, the equalizer switch is often one blade of a three-pole switch, the other two being the bus switch S, as in Fig. 15.1.56. When compound generators are used on a three-wire system, two series fields—one at each armature terminal—and two equalizers are necessary. It is possible to operate any number of compound generators in parallel provided their characteristics are not too different and the equalizer connection is used.

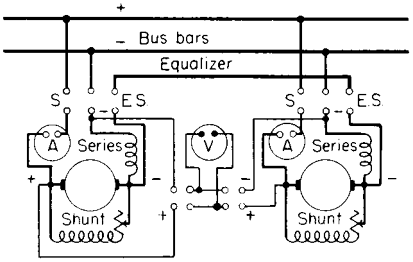


**Fig. 15.1.56** Connections for compound-wound generators operating in parallel.

## DC MOTORS

Motors operate on the principle that a conductor carrying current in a magnetic field tends to move at right angles to that field (see Fig. 15.1.11). The ordinary dc generator will operate entirely satisfactorily as a motor and will have the same rating. The conductors of the motor rotate in a magnetic field and therefore must generate an emf just as does the generator. The induced emf

$$E = K\phi N \qquad (15.1.89)$$

where $K$ = constant, $\phi$ flux entering the armature from one north pole, and $N$ = r/min [see Eq. (15.1.87)]. This emf is in opposition to the terminal voltage and tends to oppose current entering the armature. Its value is

$$E = V - I_a R_a \qquad (15.1.90)$$

where $V$ = terminal voltage, $I_a$ = armature current, and $R_a$ = armature resistance [compare with Eq. (15.1.88)]. From Eq. (15.1.89) it is seen that the speed

$$N = K_s E/\phi \qquad (15.1.91)$$

when $K_s = 1/K$. This is the fundamental speed equation for a motor. By substituting in Eq. (15.1.90)

$$N = K_s(V - I_a R_a)/\phi \qquad (15.1.92)$$

which is the general equation for the speed of a motor.

The internal or electromagnetic torque developed by an armature is proportional to the flux and to the armature current; i.e.,

$$T_t = K_t \phi I_a \qquad (15.1.93)$$

when $K_t$ is a constant. The torque at the pulley is slightly less than the internal torque by the torque necessary to overcome the rotational losses, such as friction, windage, eddy-current and hysteresis losses in the armature iron and in the pole faces.

The total mechanical power developed internally

$$P_m = EI_a \quad \text{W} \quad (= EI_a/746 \quad \text{hp}) \qquad (15.1.94)$$

The internal torque thus becomes

$$T = EI_a 33{,}000/(2\pi \times 746N) = 7.04EI_a/N \qquad (15.1.95)$$

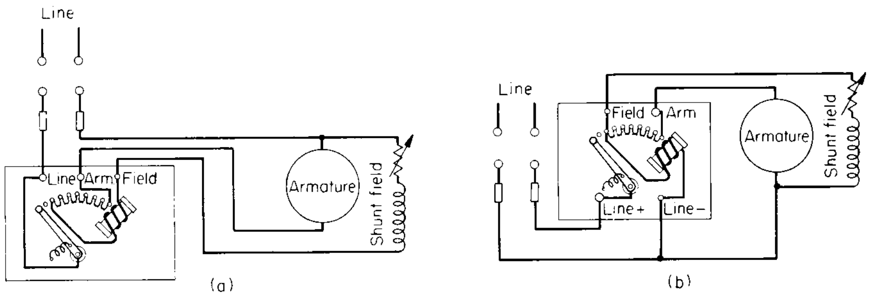


**Fig. 15.1.57** Connections for shunt dc motors and starters. (*a*) Three-point box; (*b*) four-point box.

Let $VI$ be the motor input. The output is $VI\eta$ where $\eta$ is the efficiency. The horsepower is

$$P_H = VI\eta/746 \qquad (15.1.96)$$

and the torque is

$$T = 33{,}000P_H/2\pi N = 5{,}260P_H/N \quad \text{lb}\cdot\text{ft} \qquad (15.1.97)$$

where $N$ is r/min.

**Shunt Motor** In the shunt motor (Fig. 15.1.57) the flux is substantially constant and $I_aR_a$ is 2 to 6 percent of $V$. Hence from Eq. (15.1.92), the speed varies only slightly with load (Fig. 15.1.58), so that the motor is adapted to work requiring constant speed. The speed regulation of constant-speed motors is defined by ANSI/IEEE Std. 100-1992 Standard Dictionary of Electrical and Electronic terms as follows:

> The speed regulation of a constant-speed direct-current motor is the change in speed when the load is reduced gradually from the rated value to zero with constant applied voltage and field rheostat setting expressed as a percent of speed at rated load.

In Fig. 15.1.61 the speed regulation under each condition is $100(ac - bc)/bc$ (Fig. 15.1.58*a*). Also from Eq. (15.1.93) it is seen that the torque is practically proportional to the armature current (see Fig. 15.1.58*b*). The motor is able to develop full-load torque and more on starting, but the ordinary starter is not designed to carry the current necessary for starting under load. If a motor is to be started under load, the starter should be provided with resistors adapted to carry the required current without overheating. A controller is also adapted for starting duty under load.

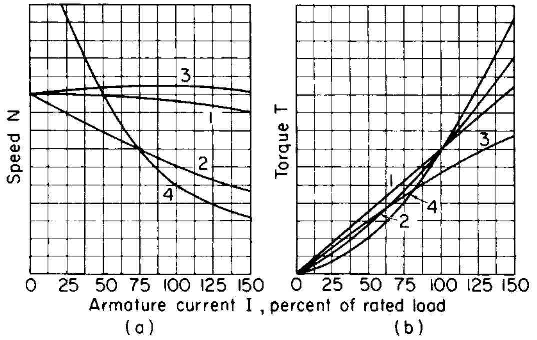


**Fig. 15.1.58** Speed and torque characteristics of dc motors. (1) Shunt motor (2) cumulative compound motor; (3) differential compound motor; (4) series motor.

**Commutating poles** have so improved commutation in dc machines that it is possible to use a much shorter air gap than formerly. Since, with the shorter air gap, fewer field ampere-turns are required, the armature becomes magnetically strong with respect to the field. Hence, a sudden overload might weaken the field through armature reaction, thus causing an increase in speed; the effect may become cumulative and the motor run away. To prevent this, modern shunt motors are usually provided with a **stabilizing winding,** consisting of a few turns of the field in series with the armature and aiding the shunt field. The resulting increase of field ampere-turns with load will more than compensate for any weakening of the field through armature reaction. The series turns are so few that they have no appreciable compounding effect. The shunt motor is used to drive constant-speed line shafting, for machine tools, etc. Since its speed may be efficiently varied, it is very useful when **adjustable speeds** are necessary, such as individual drive for machine tools.

**Shunt-Motor Starters** At standstill the counter emf of the motor is zero and the armature resistance is very low. Hence, except in motors of very small size, series resistance in the armature circuit is necessary on starting. The field must, however, be connected across the line so that it may obtain full excitation.

Figure 15.1.57 shows the two common types of starting boxes used for starting shunt motors. The armature resistance remains in circuit only during starting. In the **three-point box** (Fig. 15.1.57*a*) the starting lever is held, against the force of a spring, in the running position, by an electromagnet in series with the field circuit, so that, if the field circuit is interrupted or the line voltage becomes too low, the lever is released and the armature circuit is opened automatically. In the **four-point starting box** the electromagnet is connected directly across the line, as shown in Fig. 15.1.57*b*. In this type the arm is released instantly upon failure of the line voltage. In the three-point type some time elapses before the field current drops enough to effect the release. Some starting rheostats are provided with an overload device so that the circuit is automatically interrupted if too large a current is taken by the armature. The four-point box is used where a wide speed range is obtained by means of the field rheostat. The electromagnet is not then affected by changes in field current.

In large motors and in many small motors, automatic starters are widely used. The advantages of the automatic starter are that the current is held between certain maximum and minimum values so that the circuit does not become opened by too rapid starting as may occur with manual operation; the acceleration is smooth and nearly uniform. Since workers can stop and start a motor merely by the pushing of a button, there results considerable saving by the shutting down of the motor when it is not needed. Automatic controls are essential to elevator motors so that smooth rapid acceleration with frequent starting and stopping may be obtained. Also automatic starting is very necessary with multiple-unit operation of electric-railway cars and with rolling-mill motors which are continually subjected to rapid acceleration, stopping, and reversing.

**Series Motor** In the series motor the armature and field are in series. Hence, if saturation is neglected, the flux is proportional to the current and the torque [Eq. (15.1.93)] varies as the current squared. Therefore any increase in current will produce a much greater proportionate increase in torque (see Fig. 15.1.58*b*). This makes the motor particularly well adapted to traction work, cranes, hoists, fork-lift trucks, and other types of work which require large starting torques. A study of Eq. (15.1.92) shows that with increase in current the numerator changes only slightly, whereas the change in the denominator is nearly proportional to the change in current. Hence the speed of the series motor is practically inversely proportional to the current. With overloads the speed drops to very low values (see Fig. 15.1.58*a*). With decrease in load the speed approaches infinity, theoretically. Hence the series motor should always be connected to its load by a direct drive, such as gears, so that it cannot reach unsafe speeds (see Speed Control of Motors). A series-motor starting box with no-voltage release is shown in Fig. 15.1.59.

**Differential Compound Motors** The cumulative compound winding of a generator becomes a differential compound winding when the machine is used as a motor. Its speed may be made more nearly constant than that of a shunt motor, or, if desired, it may be adjusted to increase with increasing load.

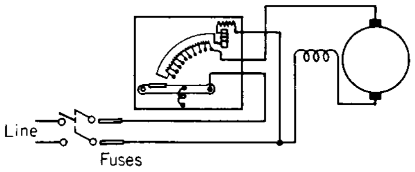


**Fig. 15.1.59** Series motor starter, no-voltage release.

The speed as a function of armature current is shown in Fig. 15.1.58*a* and the torque as a function of armature current is shown in Fig. 15.1.58*b*.

Since the speed of the shunt motor is sufficiently constant for most purposes and the differential motor tends toward instability, particularly in starting and on overloads, the differential motor is little used.

**Cumulative compound motors** develop a more rapid increase in torque with load than shunt motors (Fig. 15.1.58*b*); on the other hand, they have much poorer speed regulation (Fig. 15.1.58*a*). Hence they are used where larger starting torque than that developed by the shunt motor is necessary, as in some industrial drives. They are particularly useful where large and intermittent increases of torque occur as in drives for shears, punches, rolling mills, etc. In addition to the sudden increase in torque which the motor develops with sudden applications of load, the fact that it slows down rapidly and hence causes the rotating parts to give up some of their kinetic energy is another important advantage in that it reduces the peaks on the power plant. Performance data for compound motors are given in Table 15.1.11.

**Commutation** The brushes on the commutator of either a motor or generator should be set in such a position that the induced emf in the armature coils undergoing commutation and hence short-circuited by the brushes, is zero. In practice, this condition can at best be only approximately realized. Frequently conditions are such that it is far from being realized. At no load, the brushes should be set in a position corresponding to the geometrical neutral of the machine, for under these conditions the induced emf in the coils short-circuited by the brushes is zero. As load is applied, two factors cause sparking under the brushes. The mmf of the armature, or **armature reaction,** distorts the flux; when the current in the coils undergoing commutation reverses, an emf of self-induction $-L\ di/dt$ tends to prolong the current flow which produces sparking. In a generator, armature reaction distorts the flux in the direction of rotation and the brushes should be advanced. In order to neutralize the emf of self-induction the brushes should be set a little ahead of the neutral plane so that the emf induced in the short-circuited coils by the cutting of the flux at the fringe of the next pole is opposite to this emf of self-induction. In a motor the brushes are correspondingly moved backward in the direction opposite rotation.

Theoretically, the brushes should be shifted with every change in load. However, practically all dc generators and motors now have **commutating poles** (or **interpoles**) and with these the brushes can remain in the no-load neutral plane, and good commutation can be obtained over the entire range of load. Commutating poles are small poles between the main poles (Fig. 15.1.60) and are excited by a winding in series with the armature. Their function is to neutralize the flux distortion in the **neutral plane** caused by armature reaction and also to supply a flux that will cause an emf to be induced in the conductors undergoing commutation, opposite and equal to the emf of self-induction. Since armature reaction and the emf of self-induction are both proportional to the armature current, saturation being neglected, they are neutralized theoretically at every load. Commutating poles have made possible dc generators and motors of very much higher voltage, greater speeds, and larger kW ratings than would otherwise be possible.

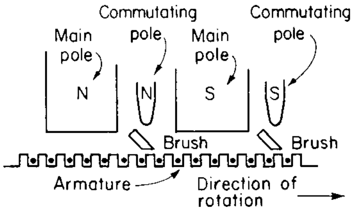


**Fig. 15.1.60** Commutating poles in motor.

Occasionally, the commutating poles may be connected incorrectly. In a motor, passing from an N main pole in the direction of rotation of the armature, an N commutating pole should be encountered as shown in Fig. 15.1.60. In a generator under these conditions an S commutating pole should be encountered. The test can easily be made with a compass. If poor commutation is caused by too strong interpoles, the winding may be shunted. If the poles are too weak and the shunting cannot be reduced, they may be strengthened by inserting sheet-iron shims between the pole and the yoke thus reducing the air gap.

Although the emfs induced in the coils undergoing commutation are relatively small, the resistance of the coils themselves is low so that unless further resistance is introduced, the short-circuit currents would be large. Hence, with the exception of certain low-voltage generators, carbon brushes that have relatively large contact resistance are almost always used. Moreover, the graphite in the brushes has a lubricating action, and the usual carbon brush does not score the commutator.

**Table 15.1.11 Test Performance of Compound-Wound DC Motors**

| | | 115 V | | 230 V | | 550 V | |
|---|---|---|---|---|---|---|---|
| Power, hp | Speed, r/min | Current, A | Full-load efficiency, % | Current, A | Full-load efficiency, % | Current, A | Full-load efficiency, % |
| 1 | 1,750 | 8.4 | 78 | 4.3 | 79 | 1.86 | 73.0 |
| 2 | 1,750 | 16.0 | 80 | 8.0 | 81 | 3.21 | 82.0 |
| 5 | 1,750 | 40.0 | 82 | 20.0 | 83 | 8.40 | 81.0 |
| 10 | 1,750 | 75.0 | 85.6 | 37.5 | 85 | 15.4 | 86.5 |
| 25 | 1,750 | 182.0 | 87.3 | 91.7 | 87.5 | 38.1 | 88.5 |
| 50 | 850 | — | — | 180.0 | 89 | 73.1 | 90.0 |
| 100 | 850 | — | — | 350.0 | 90.5 | 149.0 | 91.0 |
| 200 | 1,750 | — | — | 700.0 | 91 | 295.0 | 92.0 |

SOURCE: Westinghouse Electric Corp.

### Speed Control of Motors

**Shunt Motors** In Eq. (15.1.91) the speed of a shunt motor $N = K_s E/\phi$, where $K_s$ is a constant involving the design of the motor such as conductors on armature surface and number of poles. Obviously, in order to change the speed of a motor, without changing its construction, two factors may be varied, the counter emf $E$ and the flux $\phi$.

**Armature-Resistance Control** The counter emf $E = V - I_a R_a$, where $V$ is the terminal voltage, assumed constant. $R_a$ must be small so that the armature heating can be maintained within permissible limits. Under these conditions the speed change with load is small. By inserting an external resistor, however, into the armature circuit the counter emf $E$ may be made to decrease rapidly with increase in load; that is, $E = V - I_a(R_a + R)$ [see Eq. (15.1.90)] where $R$ is the resistance of the external resistor. The resistor $R$ must be inserted in the **armature** circuit only. The advantages of this method are its simplicity, the full torque of the motor is developed at any speed, and the method introduces no commutating difficulties. Its disadvantages are the increased speed regulation with change of load (Fig. 15.1.61), the low efficiency, particularly at the lower speeds, and the fact that provision must be made to dissipate the comparatively large power losses in the series resistor. Figure 15.1.61 shows typical speed-load curves without and with series resistors in the armature circuit. The armature efficiency is nearly equal to the ratio of the operating speed to the no-load speed. Hence at 25 percent speed the armature efficiency is practically 25 percent. Frequently the controlling and starting resistors are one, and the device is called a **controller**. Starting rheostats themselves are not designed to carry the armature current continuously and must not be used as controllers. The armature-resistance method of speed control is frequently used to regulate the speed of ventilating fans where the power demand diminishes rapidly with decrease in speed.

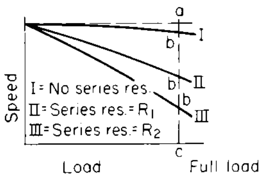


**Fig. 15.1.61** Speed-load characteristics with armature resistance control.

**Control by Changing Impressed Voltage** From Eq. (15.1.92) it is evident that the speed of a motor may be changed if $V$ is changed by connecting the armature across different voltages. Speed control by this method is accomplished by having mains (usually four), which are maintained at different voltages, available at the motor.

The shunt field of the motor is generally permanently connected to one pair of mains, and the armature circuit is provided with a controller by means of which the operator can readily connect the armature to any pair of mains. Such a system gives a series of distinct and widely separated speeds and generally necessitates the use of field-resistance control, in combination, to obtain intermediate speeds. This method, known as the **multivoltage method,** has the disadvantage that the system is expensive, for it requires several generating machines, a somewhat complicated switchboard, and a number of service wires. The system is used somewhat in machine shops and is extensively used for dc elevator starting and speed control.

In the **Ward Leonard system,** the variable voltage is obtained from a separately excited generator whose armature terminals are connected directed to the armature terminals of the working motor. The generator is driven at essentially constant speed by a dc shunt motor if the power supply is direct current, or by an induction motor or a synchronous motor if the power supply is alternating current. The field circuit of the generator and that of the motor are connected across a constant-voltage dc supply. The terminal voltage of the generator, and hence the voltage applied to the armature of the motor, is varied by changing the generator-field current with a field rheostat. The rheostat has a wide range of resistance so that the speed of the motor may be varied smoothly from 0 to 100 percent. Since three machines are involved the system is costly, somewhat complicated, and has low power efficiency. However, because the system is flexible and the speed can be smoothly varied over wide ranges, it has been used in many applications, such as elevators, mine hoists, large printing presses, paper machines, and electric locomotives.

The **Ward-Leonard system** has been largely replaced by a **static converter system** where a silicon-controlled-rectifier bridge is used to convert three-phase alternating current, or single-phase on smaller drives, to dc voltage that can be smoothly varied by **phase-angle firing** of the rectifiers from full voltage to zero. This system is smaller, lighter, and less expensive than the motor-generator system. Care must be taken to assure that the dc motor will accept the **harmonics** present in the dc output without overheating.

**Control by Changing Field Flux** Equation (15.1.91) shows that the speed of a motor is inversely proportional to the flux $\phi$. The flux can be changed either by varying the shunt-field current or by varying the reluctance of the magnetic circuit. The variation of the **shunt-field current** is the simplest and most efficient of all the methods of speed control.

With the ordinary motor, speed variation of 1.5 to 1.0 is obtainable with this method. If attempt is made to obtain greater ratios, severe sparking at the brushes results, owing to the field distortion caused by the armature mmf becoming large in comparison with the weakened field of the motor. Speed ratios of 5 : 1 and higher are, however, obtainable with motors which have commutating poles. Since the field current is a small proportion of the total current (1 to 3 percent), the rheostat losses in the field circuit are always small. This method is efficient. Also for any given speed adjustment the speed regulation is excellent, which is another advantage. Because of its simplicity, efficiency, and excellent speed regulation, the control of speed by means of the field current is by far the most common method. Output power remains constant when the field is weakened, so output torque varies inversely with motor speed.

**Speed Control of Series Motors** The series motor is fundamentally a variable-speed motor, the speed varying widely from light load to full load and more (see Fig. 15.1.58*a*). From Eq. (15.1.92) the speed for any value of $\phi$, or current, can be changed by varying the impressed voltage. Hence the speed can be controlled by inserting resistance in series with the motor. This method, which is practically the same as the armature-resistance control method for shunt motors, has the same objections of low efficiency and poor regulation with fluctuating loads. It is extensively used in controlling the speed of hoist and crane motors.

The **series-parallel** system of series-motor speed control is almost universally used in electric traction. At least two motors are necessary. The two motors are first connected in series with each other and with the starting resistor. The starting resistor is gradually cut out and, since each motor then operates at half line voltage, the speed of each is approximately half speed. Both motors take the same current, and each can develop full torque. This condition of operation is efficient since there is no external resistance in circuit. When the controller is moved to the next position, the motors are connected in parallel with each other and each in series with starting resistors. Full speed of the motors is obtained by gradually cutting out these resistors. Connecting the two motors in series on starting reduces the current to one-half the value that would be required for a given torque were both motors connected in parallel on starting. The power taken from the trolley is halved, and an intermediate running speed is efficiently obtained.

In the **multiple-unit** method of speed control which is used for electric railway trains, the starting contactors, reverser, etc., for each car are located under that car. The relays operating these control devices are actuated by energy taken from the train line consisting usually of seven wires. The train line runs the entire length of the train, the connections between the individual cars being made through the couplers. The train line is energized by the action of the motorman operating any one of the small master controllers which are located in each car. Hence corresponding relays, contactors, etc., in every car all operate simultaneously. High accelerations may be reached with this system because of the large tractive effort exerted by the wheels on every car.

## SYNCHRONOUS GENERATORS

The synchronous generator is the only type of ac generator now in general use at power stations.

**Construction** In the usual synchronous generator the armature or stator is the stationary member. This construction has many advantages. It is possible to make the slots any reasonable depth, since the tooth necks increase in cross section with increase in depth of slot; this is not true of the rotor. The large slot section which is thus obtainable gives ample space for copper and insulation. The conductors from the armature to the bus bars can be insulated throughout their entire lengths, since no rotating or sliding contacts are necessary. The insulation in a stationary member does not deteriorate as rapidly as that on a rotating member, for it is not subjected to centrifugal force or to any considerable vibration.

The **rotating member** is ordinarily the field. There are two general types of field construction: the **salient-pole type** and the **cylindrical,** or **nonsalient-pole, type**. The salient-pole type is used almost entirely for slow and moderate-speed generators since this construction is the least expensive and permits ample space for the field ampere-turns.

It is not practicable to employ salient poles in high-speed turboalternators because of the excessive windage and the difficulty of obtaining sufficient mechanical strength. The **cylindrical type** consists of a cylindrical steel forging with radial slots in which the field copper, usually in strip form, is placed. The fields are ordinarily excited at low voltage, 125 and 250 V, the current being conducted to the rotating member by means of slip rings and brushes. An ac generator armature to supply **field voltage** can be mounted on the generator shaft and supply dc to the motor field through a static rectifier bridge, also mounted on the shaft, eliminating all slip rings and brushes. The field power is ordinarily only 1.5 percent and less of the rated power of the machine (see Table 15.1.12).

**Classes of Synchronous Generators** Synchronous generators may be divided into three general classes: (1) the slow-speed engine-driven type; (2) the moderate-speed waterwheel-driven type; and (3) the high-speed turbine-driven type. In (1) a hollow box frame is used as the stator support, and the field consists of a spider to which a larger number of salient poles are attached, usually bolted. The speed seldom exceeds 75 to 90 r/min, although it may run as high as 150 r/min. Waterwheel generators also have salient poles which are usually dovetailed to a cylindrical spider consisting of steel plates riveted together. Their speeds range from 80 to 900 r/min and sometimes higher, although the 9,000-kVA Keokuk synchronous generators rotate at only 58 r/min, operating at a very low head. The speed rating of direct-connected waterwheel generators decreases with decrease in head. It is desirable to operate synchronous generators at the highest permissible speed since the weight and costs diminish with increase in speed. Waterwheel-driven generators must be able to run at double speed, as a precaution against accident, should the governor fail to shut the gate sufficiently rapidly in case the circuit breakers open or should the governing mechanism become inoperative.

Turbine-driven generators operate at speeds of 720 to 3,600 r/min. Direct-connected exciters, belt-driven exciters from the generator shaft, and separately driven exciters are used. In large stations separately driven (usually motor) exciters may supply the excitation energy to excitation bus bars. Steam-driven exciters and storage batteries are frequently held in reserve. With slow-speed synchronous generators, the belt-driven exciter is frequently used because it can be driven at higher speed, thus reducing the cost.

**Table 15.1.12 Performance Data for Synchronous Generators**

80% pf, 3 phase, 60 Hz, 240 to 2,400 V, horizontal-coupled or belted-type engine

| kVA | Poles | Speed, r/min | Excitation, kW | Efficiencies, % ½ load | ¾ load | Full load | Approx. net weight, lb |
|---|---|---|---|---|---|---|---|
| 25 | 4 | 1,800 | 0.8 | 81.5 | 85.7 | 87.6 | 900 |
| 93.8 | 8 | 900 | 2 | 87 | 89.5 | 90.9 | 2,700 |
| 250 | 12 | 600 | 5 | 90 | 91.3 | 92.2 | 6,000 |
| 500 | 18 | 400 | 8 | 91.7 | 92.6 | 93.2 | 10,000 |
| 1,000 | 24 | 300 | 14.5 | 92.6 | 93.4 | 93.9 | 16,100 |
| 3,125 | 48 | 150 | 40 | 93.4 | 94.2 | 94.6 | 52,000 |

Industrial-size turbine generators, direct-connected type, 80% pf, 3 phase, 60 Hz, air-cooled

| kVA | Poles | Speed, r/min | Excitation kW | Excitation V | Efficiency, % ½ load | ¾ load | Full load | Volume of air, $ft^3$/min | Voltage | Approx. weight, including exciter, lb |
|---|---|---|---|---|---|---|---|---|---|---|
| 1,875 | 2 | 3,600 | 18 | 125 | 95.3 | 96.1 | 96.3 | 3,500 | 480–6,900 | 21,900 |
| 2,500 | 2 | 3,600 | 22 | 125 | 95.3 | 96.1 | 96.3 | 5,000 | 2,400–6,900 | 22,600 |
| 3,125 | 2 | 3,600 | 24 | 125 | 95.3 | 96.3 | 96.5 | 5,500 | 2,400–6,900 | 25,100 |
| 3,750 | 2 | 3,600 | 24 | 125–250 | 95.3 | 96.3 | 96.6 | 6,500 | 2,400–6,900 | 27,900 |
| 5,000 | 2 | 3,600 | 29 | 125–250 | 95.3 | 96.3 | 96.6 | 11,000 | 2,400–6,900 | 40,100 |
| 6,250 | 2 | 3,600 | 38 | 125–250 | 95.3 | 96.3 | 96.7 | 12,000 | 2,400–13,800 | 43,300 |
| 7,500 | 2 | 3,600 | 42 | 125–250 | 95.5 | 96.5 | 96.9 | 15,000 | 2,400–13,800 | 45,000 |
| 9,375 | 2 | 3,600 | 47 | 125–250 | 95.5 | 96.5 | 96.9 | 16,500 | 2,400–13,800 | 61,200 |

Central-station-size turbine generators, direct-connected type, 85% pf, 3 phase, 60 Hz, 11,500 to 14,400 V

| kVA | Poles | Speed, r/min | Excitation kW | Excitation V | Efficiency, % ½ load | ¾ load | Full load | Volume of air, $ft^3$/min | Ventilation | Approx. weight, including exciter, lb |
|---|---|---|---|---|---|---|---|---|---|---|
| 13,529 | 2 | 3,600 | 70 | 250 | 96.3 | 97.1 | 97.3 | 22,000 | Air-cooled | 116,700 |
| 17,647 | 2 | 3,600 | 100 | 250 | 97.7 | 97.9 | 97.9 | 22,000 | $H_2$-cooled | 115,700 |
| 23,529 | 2 | 3,600 | 115 | 250 | 98.0 | 98.2 | 98.2 | 25,000 | $H_2$-cooled | 143,600 |
| 35,294 | 2 | 3,600 | 145 | 250 | 98.1 | 98.3 | 98.3 | 34,000 | $H_2$-cooled | 194,800 |
| 47,058 | 2 | 3,600 | 155 | 250 | 98.3 | 98.5 | 98.5 | 42,000 | $H_2$-cooled | 237,200 |
| 70,588 | 2 | 3,600 | 200 | 250 | 98.4 | 98.7 | 98.7 | 50,000 | $H_2$-cooled | 302,500 |

SOURCE: Westinghouse Electric Corp.

**Synchronous-Generator Design** At the present time single-phase generators are seldom built. For single-phase service two phases of a standard three-phase Y-connected generator are used. A single-phase load or unbalanced three-phase load produces flux pulsations in the magnetic circuits of synchronous generators, which increase the iron losses and introduce harmonics into the emf wave. Two-phase windings consist of two similar single-phase windings displaced 90 electrical space degrees on the armature and ordinarily occupying all the slots on the armature. The most common type of winding is the three-phase lap-wound two-layer type of winding. In three-phase windings three windings are spaced 120 electrical space degrees apart, the individual phase belts being spaced 60° apart. Usually, all the slots on the armature are occupied. Standard voltages are 550, 1,100, 2,200, 6,600, 13,200, and 20,000 V. It is much more difficult to insulate for 20,000 V than it is for the lower voltages. However, if the power is to be transmitted at this voltage, its use would be justified by the saving of transformers. In machines of moderate and larger ratings it is common to generate at 6,600 and 13,200 V if transformers must be used. The higher voltage is preferable, particularly for the higher ratings, because it reduces the cross section of the connecting leads and bus bars.

The **standard frequency** in the United States for lighting and power systems is 60 Hz; the few former 50-Hz systems have practically all been converted to 60 Hz. The frequency of 25 Hz is commonly used in street-railway and subway systems to supply power to the synchronous converters and other ac-dc conversion apparatus; it is also commonly used in railroad electrification, particularly for single-phase series-motor locomotives (see Sec. 11). At 25 Hz incandescent lamps have noticeable flicker. In European (and most other) countries 50 Hz is standard. The frequency of a synchronous machine

$$f = P \times \text{r/min}/120 \qquad \text{Hz} \tag{15.1.98}$$

where $P$ is the number of poles. Synchronous generators are rated in kVA rather than in kW, since heating, which determines the rating, is dependent only on the current and is independent of power factor. If the kilowatt rating is specified, the power factor should also be specified.

**Induced EMF** The induced emf per phase in synchronous generator is

$$E = 2.22 k_b k_p \Phi f Z \qquad \text{V/phase} \tag{15.1.99}$$

where $k_b$ = breadth factor or belt factor (usually 0.9 to 1.0), which depends on the number of slots per pole per phase, 0.958 for three-phase, four slots per pole per phase; $k_p$ = pitch factor = 1.0 for full pitch, 0.966 for ⅚ pitch; $\Phi$ = total flux Wb, entering armature from one north pole and is assumed to be sinusoidally distributed along the air gap; $f$ = frequency; and $Z$ = number of series conductors per phase.

Synchronous generators usually are Y-connected. The advantages are that for a given line voltage the voltage per phase is $1/\sqrt{3}$ that of the delta-connected winding; third-harmonic currents and their multiples cannot circulate in the winding as with a delta-connected winding; third-harmonic emfs and their multiples cannot exist in the line emfs; a neutral point is available for grounding.

**Regulation** The terminal voltage of synchronous generator at constant frequency and field excitation depends not only on the current load but on the power factor as well. This is illustrated in Fig. 15.1.62, which shows the voltage-current characteristics of a synchronous generator with lagging current, leading current and in-phase current (pf = 1.00). With leading current the voltage may actually rise with increase in load; the rate of voltage decrease with load becomes greater as the lag of the current increases. The regulation of a synchronous generator is defined by the ANSI/IEEE Std. 100-1992 Standard Dictionary of Electrical and Electronic Terms as follows:

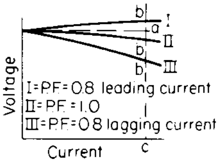


**Fig. 15.1.62** Synchronous generator characteristics.

> The voltage regulation of a synchronous generator is the rise in voltage with constant field current, when, with the synchronous generator operated at rated voltage and rated speed, the specified load at the specified power factor is reduced to zero, expressed as a percent of rated voltage.

For example, in Fig. 15.1.62 the regulation under each condition is

$$100(ac - bc)/bc \tag{15.1.100}$$

With leading current the regulation may be negative.

Three factors affect the regulation of synchronous generators; the **effective armature resistance,** the **armature leakage reactance,** and the **armature reaction**. With alternating current the armature loss is greater than the value obtained by multiplying the square of the armature current by the ohmic resistance. This is due to hysteresis and eddy-current losses in the iron adjacent to the conductor and to the alternating flux-producing losses in the conductors themselves. Also the current is not distributed uniformly over conductors in the slot, but the current density tends to be greatest in the top of the slot. These factors all have the effect of increasing the resistance. The ratio of effective to ohmic resistance varies from 1.2 to 1.5. The **armature leakage reactance** is due to the flux produced by the armature current linking the conductors in the slots and also the end connections.

The armature mmf reacts on the field to change the value of the flux. With a single-phase generator and with an unbalanced load on a polyphase generator, the armature mmf is pulsating and causes iron losses in the field structure. With polyphase machines under a constant balanced load, the armature mmf is practically constant in magnitude and fixed in its relation to the field poles. Its direction with relation to the field-pole axis is determined by the power factor of the load.

A component of current in phase with the no-load induced emf, or the excitation emf, merely distorts the field by strengthening the trailing pole tip and weakening the leading pole tip. A component of current lagging the excitation emf by 90° weakens the field without distortion. A component of current leading the excitation emf by 90° strengthens the field without distortion. Ordinarily, both cross magnetization and one of the other components are acting simultaneously.

The foregoing effects are called **armature reaction**. Frequently the effects of armature reactance and armature reaction can be combined into a single quantity.

It is difficult to determine the regulation of synchronous generator by actual loading, even when in service, owing to the difficulty of obtaining, controlling, and absorbing the large balanced loads. Hence methods of **predetermining regulation without actually loading** the machine are used.

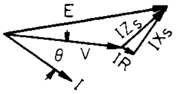


**Fig. 15.1.63** Phasor diagram for synchronous impedance method.

**Synchronous Impedance Method** Both armature reactance and armature reaction have the same effect on the terminal voltage. In the synchronous impedance method the generator is considered as having no armature reaction, but the armature reactance is increased a sufficient amount to account for the effect of armature reaction. The phasor diagram for a current $I$ lagging the terminal voltage $V$ by an angle $\theta$ is shown in Fig. 15.1.63. In a polyphase generator the phasor diagram is applicable to one phase, a balanced load almost always being assumed.

The power factor of the load is cos $\theta$; $IR$ is the effective armature resistance drop and is parallel to $I$; $IX_s$ is the synchronous reactance drop and is at right angles to $I$ and leading it by 90°. $IX_s$ includes both the reactance drop and the drop in voltage due to armature reaction. That part of $IX_s$ which replaces armature reaction is in reality a fictitious quantity. The synchronous impedance drop is given by $IZ_s$. The no-load or open-circuit (excitation) voltage

$$E = \sqrt{(V\cos\theta + IR)^2 + (V\sin\theta \pm IX_s)^2} \quad \text{V} \quad (15.1.101)$$

All quantities are per phase. The negative sign is used with leading current.

$$\text{Regulation} = 100(E - V)/V \quad (15.1.102)$$

With leading current $E$ may be less than $V$ and a negative regulation results.

The synchronous impedance is determined from an open-circuit and a short-circuit test, made with a weak field. The voltage $E'$ on open circuit is divided by the current $I'$ on short circuit for the same value of field current.

$$Z_s = E'/I' \qquad X_s = \sqrt{Z_s^2 - R^2} \quad \Omega \quad (15.1.103)$$

$R$ is so small compared with $X_s$ that for all practical purposes $X_s = Z_s$. $R$ may be determined by measuring the ohmic resistance per phase and multiplying by 1.4 to 1.5 to obtain the effective resistance. This value of $R$ and the value of $X_s$ obtained from Eq. (15.1.103) may then be substituted in Eq. (15.1.101) to obtain $E$ at the specified load and power factor.

Since the synchronous reactance is determined at low saturation of the iron and used at high saturation, the method gives regulations that are too large; hence it is called the **pessimistic method**.

**MMF Method** In the mmf method the generator is considered as having no armature reactance but the armature reaction is increased by an amount sufficient to include the effect of reactance. That part of armature reaction which replaces the effect of armature reactance is in reality a fictitious quantity. To obtain the data necessary for computing the regulation, the generator is short-circuited and the field adjusted to give rated current in the armature. The corresponding value of field current $I_a$ is read. The field is then adjusted to give voltage $E'$ equal to rated terminal voltage + $IR$ drop (= $V + IR$, as phasors, Fig. 15.1.64) on open circuit and the field current $I'$ read.

$I_a$ is 180° from the current phasor $I$, and $I'$ leads $E'$ by 90° (Fig. 15.1.64). The angle between $I'$ and $I_a$ is $90 - \theta + \phi$, but since $\phi$ is small, it can usually be neglected. The phasor sum of $I_a$ and $I'$ is $I_o$. The open-circuit voltage $E$ corresponding to $I_o$ is the no-load voltage and can be found on the saturation curve. The regulation is then found from Eq. (15.1.102). This method gives a value of regulation less than the actual value and hence is called the **optimistic method**. The actual regulation lies somewhere between the values obtained by the two methods but is more nearly equal to the value obtained by the mmf method.

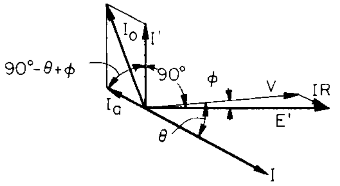


**Fig. 15.1.64** Phasor diagram for the mmf method.

**ANSI Method** The ANSI method (American Standard 50, Rotating Electrical Machinery) which has become the accepted standard for the predetermination of synchronous generator operation, eliminates in large measure the errors due to saturation which are inherent in the synchronous impedance and mmf methods. In Fig. 15.1.65*a* is shown the saturation curve $OAF$ of the generator. The axis $OP$ is not only the field-current axis but also the axis of the current phasor $I$ as well. $V$ the terminal voltage is drawn $\theta$ deg from $I$ or $OP$, where $\theta$ is the power factor angle. The effective resistance drop $IR$ and the **leakage reactance** drop $IX$ are drawn parallel and perpendicular to the current phasor. $E_a$, the phasor sum of $V$, $IR$, and $IX$, is the internal **induced** emf. Arcs are swung with $O$ as the center and $V$ and $E_a$ as radii to intercept the axis of ordinates at $B$ and $C$. $OK$, tangent to the straight portion of the saturation curve, is the **air-gap line**. If there is no saturation, $I_v$ is the field current necessary to produce $V$, and $CK$ is the field current necessary to produce $E_a$. The field current $I_s$ is the increase in field current necessary to take into account the saturation corresponding to $E_a$.

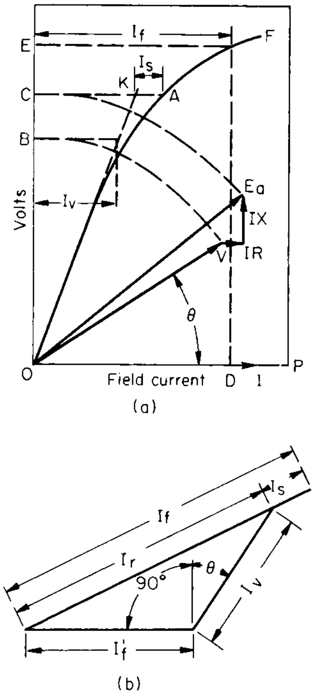


**Fig. 15.1.65** ANSI method of synchronous generator regulation.

The corresponding phasor diagram to a larger scale is shown in Fig. 15.1.65*b*. $I_f'$, the field current necessary to produce rated current at short circuit, corresponding to $I_a$ (Fig. 15.1.64), is drawn horizontally. The field current $I_v$ is drawn at an angle $\theta$ to the right of a perpendicular erected at the right-hand end of $I_f'$. $I_r$ is the resultant of $I_f'$ and $I_v$. $I_s$ is added to $I_r$ giving $I_f$ the resultant field current. The no-load emf $E$ is found on the saturation curve, Fig. 15.ž.65*a*, corresponding to $I_f = OD$.

**Excitation** is commonly supplied by a small dc generator driven from the generator shaft. On account of commutation, except in the smaller sizes, the dc generator cannot be driven at 3,600 r/min, the usual speed for turbine generators, and belt or gear drives are necessary. The use of the silicon rectifier has made possible simpler means of excitation as well as voltage regulation. In one system the exciter consists of a small rotating-armature synchronous generator (which can run at high speed) mounted directly on the main generator shaft. The three-phase armature current is rectified by six silicon rectifiers and is conducted directly to the main generator field without any sliding contacts. The main generator field current is controlled by the current to the stationary field of the exciter generator. In another system there is no rotating exciter, the generator excitation being supplied directly from the generator terminals, the 13,800 V, three-phase, being stepped down to 115 V, three-phase, by small transformers and rectified by silicon rectifiers. Voltage regulation is obtained by saturable reactors actuated by potential transformers connected across the generator terminals.

Most regulators such as the following operate through the field of the exciter. In the **Tirrill regulator** the field resistance of the exciter is short-circuited temporarily by contacts when the bus-bar voltage drops. Actually, the contacts are vibrating continuously, the time that they are closed depending on the value of the bus-bar voltage. The General Electric Co. manufactures a direct-acting regulator in which the regulating rheostat is part of the regulator itself. The rheostat consists of stacks of graphite plates, each plate being pivoted at the center. Tilting the plates changes the path of the current through the rheostat and thus changes the resistance. The plates are tilted by a sensitive torque armature which is actuated by variations of voltage from the normal value (for regulators employing silicon rectifiers).

**Parallel Operation of Synchronous Generators** The kilowatt division of load between synchronous generators in parallel is determined entirely by the speed-load characteristics of their prime movers and not by the characteristics of the generators themselves. No appreciable adjustment of kilowatt load between synchronous generators in parallel can be made by means of their field rheostats, as with dc generators. Consider Fig. 15.1.66, which gives the speed-load characteristics in terms of frequency, of two synchronous generators, no. 1 and no. 2, these characteristics being the speed-load characteristics of their prime movers. These speed-load characteristics are drooping, which is necessary for stable parallel operation. The total load on the two machines is $P_1 + P_2$ kW. Both machines must be operating at the same frequency $F_1$. Hence generator 1 must be delivering $P_1$ kW, and generator 2 must be delivering $P_2$ kW (the small generator losses being neglected). If, under the foregoing conditions, the field of either machine is strengthened, it cannot deliver a greater kilowatt load, for its prime mover can deliver more power only by dropping its speed. This is impossible, for both generators must operate always at the same frequency $f_1$. For any fixed total power load, the division of kilowatt load between synchronous generators can be changed only by modifying in some manner the speed-load characteristics of their prime movers, such, for example, as changing the tension in the governor spring. Synchronous generators in parallel are of themselves in stable equilibrium. If the driving torque of one machine is increased, the resulting electrical reactions between the machines cause a circulating current to flow between machines. This current puts more electrical load on the machine whose driving torque is increased and tends to produce motor action in the other machines. In an extreme case, the driving torque of one prime mover may be removed entirely, and its generator will operate as a synchronous motor, driving the prime mover mechanically.

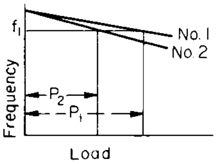


**Fig. 15.1.66** Speed-load characteristics of synchronous generators in parallel.

Variations in driving torques cause currents to circulate between synchronous generators, transferring power which tends to keep the generators in synchronism. If the power transfer takes the form of recurring pulsations, it is called **hunting,** which may be reduced by building heavy copper grids called **amortisseurs,** or **damper windings,** into the pole faces. Turbine- and waterwheel-driven synchronous generators are much better adapted to parallel operation than are synchronous generators which are driven by reciprocating engines, because of their uniformity of torque.

Increasing the field current of synchronous generators in parallel with others causes it to deliver a greater lagging component of current. Since the character of the load determines the total current delivered by the system, the lagging components of current delivered by the other generators must decrease and may even become leading components. Likewise if the field of one generator is weakened, it delivers a greater leading component of current and the other machines deliver components of current which are more lagging. These leading and lagging currents do not affect appreciably the division of **kilowatt** load between the synchronous generators. They do, however, cause unnecessary heating in their armatures. The fields of all synchronous generators should be so adjusted that the heating due to the quadrature components of currents is a minimum. With two generators having equal armature resistances, this occurs when both deliver equal quadrature currents.

Armature reactance in the armature of machines in parallel is desirable. If not too great, it stabilizes their operation by producing the synchronizing action. Synchronous generators with too little reactance are sensitive, and if connected in parallel with slight phase displacement or inequality of voltage, considerable disturbance results. Armature reactance also reduces the current on short circuit, particularly during the first few cycles when the short-circuit current is a maximum. Frequently, external power-limiting reactances are connected in series to protect the generators and equipment from injury that would result from the tremendous short-circuit currents. For these reasons, poor regulation in large synchronous generators is frequently considered to be an advantage rather than a disadvantage.

**Ground Resistors** Most power systems operate with a grounded neutral. When the station generators deliver current directly to the system (without intervening transformers), it is customary to ground the neutral (of the Y-connected windings) or one generator in a station; this is usually done through a grounding resistor of from 2 to 6 $\Omega$. If the neutral of more than one generator is grounded, third-harmonic (and multiples thereof) currents can circulate between the generators. The ground resistor reduces the short-circuit currents when faults to ground occur, and hence reduces the violence of the short circuit as well as the duty of the circuit breakers. Grounding reactors are sometimes used but have limited application owing to the danger of high voltages resulting from resonant conditions.

## INDUCTION GENERATORS

The **induction generator** is an induction motor driven above synchronous speed. The rotor conductors cut the rotating field in a direction to convert shaft mechanical power to electrical power. Load increases as speed increases, so the generator is self-regulating and can be used without governor control. On short circuits the induction generator will deliver current to the fault for only a few cycles because, unlike the synchronous generator, it is not self-exciting. Since it is not self-excited, an induction generator must always be used in parallel with an electrical system where there are some synchronous machines, or capacitor banks, to deliver lagging current (VARs) to the induction generator for excitation.

Induction generators have found favor in industrial **cogeneration** applications and as **wind-driven** generators where they provide a small part of the total load.

## CELLS

**Fuel cells** convert chemical energy of fuel and oxygen directly to electrical energy. **Solar cells** convert solar radiation to electrical energy. At present, these conversion methods are not economically competitive with historic generating techniques, but they have found applications in isolated areas, such as microwave relaying stations, satellites, and residential lighting, where power requirements are small and costs for transmitting electrical power from more conventional sources is prohibitive. As solar technology continues to improve, many other applications will be evaluated.

## TRANSFORMERS

**Transformer Theory** The transformer is a device that transfers energy from one electric circuit to another without change of frequency and usually, but not always, with a change in voltage. The energy is transferred through the medium of a magnetic field: it is supplied to the transformer through a primary winding and is delivered by means of a secondary winding. Both windings link the same magnetic circuit. With no load on the secondary, a small current, called the exciting current, flows in the primary and produces the alternating flux. This flux links both primary and secondary windings and induces the same volts per turn in each. With a sine wave the emf is

$$E = 4.44\Phi_m nf \qquad \text{V} \qquad (15.1.104)$$

where $\Phi_m$ = maximum instantaneous flux in webers, $n$ = turns on either winding, and $f$ = frequency. Equation (15.1.104) may also be written

$$E = 4.44B_m Anf \qquad \text{V} \qquad (15.1.105)$$

$B_m$ = maximum instantaneous flux density in iron and $A$ = net cross section of iron. If $B_m$ is in T, $A$ is in m$^2$; if $B_m$ is in Mx/in$^2$, $A$ is in in$^2$.

In English units, Eq. (15.1.104) becomes

$$E = 4.44\Phi_m nf\, 10^{-8} \qquad \text{V} \qquad (15.1.104a)$$

where $\Phi_M$ is in maxwells; Eq. (15.1.105) becomes

$$E = 4.44B_m Anf\, 10^{-8} \qquad \text{V} \qquad (15.1.105a)$$

where $B_m$ is in Mx/in$^2$ and $A$ is in in$^2$.

$B_m$ is practically fixed. In large transformers with silicon steel it varies between 60,000 and 75,000 Mx/in$^2$ at 60 Hz and between 75,000 and 90,000 Mx/in$^2$ at 25 Hz. It is desirable to operate the iron at as high density as possible in order to minimize the weight of iron and copper. On the other hand, with too high densities the eddy-current and hysteresis losses become too great, and with low frequency the exciting current may become excessive. It follows from Eq. (15.1.104) that

$$E_1/E_2 = n_1/n_2 \qquad (15.1.106)$$

where $E_1$ and $E_2$ are the primary and secondary emfs and $n_1$ and $n_2$ are the primary and secondary turns. Since the impedance drops in ordinary transformers are small, the terminal voltages of primary and secondary are also practically proportional to their number of turns. As the change in secondary terminal voltage in the ordinary constant-potential transformer over its range of operation is small (1.5 to 3 percent), the flux must remain substantially constant. Therefore, the added ampere-turns produced by any secondary load must be balanced by opposite and equal primary ampere-turns. Since the exciting current is small compared with the load current (1.5 to 5 percent) and the two are usually out of phase, the exciting current may ordinarily be neglected. Hence,

$$n_1I_1 = n_2I_2 \qquad (15.1.107)$$
$$I_1/I_2 = n_2/n_1 \qquad (15.1.108)$$

where $I_1$ and $I_2$ are the primary and secondary currents.

When load is applied to the secondary of a transformer, the secondary ampere-turns reduce the flux slightly. This reduces the counter emf of the primary, permitting more current to enter and thus supply the increased power demanded by the secondary.

Both primary and secondary windings must necessarily have resistance. All the flux produced by the primary does not link the secondary; the counter ampere-turns of the secondary produce some flux which does not link the primary. These **leakage fluxes** produce reactance in each winding. The combined effect of the resistance and reactance produces an impedance drop in each winding when current flows. These impedance drops produce a slight drop in the secondary terminal voltage with load.

**Transformer Testing** Transformer regulation and losses are so small that it is far more accurate to compute the regulation and efficiency than to determine them by actual measurement. The necessary measurements and computations are comparatively simple, and little power is involved in making the tests. In the **open-circuit** test, the power input to either winding is measured at its rated voltage. Usually it is more convenient to make this test on the low-voltage winding, particularly if it is rated at 110, 220, or 550 V. The open-circuit power practically all goes to supply the core losses, consisting of eddy-current and hysteresis losses. Let this value of power be $P_0$. The eddy-current loss varies as the square of the voltage and frequency; the hysteresis loss varies as the 1.6 power of the voltage, and directly as the frequency. In the **short-circuit** test one winding is short-circuited, and the current in the other is adjusted to near its rated value. The voltage $V_c$, the current $I_1$, and the power input $P_c$ are measured. When one winding of a transformer is short-circuited, the voltage across the other winding is 3 to 4 percent of rated value when rated current flows. Since a voltage range of from 110 to 250 V is best adapted to measuring instruments, that winding whose rated voltage, multiplied by 0.03 or 0.04, is closest to this voltage range should be used for making the short-circuit test, the other winding being short-circuited. Practically all the power on short circuit goes to supply the copper loss of primary and secondary. If the measurements are made on the primary,

$$R_{01} = P_c/I_1^2 \qquad (15.1.109)$$
$$Z_{01} = V_c/I_1 \qquad (15.1.110)$$
$$X_{01} = \sqrt{Z_{01}^2 - R_{01}^2} \qquad (15.1.111)$$

where $R_{01}$, $Z_{01}$, and $X_{01}$ are the equivalent resistance, impedance, and reactance referred to the primary. Also $R_{02} = R_{01}(n_2/n_1)^2$; $Z_{02} = Z_{01}(n_2/n_1)^2$; $X_{02} = X_{01}(n_2/n_1)^2$, these quantities being the equivalent resistance, impedance, and reactance referred to the secondary. If the dc resistances $R_1$ and $R_2$ of the primary and secondary are measured,

$$R_{01} = R_1 + (n_1/n_2)^2R_2 \qquad (15.1.112)$$
$$R_{02} = R_2 + (n_2/n_1)^2R_1 \qquad (15.1.113)$$

The ac or effective resistances, determined from Eq. (15.1.109), are usually 10 to 15 percent greater than these values.

**Regulation** The regulation may be computed from the foregoing data as follows:

$$V_1' = \sqrt{(V_1 \cos\theta + I_1R_{01})^2 + (V_1 \sin\theta \pm I_1X_{01})^2} \qquad (15.1.114)$$
$$\text{Regulation} = 100(V_1' - V_1)/V_1 \qquad (15.1.115)$$

$V_1$ = rated primary terminal voltage; $\cos\theta$ = load power factor; $I_1$ = rated primary current; $R_{01}$ = equivalent resistance referred to primary [from Eq. (15.1.109)]; $X_{01}$ = equivalent reactance referred to primary. The + sign is used with lagging current and the − sign with leading current. Equations (15.1.114) and (15.1.115) are equally applicable to the secondary if the subscripts are changed.

**Efficiency** The only two losses in a constant-potential transformer are the core loss in W, $P_0$, which is practically independent of load, and $P_c$ the copper loss in W, which varies as the load current squared. The efficiency for any current $I_1$ is

$$\eta = V_1I_1 \cos\theta/(V_1I_1 \cos\theta + P_0 + I_1^2R_{01}) \qquad (15.1.116)$$

Equation (15.1.116) applies equally well to the secondary if the subscripts are changed. The maximum efficiency occurs when the core and copper losses are equal.

**All-Day Efficiency** Since transformers must usually be on the line 24 h/day, part of which time the load may be very light, the all-day efficiency is important. This is equal to the total energy or watthour output divided by the total energy or watthour input for the 24 h. That is,

$$\eta = \frac{(V_1I_1 \cos\theta_1)t_1 + \cdots}{(V_1I_1 \cos\theta_1)t_1 + \cdots + (I_1^2R_{01})t_1 + \cdots + 24\,P_0} \qquad (15.1.117)$$

where $t_1$ = time in hours that load $V_1I_1 \cos\theta_1$ is being delivered, etc.

**Polyphase Transformer Connections** Three-phase transformer banks may be connected Δ-Δ, Δ-Y, Y-Y, and Y-Δ. The Δ-Δ connection is very common, particularly at the lower voltages, and has the important advantage that the bank will operate V-connected if one transformer is disabled. The Δ-Y connection is advantageous for stepping up to high voltages since the secondary of the transformers need be wound only for 58 percent $(1/\sqrt{3})$ of the line voltage; it is also necessary when a four-wire three-phase system is obtained from a three-wire three-phase system since ‘‘a floating neutral’’ on the secondary cannot occur. This connection has found increased application in step-down distribution at 600 V and lower because of the relative ease of applying sensitive fault protection. The Y-Y system may be used for stepping up voltage. It should not be used for obtaining a three-phase four-wire system from a three-phase three-wire system, because of the ‘‘floating neutral’’ on the

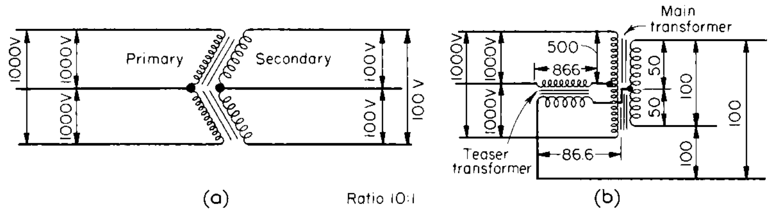


**Fig. 15.1.67** Transformer connections for transforming moderate amounts of three-phase power. (*a*) Open delta connection; (*b*) T connection.

secondary and the resulting high degree of unbalance of the secondary voltages. The Y-Δ system may be used to step down high voltages, the reverse of the Δ-Y connection. Y-connected windings also preclude third harmonic, and their multiples, circulating currents in the transformer windings. In the Δ-Y and Y-Δ systems the ratio of line voltage is obviously not that of the individual transformers. Because of different phase displacement between primaries and secondaries, a Δ-Δ bank cannot be connected in parallel (on both sides) with a Δ-Y bank, etc., even if they both have the correct voltage ratios between lines.

**Three-phase transformers** combine the magnetic circuits of three single-phase transformers so that they have parts in common. A material saving in cost, in weight, and in space results, the greatest saving occurring in the core and oil. The advantages of three-phase transformers are often outweighed by their lack of flexibility. The failure of a single phase shuts down the entire transformer. With three single units, one unit may be readily replaced with a single spare. The primaries of single-phase transformers may be connected in Y or Δ at will and the secondaries properly phased. The primaries, as well as the secondaries of three-phase transformers, must be phased.

For the transformation of moderate amounts of power from three-phase to three-phase, two transformers employing either the **open delta** or **T connection** (Fig. 15.1.67) may be used. With each connection the ratio of line voltages is the same as the transformer ratios. In the figure, ratios 10 : 1 are shown. In the T connection the primary and the secondary of the main transformer must be provided with a center tap to which one end of the teaser transformer is connected. The ratings of these systems are only 58 percent of the rating of the system using three similar transformers, one for each phase. Owing to dissymmetry, the terminal voltages become somewhat unbalanced even with a balanced load.

To transform from two- to three-phase or the reverse, the **T connection** of Fig. 15.1.68 is used. To make the secondary voltages symmetrical a tap (called a **Scott tap**) is brought out at 86.6 percent ($\sqrt{3}/2$) of the primary winding of the teaser transformer as shown in Fig. 15.1.68. With balanced no-load voltages the voltages become slightly unbalanced even under a symmetrical load, owing to unequal phase differences in the individual coils. The three-phase neutral *O* is one-third the winding of the teaser transformer from the junction. In Fig. 15.1.68*a* the transformation is from three-phase to a two-phase three-wire system. In Fig. 15.1.68*b* the transformation is from three-phase to a four-phase, five-wire system. The voltages are given on the basis of 100-V primaries with 1 : 1 transformer ratios.

An **autotransformer,** also called **compensator,** consists essentially of a single winding linking a magnetic circuit. Part of the energy is transformed, and the remainder flows through conductively. Suitable taps are provided so that, if the primary voltage is applied to two of the taps, a voltage may be taken from any other two taps. The ratio of voltages is equal practically to the ratio of the turns between their taps. An autotransformer should be installed only when the ratio of transformation is not large. The ratio of power transformed to total power is $1 - n$, where *n* is the ratio of low-voltage to high-voltage emf. This gives the saving over the ordinary transformer and is greatest when the ratio is not far from unity. Figure 15.1.69*a* shows 100 kW being changed from 3,300 to 2,300 V; 30.3 kW only are being actually transformed, and the remainder of the power flows through conductively. Figure 15.1.69*b* shows how an ordinary 10 : 1, 10-kW lighting transformer may be connected to boost 110 kW 10 percent in voltage. In Fig. 15.1.69*b*, however, the 230-V secondary must be insulated for 2,300 V to the core and ground. The voltage may likewise be reduced by reversing the 230-V coil. An autotransformer should never be used when it is desired to keep dangerous primary potentials from the secondary. It is used for starting induction motors (Fig. 15.1.71) and for a number of similar purposes.

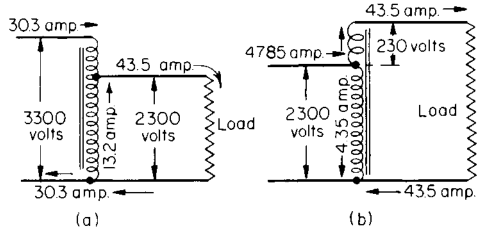


**Fig. 15.1.69** Autotransformer.

**Data on Transformers** Single-phase 55° self-cooled oil-insulated transformers for 2,300-V primaries, 230/115-V secondaries, and in sizes from 5 to 200 kVA for 60(25) Hz have efficiencies from one-half to full load of about 98 (97 to 98.7) percent and regulation of 1.5 (1.1 to 2.1) percent with pf = 1, and 3.5 (2.7 to 4.1) percent with pf = 0.8. Power transformers with 13,200-V primaries and 2,300-V secondaries in sizes from 667 to 5,000 kVA and for both 60 and 25 Hz have efficiencies from one-half to full load of about 99.0 percent and regulation of about 1.0 (4.2) percent with pf = 1 (0.8).

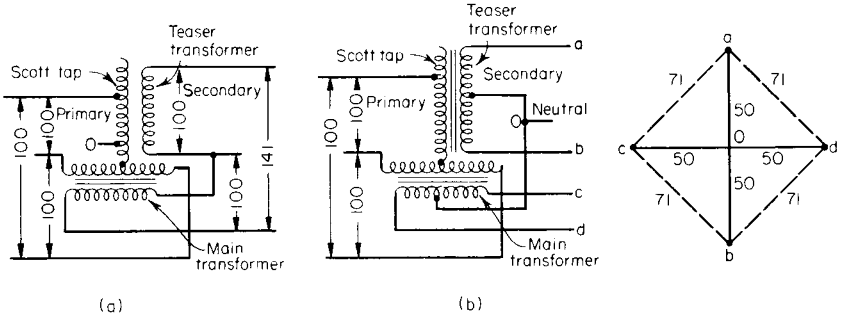


**Fig. 15.1.68** Connections for transforming from three-phase to two- and four-phase power.

## AC MOTORS

**Polyphase Induction Motor** The polyphase induction motor is the most common type of motor used. It consists ordinarily of a stator which is wound in the same manner as the synchronous-generator stator. If two-phase current is supplied to a two-phase winding or three-phase current to a three-phase winding, a rotating magnetic field is produced in the air gap. The number of poles which this field has is the same as the number of poles that a synchronous generator employing the same stator winding would have. The speed of the rotating field, or the **synchronous speed,**

$$N = 120f/P \qquad \text{r/min} \tag{15.1.118}$$

where $f$ = frequency and $P$ = number of poles.

There are two general types of rotors. The **squirrel-cage type** consists of heavy copper or aluminum bars short-circuited by end rings, or the bars and end rings may be an integral aluminum casting. The **wound rotor** has a polyphase winding of the same number of poles as the stator, and the terminals are brought out to slip rings so that external resistance may be introduced. The rotor conductors must be cut by the rotating field, hence the rotor cannot run at synchronous speed but must slip. The per unit **slip** is

$$s = (N - N_2)/N \tag{15.1.119}$$

where $N_2$ = the rotor speed, r/min. The rotor frequency

$$f_2 = sf \tag{15.1.120}$$

The torque is proportional to the air-gap flux and the components of rotor current in space phase with it. The rotor currents tend to lag the emfs producing them, because of the rotor-leakage reactance. From Eq. (15.1.120) the rotor frequency and hence the rotor reactance ($X_2 = 2\pi f_2 L_2$) are low when the motor is running near synchronous speed, so that there is a large component of rotor current in space phase with the flux. With large values of slip the increased rotor frequency increases the rotor reactance and hence the lag of the rotor currents behind their emfs, and therefore considerable space-phase difference between these currents and the flux develops. Consequently even with large values of current the torque may be small. The torque of the induction motor increases with slip until it reaches a maximum value called the **breakdown torque,** after which the torque decreases (see Fig. 15.1.72). The breakdown torque varies as the square of the voltage, inversely as the stator impedance and rotor reactance, and is independent of the rotor resistance.

The squirrel-cage motor develops moderate torque on starting ($s = 1.0$) even though the current may be three to seven times rated current. For any value of slip the torque of the induction motor varies as the square of the voltage. The torque of the squirrel-cage motor which, on starting, is only moderate may be reduced in the larger motors because of starting voltage drop from inrush and possible necessity of applying reduced-voltage starting.

**Polyphase squirrel-cage motors** are used mostly for constant-speed work; however, recent developments in variable-frequency pulse-width modulation (PWM) ac drives have seen these motors used in variable-speed applications where the ratio of maximum to minimum speed does not exceed 4 : 1. They are used widely on account of their rugged construction and the absence of moving electrical contacts, which makes them suitable for operation when exposed to flammable dust or gas. General-purpose squirrel-cage motors have starting torques of 100 to 250 percent of full load torque at rated voltage. The highest torques occur at the higher rated speeds. The locked rotor currents vary between four and seven times full-load current. In the **double-squirrel-cage** type of motor there is a high-resistance winding in the top of the rotor slots and a low-resistance winding in the bottom of the slots. The low-resistance winding is made to have a high leakage reactance, either by separating the windings with a magnetic bridge, Fig. 15.1.70*a*, or by making the slot very narrow in the area between the two windings, Fig. 15.1.70*b*. On starting, because of the high reactance of the low-resistance winding, most of the rotor current will flow in the high-resistance winding, giving the motor a large starting torque. As the rotor approaches the low value of slip at which it normally operates, the rotor frequency and hence the rotor reactance become low and most of the rotor current now flows in the low-resistance winding. Cage bars can be shaped so that one winding gives comparable results. See Fig. 15.1.70*c*. The rotor operates with a low value of slip. The high starting torque of the high-resistance motor and the excellent constant-speed operating characteristics of the low-resistance squirrel-cage rotor are combined in one motor.

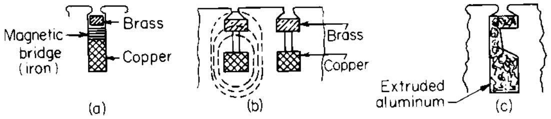


**Fig. 15.1.70** Types of slots for squirrel-cage windings.

The **single shaped** cage bar is more economical, and almost any shape for required characteristics can be extruded from aluminum. Single bars also eliminate the problems of differential expansion with double cage bars.

Nameplates of polyphase integral-hp squirrel-cage induction motors carry a *code* letter and a *design* letter. These provide information about motor characteristics, the former on locked rotor or starting inrush current (see Table 15.1.26) and the latter on torque characteristics. National Electrical Manufacturers Association standards publication No. MG1-1978 defines four design letters: A, B, C, and D. In all cases the motors are designed for full voltage starting. Locked rotor current and torque, pull-up torque and breakdown torque are tabulated according to horsepower and speed. Designs A, B, and C have full load slips less than 5 percent and design D more than 5 percent. The nature of the various designs can be understood by reference to the full voltage values for a 100-hp, 1800-r/min motor which follow:

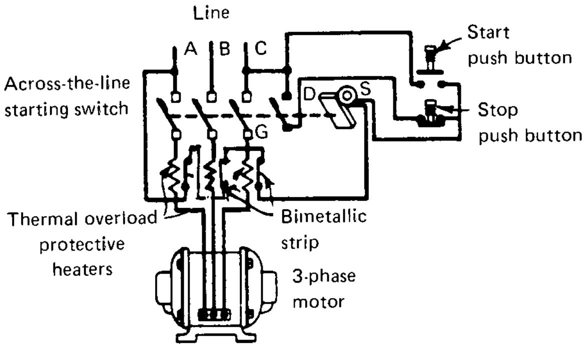
| | Design | | | |
|---|---|---|---|---|
| | A | B | C | D |
| Locked rotor torque | 125* | 125* | 200* | 275* |
| Pull-up torque | 100† | 100† | 140† | . . . |
| Breakdown torque | 200† | 200† | 190† | . . . |
| Locked rotor current | . . . | 600* | 600* | 600* |
| Full load slip (%) | 5§ | 5§ | 5§ | 5‡ |

NOTE: All quantities, except slip, are percent of full load value.
* Upper limit.
† Not less than.
‡ Greater than.
§ Less than.

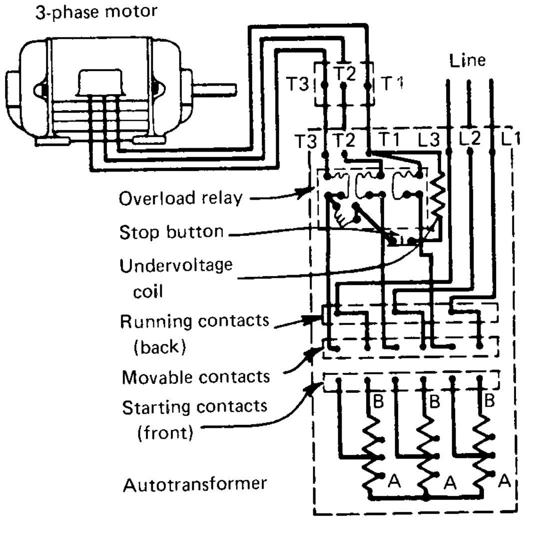
**Starting** It is desirable to start induction motors by direct connection across the line, since reduced voltage starters are expensive and almost always reduce the starting torque. The capacity of the distribution system dictates when reduced voltage starting must be used to limit voltage dips on the system. On stiff industrial systems 25,000-hp motors have been successfully started **across-the-line.**

In Fig. 15.1.71*a* is shown an **"across-the-line" starter** which may be operated from different push-button stations. The START push button closes the solenoid circuit between phases *C* and *A* through three bimetallic strips in series. This energizes solenoid *S*, which attracts armature *D*, which in turn closes the starting switch and the auxiliary blade *G*. This blade keeps the solenoid circuit closed when the START push button is released. Pressing the STOP push button opens the solenoid circuit, permitting the starting switch to open. A prolonged heavy overload raises the temperature of the heaters by an amount that will cause at least one of the bimetallic strips to open the solenoid circuit, releasing the starting switch.

A common method of applying reduced-voltage start is to use a **compensator** or **autotransformer** or **autostarter** (Fig. 15.1.71*b*). When the switch is in the starting position, the three windings *AB* of the three-phase autotransformer are connected in Y across the line and the motor terminals are connected to the taps which supply reduced voltage. When the switch is in the running position, the starter is entirely disconnected



(a) Across-the-line-starter



(b) Autostarter

**Fig. 15.1.71** Starters for squirrel-cage induction motor. (*a*) Across-the-line starter; (*b*) autostarter.

from the line. In modern practice, motors are protected by thermal or magnetic overload relays (Fig. 15.1.71) which operate to trip the circuit breaker. Since a time element is involved in the operation of such relays, they do not respond to large starting currents, because of their short duration. To limit the current to as low a value as possible, the lowest taps that will give the motor sufficient voltage to supply the required starting torque should be used. As the torque of an induction motor varies as the square of the voltage, the compensator produces a very low starting torque.

**Resistors in series with the stator** may also be used to start squirrel-cage motors. They are inserted in each phase and are gradually cut out as the motor comes up to speed. The resistors are generally made of wire-type resistor units or of graphite disks enclosed within heat-resisting porcelain-lined iron tubes. The disadvantage of resistors is that if the motor is started slowly the resistor becomes very hot and may burn out. Resistor starters are less expensive than autotransformers. Their application is to motors that start with light loads at infrequent intervals.

A **phase-controlled,** silicon-controlled rectifier (SCR) may be used to limit the motor-starting current to any value that will provide sufficient starting torque by reducing voltage to the motors. The SCR can also be used to start and stop the motors. A positive opening device such as a contactor or circuit breaker should be used in series with the SCR to stop the motor in case of a failed SCR, which will normally fail shorted and apply full voltage to the motor. The SCR starter has been combined with a microprocessor to provide gradual motor terminal voltage increases during an adjustable acceleration period. This is commonly called *soft start.* Other features include the ability to limit motor starting current and save energy when the motor is lightly loaded.

By **introducing resistance into the rotor circuit** through slip rings, the rotor currents may be brought nearly into phase with the air-gap flux and, at the same time, any value of torque up to maximum torque obtained. As the rotor develops speed, resistance may be cut out until there is no external resistance in the rotor circuit. The speed may also be controlled by inserting resistance in the rotor circuit. However, like the armature-resistance method of speed control with shunt motors, this method is also inefficient and gives poor speed regulation. Figure 15.1.72 shows graphically the effect on the torque of applying reduced voltage (curves *b*, *c*) and of inserting resistance in the rotor circuit (curve *d*). As shown by curves *b* and *c*, the torque for any given slip is proportional to the square of the line voltage. The effect of introducing resistance into the rotor circuit is shown by curve *d*. The point of maximum torque is shifted toward higher values of slip. The maximum torque at starting (slip = 1.0) occurs when the rotor resistance is equal to the rotor reactance at standstill. The wound-rotor motor is used where large starting torque is necessary as in railway work, hoists, and cranes. It has better starting characteristics than the squirrel-cage motor, but, because of the necessarily higher resistance of the rotor, it has greater slip even with the rotor resistance all cut out. Obviously, the wound rotor, controller, and external resistance make it more expensive than the squirrel-cage type. See Table 15.1.13 for performance data.

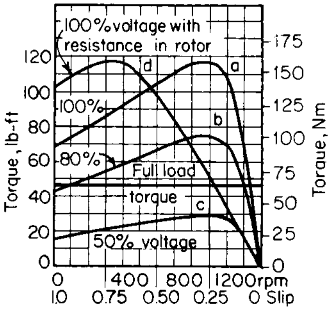


**Fig. 15.1.72** Speed-torque curve for 10-hp, 60-Hz, 1,140-r/min induction motor.

One **disadvantage of induction motors** is that they take lagging current, and the power factor at half load and less is low. The speed- and torque-load characteristics of induction motors are almost identical with those of the shunt motor. The speed decreases slightly to full load, the slip being from 10 percent in small motors to 2 percent in very large motors. The torque is almost proportional to the load nearly up to the breakdown torque. The power factor is 0.8 to 0.9 at full load. The direction of rotation of any three-phase motor may be reversed by interchanging any two stator wires.

**Speed Control of Induction Motors** The induction motor inherently is a constant-speed motor. From Eqs. (15.1.118) and (15.1.119) the rotor speed is

$$N_2 = 120f(1 - s)/P \qquad (15.1.121)$$

The speed can be changed only by changing the frequency, poles, or slip. In some applications where the motors constitute the only load on the generators, as with electric propulsion of ships, their speed may be changed by changing the frequency. Even then the range is limited, for both turbines and generators must operate near their rated speeds for good efficiency. By employing two distinct windings or by reconnecting a single winding by switching it is possible to change the number of poles. Complications prevent more than two speeds being readily obtained in this manner. Elevator motors frequently have two distinct

**Table 15.1.13 Drip-Proof Motors**

| | | | Power factor, % | | | Efficiency, %* | | |
|---|---|---|---|---|---|---|---|---|
| hp | Weight, lb | Current, A | ½ load | ¾ load | Full load | ½ load | ¾ load | Full load |
| 3 phase, 230 V, 60 Hz, 1,750 r/min, squirrel cage | | | | | | | | |
| 1 | 40 | 3.8 | 45.3 | 64.8 | 66.2 | 63.8 | 71.4 | 75.5 |
| 2 | 45 | 6.0 | 54.3 | 67.6 | 76.5 | 75.2 | 79.9 | 81.5 |
| 5 | 65 | 14.2 | 61.3 | 73.7 | 80.7 | 77.0 | 80.9 | 81.5 |
| 10 | 110 | 26.0 | 66.3 | 77.7 | 83.1 | 83.5 | 86.0 | 86.5 |
| 20 | 190 | 53.6 | 69.5 | 78.4 | 80.9 | 85.0 | 87.0 | 86.5 |
| 40 | 475 | 101.2 | 69.8 | 79.4 | 83.6 | 86.8 | 88.3 | 88.5 |
| 100 | 830 | 230.0 | 83.7 | 88.2 | 89.0 | 92.2 | 92.4 | 91.7 |
| 200 | 1,270 | 446.0 | 82.5 | 87.8 | 89.2 | 93.5 | 94.2 | 94.1 |
| 3 phase, 230 V, 60 Hz, 1,750 r/min, wound rotor | | | | | | | | |
| 5 | 155 | 15.6 | 50.7 | 64.1 | 74.0 | 77.6 | 81.0 | 81.4 |
| 10 | 220 | 27.0 | 66.8 | 77.5 | 82.5 | 84.3 | 85.4 | 84.8 |
| 25 | 495 | 60.0 | 79.2 | 86.6 | 89.4 | 88.1 | 88.6 | 87.8 |
| 50 | 650 | 122.0 | 72.4 | 82.3 | 86.8 | 86.7 | 87.9 | 87.7 |
| 100 | 945 | 234.0 | 78.4 | 86.2 | 89.4 | 90.0 | 90.4 | 89.8 |
| 200 | 2,000 | 446.0 | 79.8 | 87.6 | 90.8 | 90.5 | 92.1 | 92.5 |
| 3 phase, 2,300 V, 60 Hz, 1,750 r/min, squirrel cage | | | | | | | | |
| 300 | 2,300 | 70.4 | 76.2 | 83.4 | 86.0 | 90.8 | 92.5 | 92.8 |
| 700 | 3,380 | 155.0 | 85.5 | 89.4 | 90.0 | 91.7 | 93.4 | 93.7 |
| 1,000 | 4,345 | 221.0 | 86.2 | 89.5 | 90.0 | 92.1 | 93.8 | 94.1 |
| 3 phase, 2,300 V, 60 Hz, 1,750 r/min, wound rotor | | | | | | | | |
| 300 | 3,900 | 68 | 84.4 | 86.2 | 89.9 | 90.8 | 92.5 | 92.8 |
| 700 | 5,750 | 154 | 82.7 | 87.7 | 90.9 | 91.7 | 93.4 | 93.7 |
| 1,000 | 8,450 | 218 | 82.9 | 87.9 | 91.1 | 92.1 | 93.8 | 94.1 |

* High-efficiency motors are available at premium cost.
SOURCE: Westinghouse Electric Corp.

windings. Another objection to changing the number of poles is the fact that the design is a compromise, and sacrifices of desirable characteristics usually are necessary at both speeds.

The change of slip by introducing resistance into the rotor circuit has been discussed under the wound-rotor motor. It is also possible to introduce an **inverter** into the rotor circuit and convert the slip frequency power to line frequency power and return it to the distribution system.

Inverters are also used to convert line frequencies to variable frequencies to operate squirrel-cage motors at almost any speed up to their mechanical limitations. Inverters also reduce the starting stresses on a motor.

Polyphase voltages should be evenly **balanced** to prevent phase current **unbalance**. If voltages are not balanced, the motor must be derated in accordance with National Electrical Manufacturers Association (NEMA), Publication No. MG-1-14.34.

Approximately 5 percent voltage unbalance would cause about 25 percent increase in temperature rise at full load. The input current unbalance at full load would probably be 6 to 10 times the input voltage unbalance.

**Single phasing,** one phase open, is the ultimate unbalance and will cause overheating and burnout if the motor is not disconnected from the line.

**Single-Phase Induction Motor** Single-phase induction motors are usually made in fractional horsepower ratings, but they are listed by NEMA in integral ratings up to 10 hp. They have relatively high rotor resistances and can operate in the single-phase mode without overheating. Single-phase induction motors are not self-starting.

However, the single-phase motor runs in the direction in which it is started. There are several methods of starting single-phase induction motors. Short-circuited turns, or **shading coils,** may be placed around the pole tips which retard the time phase of the flux in the pole tip, and thus a weak torque in the direction of rotation is produced. A high-resistance starting winding, displaced 90 electrical degrees from the main winding, produces poles between the main poles and so provides a rotating field which is weak but is sufficient to start the motor. This is called the **split-phase** method. In order to minimize overheating this winding is ordinarily cut out by a centrifugal device when the armature reaches speed. In the larger motors a repulsion-motor start is used. The rotor is wound like an ordinary dc armature with a commutator, but with short-circuited brushes pressing on it axially rather than radially. The motor starts as a repulsion motor, developing high torque. When it nears its synchronous speed, a centrifugal device pushes the brushes away from the commutator, and at the same time causes the segments to be short-circuited, thus converting the motor into a single-phase induction motor.

**Capacitor Motors** Instead of splitting the phase by means of a high-resistance winding, it has become almost universal practice to connect a capacitor in series with the auxiliary winding (which is displaced 90 electrical degrees from the main winding). With capacitance, it is possible to make the flux produced by the auxiliary winding lead that produced by the main field winding by 90° so that a true two-phase rotating field results and good starting torque develops. However, the 90° phase relation between the two fields is obtainable at only one value of speed (as at starting), and the phase relation changes as the motor comes up to speed. Frequently the auxiliary winding is disconnected either by a centrifugal switch or a relay as the motor approaches full speed, in which case the motor is called a **capacitor-start** motor. With proper design the auxiliary winding may be left in circuit permanently (frequently with additional capacitance introduced). This improves both the power factor and torque characteristics. Such a motor is called **permanent-split capacitor motor**.

**Phase Converter** If a polyphase induction motor is operating single-phase, polyphase emfs are generated in its stator by the combination of stator and rotor fluxes. Such a machine can be utilized, therefore, for converting single-phase power into polyphase power and, when so used, is called a **phase converter.** Unless corrective means are utilized, the polyphase emfs at the machine terminals are somewhat unbalanced. The power input, being single-phase and at a power factor less than unity, not only fluctuates but is negative for two periods during each cycle. The power output being polyphase is steady, or nearly so. The cyclic differences between the power output and the power input are accounted for in the kinetic energy stored in the rotating mass of the armature. The armature accelerates and decelerates, but only slightly, in accordance with the difference between output and input. The phase converter is used principally on railway locomotives, since a single trolley wire can be used to deliver single-phase power to the locomotive, and the converter can deliver three-phase power to the three-phase wound-rotor driving motors.

**AC Commutator Motors** Inherently simple ac motors are not adapted to high starting torques and variable speed. There are a number of types of commutating motor that have been developed to meet the requirement of high starting torque and adjustable speed, particularly with single phase. These usually have been accompanied by compensating windings, centrifugal switches, etc., in order to overcome low power factors and commutation difficulties. With proper compensation, commutator motors may be designed to operate at a power factor of nearly unity or even to take leading current.

One of the simplest of the **single-phase commutator motors** is the ac series railway motor such as is used on the erstwhile New York, New Haven, and Hartford Railroad. It is based on the principle that the torque of the dc series motor is in the same direction irrespective of the polarity of its line terminals. This type of motor must be used on low frequency, not over 25 Hz, and is much heavier and more costly than an equivalent dc motor. The torque and speed curves are almost identical with those of the dc series motor. Unlike most ac apparatus the power factor is highest at light load and decreased with increasing load. Such motors operate with direct current even better than with alternating current. For example, the New Haven locomotives also operate from the 600-V dc third-rail system (two motors in series) from the New York City line (238th St.) into Grand Central Station. (See also Sec. 11.)

On account of difficulties inherent in ac operation such as commutation and high reactance drops in the windings, it is economical to construct and operate such motors only in sizes adaptable to locomotives, the ratings being of the order of 300 to 400 hp. **Universal motors** are small simple series motors, usually of fractional horsepower, and will operate on either direct or alternating current, even at 60 Hz. They are used for vacuum cleaners, electric drills, and small utility purposes.

**Synchronous Motor** Just as dc shunt generators operate as motors, a synchronous generator, connected across a suitable ac power supply, will operate as a motor and deliver mechanical power. Each conductor on the stator must be passed by a pole of alternate polarity every half cycle so that at constant frequency the rpm of the motor is constant and is equal to

$$N = 120f/P \qquad \text{r/min} \tag{15.1.122}$$

and the speed is independent of the load.

There are two types of synchronous motors in general use: the **slip-ring** type and the **brushless** type. The motor field current is transmitted to the motor by brushes and slip rings on the slip-ring type. On the brushless type it is generated by a shaft-mounted exciter and rectified and controlled by shaft-mounted static devices. Eliminating the slip rings is advantageous in dirty or hazardous areas.

The synchronous motor has the desirable characteristic that its power factor can be varied over a wide range merely by changing the field excitation. With a weak field the motor takes a lagging current. If the load is kept constant and the excitation increased, the current decreases (Fig. 15.1.73) and the phase difference between voltage and current becomes less until the current is in phase with the voltage and the power factor is unity. The current is then at its minimum value such as $I_0$, and the corresponding field current is called the **normal excitation**. Further increase in field current causes the armature current to lead and the power factor to decrease. Thus **underexcitation** causes the current to **lag; overexcitation** causes the current to **lead**. The effect of varying the field current at constant values of load is shown by the V curves (Fig. 15.1.73). Unity power factor occurs at the minimum value of armature current, corresponding to normal excitation. The power factor for any point such as $P$ is $I_0/I_1$, leading current. Because of its adjustable power factor, the motor is frequently run light merely to improve power factor or to control the voltage at some part of a power system. When so used the motor is called a **synchronous condenser**. The motor may, however, deliver mechanical power and at the same time take either leading or lagging current.

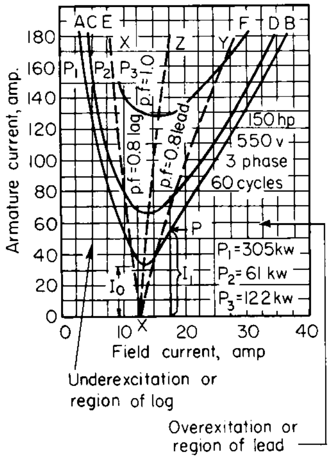


**Fig. 15.1.73** V curves of a synchronous motor.

Synchronous motors are used to drive **centrifugal** and **axial compressors,** usually through speed increasers, **pumps, fans,** and other high-horsepower applications where **constant speed, efficiency,** and **power factor** correction are important. **Low-speed** synchronous motors, under 600 r/min, sometimes called **engine** type, are used in driving **reciprocating compressors** and in **ball mills** and in other slow-speed applications. Their low length-to-diameter ratio, because of the need for many poles, gives them a high moment of inertia which is helpful in smoothing the **pulsating torques** of these loads.

If the motor **field current** is separately supported by a **battery** or **constant voltage transformer,** the synchronous motor will maintain speed on a lower voltage dip than will an induction motor because torque is proportional to voltage rather than voltage squared. However, if a synchronous motor drops **out of step,** it will normally not have the ability to reaccelerate the load, unless the driven equipment is automatically unloaded.

The synchronous motor is usually not used in smaller sizes since both the motors and its controls are more expensive than induction motors, and the ability of a small motor to supply VARs to correct power factor is limited.

If situated near an inductive load the motor may be overexcited, and its leading current will neutralize entirely or in part the lagging quadrature current of the load. This reduces the $I^2R$ loss in the transmission lines and also increases the kilowatt ratings of the system apparatus. The **synchronous condenser and motor** can also be used to control voltage and to stabilize power lines. If the condenser or motor is overexcited, its leading current flowing through the line reactance causes a rise in voltage at the motor; if it is underexcited, the lagging current flowing through the line reactance causes a drop in voltage at the motor. Thus within limits it becomes possible to control the voltage at the end of a transmission line by regulating the fields of synchronous condensers or motors. Long 220-kV lines and the 287-kV Hoover Dam–Los Angeles line require several thousand kVa in synchronous condensers floating at their load ends merely for voltage control. If the load becomes small, the voltage would rise to very high values if the synchronous condensers were not underexcited, thus maintaining nearly constant voltage. See Table 15.1.14 for characteristics.

A **salient-pole synchronous motor** may be started as an induction motor. In **laminated-pole** machines conducting bars of copper, copper alloy, or aluminum, **damper** or **amortisseur windings** are inserted in the pole face and short-circuited at the ends, exactly as a squirrel-cage winding in the

**Table 15.1.14 Performance Data for Coupled Synchronous Motors**

| Power, hp | Poles | Speed, r/min | Current, A | Excitation, kW | Efficiencies, % |  |  | Weight, lb |
|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  | ½ load | ¾ load | Full load |  |
| Unity power factor, 3 phase, 60 Hz, 2,300 V |  |  |  |  |  |  |  |  |
| 500 | 4 | 1,800 | 100 | 3 | 94.5 | 95.2 | 95.3 | 5,000 |
| 2,000 | 4 | 1,800 | 385 | 9 | 96.5 | 97.1 | 97.2 | 15,000 |
| 5,000 | 4 | 1,800 | 960 | 13 | 96.5 | 97.3 | 97.5 | 27,000 |
| 10,000 | 6 | 1,200 | 1,912 | 40 | 97.5 | 97.9 | 98.0 | 45,000 |
| 500 | 18 | 400 | 99.3 | 5 | 92.9 | 93.9 | 94.3 | 7,150 |
| 1,000 | 24 | 300 | 197 | 8.4 | 93.7 | 94.6 | 95.0 | 15,650 |
| 4,000 | 48 | 150 | 781 | 25 | 94.9 | 95.6 | 95.6 | 54,000 |
| 80% power factor, 3 phase, 60 Hz, 2,300 V |  |  |  |  |  |  |  |  |
| 500 | 4 | 1,800 | 127 | 4.5 | 93.3 | 94.0 | 94.1 | 6,500 |
| 2,000 | 4 | 1,800 | 486 | 13 | 95.5 | 96.1 | 96.2 | 24,000 |
| 5,000 | 4 | 1,800 | 1,212 | 21 | 95.5 | 96.3 | 96.5 | 37,000 |
| 10,000 | 6 | 1,200 | 2,405 | 50 | 96.8 | 97.3 | 97.4 | 70,000 |
| 500 | 18 | 400 | 125 | 7.2 | 92.4 | 93.4 | 93.6 | 9,500 |
| 1,000 | 24 | 300 | 248 | 11.6 | 93.3 | 94.2 | 94.4 | 17,500 |
| 4,000 | 48 | 150 | 982 | 40 | 94.6 | 95.3 | 95.5 | 11,500 |

SOURCE: Westinghouse Electric Corp.

induction motor is connected. The bars can be designed only for starting purposes since they carry no current at synchronous speed and have no effect on efficiency. In solid-pole motors a block of steel is bolted to the pole and performs the current-carrying function of the damper winding in the laminated-pole motor. At times the pole faces are interconnected to minimize starting-pulsating torques. When the synchronous motor reaches 95 to 98 percent speed as an induction motor, the motor field is applied by a **timer** or **slip frequency** control circuit, and the motor pulls into step at 100 percent speed. While accelerating, the motor field is connected to resistances to minimize induced voltages and currents.

Two-pole motors are built as **turbine** type or **round-rotor motors** for mechanical strength and do not have the thermal capacity or space for starting windings, so they must be started by supplementary means.

One such supplementary starting means is the use of a variable-frequency source, either a **variable-speed generator** or more commonly a static **converter-inverter**. The motor is brought up to speed in synchronism with a slowly increasing frequency. One common application is the starting of the large motor-generators used in **pump-storage** utility systems.

Variable frequency may be used to start salient-pole machines also. Requirements for a start without high torques and pulsations or high voltage drops on small electrical systems may dictate the use of something other than full voltage starting.

The **synchronous reluctance motor** is similar to an induction machine with salient poles machined in the rotors. Under light loads the motor will synchronize on reluctance torque and lock in step with the rotating field at synchronous speed. These motors are used in small sizes with variable-frequency inverters for speed control in the paper and textile industry.

The **synchronous-induction motor** is fundamentally a wound-rotor slip-ring induction motor with an air gap greater than normal, and the rotor slots are larger and fewer. On starting, resistance is inserted in the rotor circuit to produce high torque, and this is cut out as the speed increases. As synchronism is approached, the rotor windings are connected to a dc power source and the motor operates synchronously.

**Timing** or **clock motors** operate synchronously from ac power systems. Figure 15.1.74*a* illustrates the Warren Telechron motor which operates on the hysteresis principle. The stator consists of a laminated element with an exciting coil, and each pole piece is divided, a short-circuited shading turn being placed on each of the half poles so formed. The rotor consists of two or more hard-steel disks of the shape shown, mounted on a small shaft. The shaded poles produce a 3,600 r/min rotating magnetic field (at 60 Hz), and because of hysteresis loss, the disk follows the field just as the rotor of an induction motor does. When the rotor approaches the synchronous speed of 3,600 r/min, the rotating magnetic field takes a path along the two rotor bars and locks the rotor in with it. The rotor and the necessary train of reducing gears rotate in oil sealed in a small metal can. Figure 15.1.74*b* shows a subsynchronous motor. Six squirrel-cage bars are inserted in six slots of a solid cylindrical iron rotor, and the spaces between the slots form six salient poles. The motor, because of the squirrel cage, starts as an induction motor, attempting to attain the speed of the rotating field, or 3,600 r/min (at 60 Hz). However, when the rotor reaches 1,200 r/min, one-third synchronous speed, the salient poles of the rotor lock in with the poles of the stator and hold the rotor at 1,200 r/min.

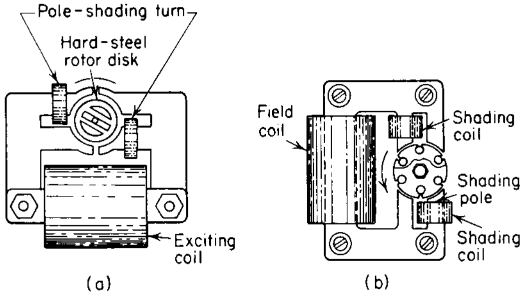


**Fig. 15.1.74** Synchronous motors for timing. (*a*) Warren Telechron motor; (*b*) Holtz induction-reluctance subsynchronous motor.

## AC-DC CONVERSION

**Static Rectifiers** Silicon devices, and to a lesser extent gas tubes, are the primary means of ac to dc or dc to ac conversion in modern installations. They are advantageous when compared to synchronous converters or motor generators because of efficiency, cost, size, weight, and reliability. Various bridge configurations for single-phase and three-phase applications are shown in Fig. 15.1.75*a*. Table 15.1.15 shows the relative outputs of rectifier circuits. The use of two three-phase bridges fed from an ac source consisting of a three-winding transformer with both a Δ and Y secondary winding so that output voltages are 30° out of phase will reduce dc ripple to approximately 1 percent.

The use of **silicon-controlled rectifiers** (SCRs) to replace rectifiers in the various bridge configurations allows the output voltages to be varied from rated output voltage to zero. The output voltage wave will not be a sine wave but a series of square waves, which may not be suitable for some applications. Dc to ac conversions are shown in Fig. 15.1.75*b*.

A new technology of ac-to-dc conversion commonly called *switch*

**Table 15.1.15 Relationships for AC-DC Conversion Static Devices**

| Device description | Voltages, % | | Currents, % | | Ripple, % |
|---|---|---|---|---|---|
| | $E_{ac}$ | $E_{dc}$ | $I_{ac}$ | $I_{dc}$ | |
| $1\phi$, half wave | 100 | 45 | 100 | 100 | 121 |
| $1\phi$, full wave | 100 | 90 | 100 | 90 | 48 |
| $3\phi$, full wave | 100 | 135 | 100 | 123 | 4.2 |

*mode power supplies* (SMPSs) is found in almost all microprocessor-based modern electronic equipment for dc supplies between 3 and 15 V. The supply voltage (120 V ac) is rectified by a single-phase full-wave bridge circuit. See Fig. 15.1.75. The output is stored in a capacitor. A switcher will then switch the dc voltage from the capacitor on and off at a high frequency, usually between 10 and 100 kHz. These high-frequency pulses are stepped down in voltage by a transformer and rectified by diodes. The diodes' output is filtered to the dc supply required. These SMPSs are small in size, have higher efficiency, and are lower in cost. They do create harmonic and power quality problems that have to be addressed.

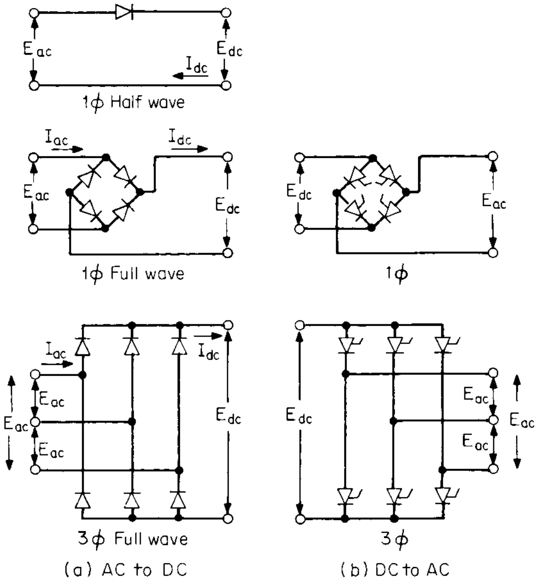


**Fig. 15.1.75** AC-DC conversion with static devices.

## SYNCHRONOUS CONVERTERS

The synchronous converter is essentially a dc generator with slip rings connected by taps to equidistant points in the armature winding. Alternating current may also be taken from and delivered to the armature. The machine may be single-phase, in which case there are two slip rings and two slip-ring taps per pair of poles; it may be three-phase, in which case there are three slip rings and three slip-ring taps per pair of poles, etc. Converters are usually used to convert alternating to direct current, in which case they are said to be operating **direct;** they may equally well convert direct to alternating current, in which case they are said to be operating **inverted**. A converter will operate satisfactorily as a dc motor, a synchronous motor, a dc generator, a synchronous generator, or it may deliver direct and alternating current simultaneously, when it is called a **double-current generator**.

The rating of a converter increases very rapidly with increase in the number of phases owing, in part, to better utilization of the armature copper and also because of more uniform distribution of armature heating.

Because of the materially increased rating, converters are nearly all operated six-phase. The rating decreases rapidly with decrease in power factor, and hence the converter should operate near unity power factor. The diametrical ac voltage is the ac voltage between two slip-ring taps 180 electrical degrees apart. With a two-pole closed winding, i.e., a winding that closes on itself when the winding is completed, the diametrical ac voltage is the voltage between any two slip-ring taps diametrically opposite each other.

With a sine-voltage wave, the dc voltage is the peak of the diametrical ac voltage wave. The voltage relations for sine waves are as follows: dc volts, 141; single phase, diametrical, 100; three-phase, 87; four-phase, diametrical, 100; four phase, adjacent taps, 71; six phase, diametrical, 100; six phase, adjacent taps, 50. These relations are obtained from the sides of polygons inscribed in a circle having a diameter of 100 V, as shown in Fig. 15.1.76.

**Selsyns** The word **selsyn** is an abbreviation of self-synchronizing and is applied to devices which are connected electrically, and in which an angular displacement of the rotating member of one device produces an equal angular displacement in the rotating member of the second device. There are several types of selsyns and they may be dc or ac, single-phase or polyphase. A simple and common type is shown in Fig. 15.1.77. The two stators $S_1$, $S_2$ are phase-wound stators, identical electrically with synchronous-generator or induction-motor stators. For simplicity Gramme-ring windings are shown in Fig. 15.1.77. The two stators are connected three-phase and in parallel. There are also two bobbin-type rotors $R_1$, $R_2$, with single-phase windings, each connected to a single-phase supply such as 115 V, 60 Hz. When $R_1$ and $R_2$ are in the same angular positions, the emfs induced in the two stators by the ac flux of the rotors are equal and opposite, there are no interchange currents between stators, and the system is in equilibrium. However, if the angular displacement of $R_1$, for example, is changed, the magnitudes of the emfs induced in the stator winding of $S_1$ are correspondingly changed. The emfs of the two stators then become unbalanced, currents flow from $S_1$ to $S_2$, producing torque on $R_2$. When $R_2$ attains the same angular position as $R_1$, the emfs in the two rotors again become equal and opposite, and the system is again in equilibrium.

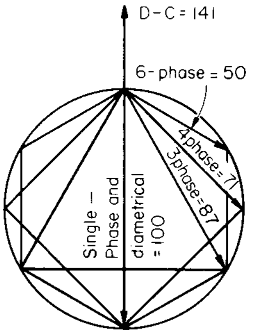


**Fig. 15.1.76** EMF relations in a converter.

If there is torque load on either rotor, a resultant current is necessary to sustain the torque, so that there must be an angular displacement between rotors. However, by the use of an auxiliary selsyn a current may be fed into the system which is proportional to the angular difference of the two rotors. This current will continue until the error is corrected. This is called **feedback**. There may be a master selsyn, controlling several secondary units.

Selsyns are used for position indicators, e.g., in bridge–engine-room signal systems. They are also widely used for fire control so that from any desired position all the turrets and guns on battleships can be turned and elevated simultaneously through any desired angle with a high degree of accuracy. The selsyn itself rarely has sufficient power to perform these operations, but it actuates control through power multipliers such as amplidynes.

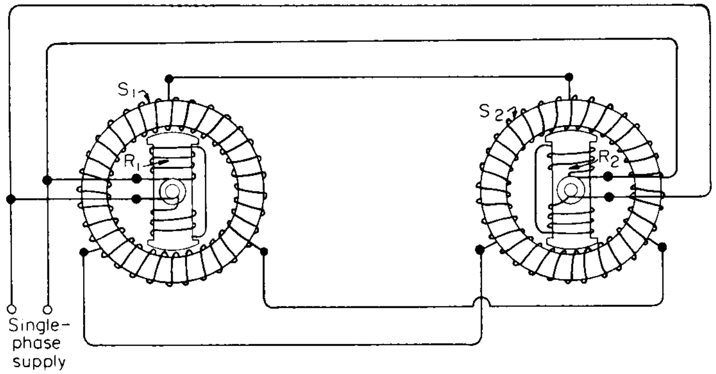


**Fig. 15.1.77** Selsyn system.

## RATING OF ELECTRICAL APPARATUS

The **rating** of electrical apparatus is almost always determined by the maximum temperature at which the materials in the machine, especially the insulation and lubricant, may be operated for long periods without deterioration. It is permissible, as far as temperature is concerned, to overload the apparatus so long as the safe temperature is not exceeded. The ANSI/IEEE Standard 100-1992 classifies **insulating materials** in seven different **classes:**

1. *Class 90 insulation.* Materials or combinations of materials such as cotton, silk, and paper without impregnation which will have suitable thermal endurance if operated continually at 90°C.
2. *Class 105 insulation.* Materials or combinations of materials such as cotton, silk, and paper when suitably impregnated or coated or when immersed in a dielectric liquid. This class has sufficient thermal endurance at 105°C.
3. *Class 130 insulation.* Materials or combinations of materials such as mica, glass fiber, asbestos, etc., with suitable bonding substances. This class has sufficient thermal endurance at 130°C.
4. *Class 155 insulation.* Same materials as class 130 but with bonding substances suitable for continuous operation at 155°C.
5. *Class 180 insulation.* Materials or combinations of materials such as silicone elastomer, mica, glass fiber, asbestos, etc., with suitable bonding substances such as appropriate silicone resins. This class has sufficient thermal life at 180°C.
6. *Class 220 insulation.* Materials suitable for continuous operation at 220°C.
7. *Class over-220 insulation.* Materials consisting entirely of mica, porcelain, glass, quartz, and similar inorganic materials which have suitable thermal life at temperatures over 220°C.

NOTE: In all cases, other materials or combinations of materials other than those mentioned above may be used in a given class if from experience or accepted tests they can be shown to have comparable thermal life. It is common practice also to specify **insulation systems in electrical machinery** by letter. For example, integral horsepower ac motors may have a maximum temperature rise in the winding (determined by winding resistance) or 60°C for **class A** insulation, 80°C for **class B,** 105°C for **class F,** and 125°C for **class H**—all based on a 40°C ambient.

The recommended methods of measurement are: (1) the thermometer method is preferred for uninsulated windings, exposed metal parts, gases and liquids, or surface methods generally; thermocouples are preferred for rapidly changing surface temperatures; (2) the applied-thermocouple method is suitable for making surface temperature measurements when it is desired to measure the temperature of surfaces that are accessible to thermocouples but not to liquid-in-glass thermometers; (3) the contact-thermocouple method is suitable for measuring temperatures of bare metal surfaces such as those of commutator bars and slip rings; (4) the resistance method is suitable for insulated windings, except for windings of such low resistance that measurements cannot be accurately made due to uncontrollable resistance in contacts or where it is impracticable to make connections to obtain measurements before an undesirable drop in temperature occurs; (5) the embedded-detector method is suitable for interior measurements at designated locations as specified in the standards for certain kinds of equipment, such as large rotating machines.

### Efficiency of Electrical Motors

Methods of determining efficiency are by **direct measurement** or by **segregated losses**. Methods are outlined in Standard Test Procedure for Polyphase Induction Motors and Generators, ANSI/IEEE Std. 112-1991; Standard Test Code for DC Machines, IEEE Std. 113-1985, Test Procedure for Single-Phase Induction Motors, ANSI/IEEE Std. 114-1982; and Test Procedures for Synchronous Machines, IEEE Std. 115-1983.

Direct measurements can be made by using calibrated **motors, generators,** or **dynamometers** for input to generators and output from motors, and precision electrical motors for input to motors and output from generators.

$$\text{Efficiencies} = \frac{\text{output}}{\text{input}} \tag{15.1.123}$$

The segregated **losses** in motors are classified as follows: (1) Stator $I^2R$ (shunt and series field $I^2R$ for dc); (2) rotor $I^2R$ (armature $I^2R$ for dc); (3) core loss; (4) stray-load loss; (5) friction and windage loss; (6) brush-contact loss (wound rotor and dc); (7) brush-friction loss (wound rotor and dc); (8) exciter loss (synchronous and dc); and (9) ventilating loss (dc). Losses are calculated separately and totaled. Measure the electrical output of the generator; then

$$\text{Efficiency} = \frac{\text{output}}{\text{output} + \text{losses}} \tag{15.1.124a}$$

Measure the electrical input of the motors; then

$$\text{Efficiency} = \frac{\text{input} - \text{losses}}{\text{input}} \tag{15.1.124b}$$

When testing dc motors, compensation should be made for the **harmonics** associated with rectified ac used to provide the variable dc voltage to the motors. Instrumentation should be chosen to accurately reflect the rms value of currents.

**Temperature rise** under full-load conditions may be measured by tests as outlined in the IEEE Standards referred to above. Methods of loading are: (1) Load motor with **dynamometer** or **generator** of similar capacity and run until temperatures stabilize; (2) load generator with **motor-generator** set or **plant** load and run until temperature stabilizes; (3) alternately apply **dual frequences** to motor until it reaches rated temperature; (4) synchronous motor may be operated as synchronous **condenser** at no load with **zero power factor** at rated current, voltage, and frequency until temperatures stabilize.

### Industrial Applications of Motors

**Alternating or Direct Current** The induction motor, particularly the squirrel-cage type, is preferable to the dc motor for constant-speed work, for the initial cost is less and the absence of a commutator reduces maintenance. Also there is less fire hazard in many industries, such as sawmills, flour mills, textile mills, and powder mills. The use of the induction motor in such places as cement mills is advantageous since with dc motors the grit makes the maintenance of commutators difficult.

For variable-speed work like cranes, hoists, elevators, and for adjustable speeds, the dc motor characteristics are superior to induction-motor characteristics. Even then, it may be desirable to use induction motors since their less desirable characteristics are more than balanced by their simplicity and the fact that ac power is available, and to obtain dc power conversion apparatus is usually necessary. Where both lights and motors are to be supplied from the same ac system, the 208/120-V four-wire three-phase system is now in common use. This gives 208 V three-phase for the motors, and 120 V to neutral for the lights.

Full-load speed, temperature rise, efficiency, and power factor as well as breakdown torque and starting torque have long been parameters of concern in the application and purchase of motors. Another qualification is service factor. The service factor of an alternating current motor is a multiplier applicable to the horsepower rating. When so applied, the result is a permissible horsepower loading under the conditions specified for the service factor. When operated at service factor load with 1.15 or higher service factor, the permissible temperature rise by resistance is as follows: class A insulation 70°C; class B, 90°C; and class F, 115°C.

Special enclosures, fittings, seals, ventilation systems, electromagnetic design, etc., are required when the motor is to be operated under unusual service conditions, such as exposure to (1) combustible, explosive, abrasive, or conducting dusts, (2) lint or very dirty conditions where the accumulation of dirt might impede the ventilation, (3) chemical fumes or flammable or explosive gases, (4) nuclear radiation, (5) steam, salt laden air, or oil vapor, (6) damp or very dry locations, radiant heat, vermin infestation, or atmosphere conducive to the growth of fungus, (7) abnormal shock, vibration, or external mechanical loading, (8) abnormal axial thrust or side forces on the motor shaft, (9) excessive departure from rated voltage, (10) deviation factors of the line voltage exceeding 10 percent, (11) line voltage unbalance exceeding 1 percent, (12) situations where low noise levels are required, (13) speeds higher than the highest rated speed, (14) operation in a poorly ventilated room, in a pit, or in an inclined attitude, (15) torsional impact loads, repeated abnormal overloads, reversing or electric braking, (16) operation at standstill with any winding continuously energized, and (17) operation with extremely low structureborne and airborne noise. For dc machines, a further unusual service condition occurs when the average load is less than 50 percent over a 24-h period or the continuous load is less than 50 percent over a 4-h period.

The standard direction of rotation for all nonreversing dc motors, ac single-phase motors, synchronous motors, and universal motors is counterclockwise when facing the end of the machine opposite the drive end. For dc and ac generators, the rotation is clockwise.

Further information may be found in Publication No. MG-1 of the National Electrical Manufacturers Association.

It must be recognized that heat is conducted by electrical conductors. Windings in motors operating in a 40°C ambient at class F temperature rises are running at temperatures 90°C higher than the maximum allowable temperature (75°C) of cable ordinarily used in interior wiring. Heat conducted by the motor leads in such a situation could cause a failure of the branch circuit cable in the terminal box. See Tables 15.1.21 and 15.1.22.

## ELECTRIC DRIVES

**Cranes and Hoists** The dc series motor is best adapted to cranes and hoists. When the load is heavy the motor slows down automatically and develops increased torque thus reducing the peaks on the electrical system. With light loads, the speed increases rapidly, thus giving a lively crane. The series motor is also well adapted to moving the bridge itself and also the trolley along the bridge. Where alternating current only is available and it is not economical to convert it, the slip-ring type of induction motor, with external-resistance speed control, is the best type of ac motor. Squirrel-cage motors with high resistance end rings to give high starting torque (design D) are used (design D motors; also see Ilgner system).

**Constant-Torque Applications** **Piston pumps, mills, extruders,** and **agitators** may require constant torque over their complete speed range. They may require high starting torque design C or D squirrel-cage motors to bring them up to speed. Where speed is to be varied while running, a variable armature voltage **dc motor** or a **variable-frequency** squirrel-cage induction-motor drive system may be used.

**Centrifugal Pumps** Low $WK^2$ and low starting torques make design B general-purpose squirrel-cage motors the preference for this application. When **variable flow** is required, the use of a **variable-frequency** power supply to vary motor speed will be energy efficient when compared to changing flow by **control-valve** closure to increase head.

**Centrifugal Fans** High $WK^2$ may require high starting torque design C or D squirrel-cage motors to bring the fan up to speed in a reasonable period of time. When **variable flow** is required, the use of a **variable-frequency** power supply or a multispeed motor to vary fan speed will be energy efficient when compared to closing **louvers**. For large fans, **synchronous-motor** drives may be considered for high efficiency and improved power factor.

**Axial or Centrifugal Compressors** For smaller compressors, say, up to 100 hp, the squirrel-cage induction motor is the drive of choice. When the $WK^2$ is high, a design C or D high-torque motor may be required. For larger compressors, the synchronous motor is more efficient and improves power factor. Where **variable flow** is required, the **variable-frequency** power supply to vary motor speed is more efficient than controlling by **valve** and in some applications may eliminate a **gearbox** by allowing the motor to run at compressor operating speed.

**Pulsating-Torque Applications** **Reciprocating compressors, rock crushers,** and **hammer mills** experience widely varying torque pulsations during each revolution. They usually have a **flywheel** to store energy, so a high-torque, high-slip design D motor will accelerate the high $WK^2$ rapidly and allow energy recovery from the flywheel when high torque is demanded. On larger drives a slow-speed, engine-type synchronous motor can be directly connected. The motor itself supplies significant $WK^2$ to smooth out the torque and current pulsations of the system.

## SWITCHBOARDS

**Switchboards** may, in general, be divided into four classes: direct-control panel type; remote mechanical-control panel type; direct-control truck type; electrically operated. With **direct-control panel-type boards** the switches, rheostats, bus bars, meters, and other apparatus are mounted on or near the board and the switches and rheostats are operated directly, or by operating handles if they are mounted in back of the board. The voltages, for both direct current and alternating current, are usually limited to 600 V and less but may operate up to 2,500 V ac if oil circuit breakers are used. Such panels are not recommended for capacities greater than 3,000 kVA. **Remote mechanical-control panel-type boards** are ac switchboards with the bus bars and connections removed from the panels and mounted separately away from the load. The oil circuit breakers are operated by levers and rods. This type of board is designed for heavier duty than the direct-control type and is used up to 25,000 kVA. **Direct-control truck-type switchboards** for 15,000 V or less consist of equipment enclosed in steel compartments completely assembled by the manufacturers. The high-voltage parts are enclosed, and the equipment is interlocked to prevent mistakes in operation. This equipment is designed for low- and medium-capacity plants and auxiliary power in large generating stations. **Electrically operated switchboards** employ solenoid or motor-operated circuit breakers, rheostats, etc., controlled by small switches mounted on the panels. This makes it possible to locate the high-voltage and other equipment independently of the location of switchboard.

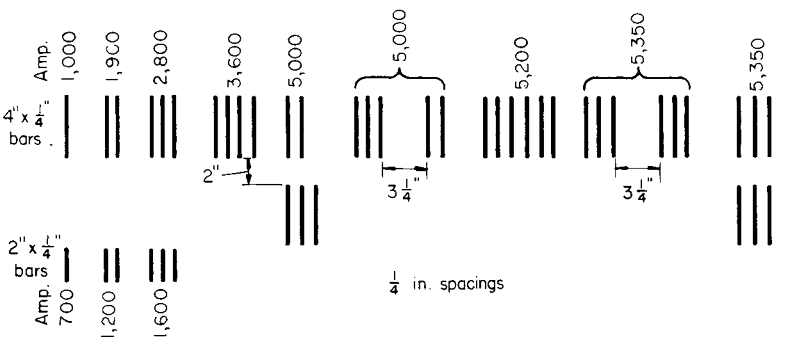


**Fig. 15.1.78** Current-carrying capacity of copper bus bars.

In all large stations the switching equipment and buses are always mounted entirely either in separate buildings or in outdoor enclosures. Such equipment is termed **bus structures** and is electrically operated from the main control board.

Marble has high dielectric qualities and was formerly used exclusively for the panels. It is now used occasionally where its appearance is desired for architectural purposes. Slate is used extensively and is finished in black enamel, marine, and natural black. Ebony asbestos is also used frequently, is lighter than marble or slate, has high dielectric strength and insulation resistivity, and can be readily cut, drilled, and machined. Steel panels, usually ⅛ in thick, are light, economical in construction and erection, and at the present time are favored over other types.

Switchboards should be erected at least 3 to 4 ft from the wall. Switchboard frames and structures should be grounded. The only exceptions are effectively insulated frames of single-polarity dc switchboards. For low-potential work, the conductors on the rear of the switchboard are usually made up of flat copper strip, known as **bus-bar** copper. The size required is based upon a current density of about 1,000 A/in$^2$. Figure 15.1.78 gives the approximate continuous dc carrying capacity of copper bus bars for different arrangements and spacings for 35°C temperature rise.

Switchboards must be individually adapted for each specific electrical system. Space permits the showing of the diagrams of only three boards each for a typical electrical system (Fig. 15.1.79). Aluminum bus bars are also frequently used.

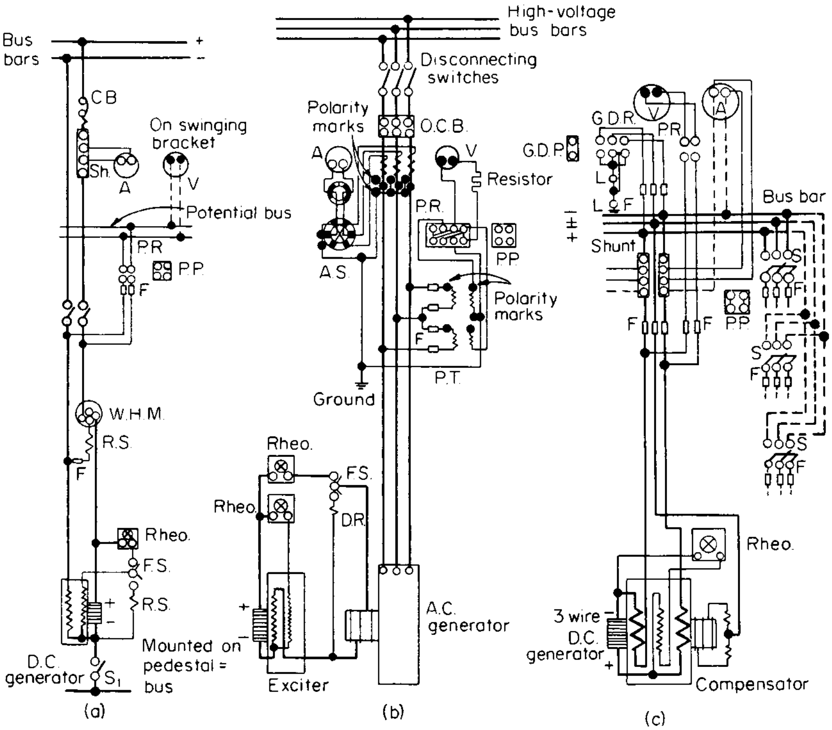


**Fig. 15.1.79** Switchboard wiring diagrams for generators. (*a*) 125-V or 250-V dc generator; (*b*) three-phase, synchronous generator and exciter for a small or isolated plant; (*c*) three-wire dc generator for a small or isolated plant. A, ammeter; AS, three-way ammeter switch; CB, circuit breaker, CT, current transformer; DR, ground detector receptacle; L, ground detector lamp; OC, overload coil; OCB, oil circuit breaker; PP, potential ring; PR, potential receptacle; PT, potential transformer; Rheo, rheostat; RS, resistor; S, switch; Sh, shunt; V, voltmeter; WHM, watthour meter.

**Equipment of Standard Panels** Following are enumerated the various parts required in the equipment of standard panels for varying services:

**Generator or synchronous-converter panel, dc two-wire system:** 1 circuit breaker; 1 ammeter; 1 handwheel for rheostat; 1 voltmeter; 1 main switch (three-pole single throw or double throw) or 2 single-pole switches.

**Generator or synchronous-converter panel, dc three-wire system:** 2 circuit breakers; 2 ammeters; 2 handwheels for field rheostats; 2 field switches; 2 potential receptacles for use with voltmeter; 3 switches; 1 four-point starting switch.

**Generator or synchronous-motor panel, three-phase three-wire system:** 3 ammeters; 1 three-phase wattmeter; 1 voltmeter; 1 field ammeter; 1 double-pole field switch; 1 handwheel for field rheostats; 1 synchronizing receptacle (four-point); 1 potential receptacle (eight-point); 1 field rheostat; 1 triple-pole oil switch; 1 power-factor indicator; 1 synchronizer; 2 series transformers; 1 governor control switch.

**Synchronous-converter panel, three-phase:** 1 ammeter; 1 power-factor indicator; 1 synchronizing receptacle; 1 triple-pole oil circuit breaker; 2 current transformers; 1 potential transformer; 1 watthour meter (polyphase); 1 governor control switch.

**Induction motor panel, three-phase:** 1 ammeter; series transformers; 1 oil switch.

**Feeder panel, dc, two-wire and three-wire:** 1 single-pole circuit breaker; 1 ammeter; 2 single-pole main switches; potential receptacles (1 four-point for two-wire panel; 1 four-point and 1 eight-point for three-wire panel).

**Feeder panel, three-wire, three-phase and single-phase:** 3 ammeters; 1 automatic oil switch (three-pole for three-phase, two-pole for single-phase); 2 series transformers; 1 shunt transformer; 1 wattmeter; 1 voltmeter; 1 watthour meter; 1 handwheel for control of potential regulator.

**Exciter panel (for 1 or 2 exciters):** 1 ammeter (2 for 2 exciters); 1 field rheostat (2 for 2 exciters); 1 four-point receptacle (2 for 2 exciters); 1 equalizing rheostat for regulator.

**Switches** The current-carrying parts of switches are usually designed for a current density of 1,000 A/in$^2$. At contact surfaces, the current density should be kept down to about 50 A/in$^2$.

**Circuit Breakers** Switches equipped with a tripping device constitutes an elementary load interrupter switch. The difference between a load interrupter switch and a circuit breaker lies in the interrupting capacity. A circuit breaker must open the circuit successfully under short circuit conditions when the current through the contacts may be several orders of magnitude greater than the rated current. As the circuit is being opened, the device must withstand the accompanying mechanical forces and the heat of the ensuing arc until the current is permanently reduced to zero.

The opening of a metallic circuit while carrying electric current causes an electric arc to form between the parting contacts. If the action takes place in air, the air is ionized (a plasma is formed) by the passage of current. When ionized, air becomes an electric conductor. The space between the parting contacts thus has relatively low voltage drop and the region close to the surface of the contacts has relatively high voltage drop. The thermal input to the contact surfaces (VI) is therefore relatively large and can be highly destructive. A major aim in circuit breaker design is to quench the arc rapidly enough to keep the contacts in a reusable state. This is done in several ways: (1) lengthening the arc mechanically, (2) lengthening the arc magnetically by driving the current-carrying plasma sideways with a magnetic field, (3) placing barriers in the arc path to cool the plasma and increase its length, (4) displacing and cooling the plasma by means of a jet of compressed air or inert gas, and (5) separating the contacts in a vacuum chamber.

By a combination of shunt and series coils the circuit breaker can be made to trip when the energy reverses. Circuit breakers may trip unnecessarily when the difficulty has been immediately cleared by a local breaker or fuse. In order that service shall not be thus interrupted unnecessarily, **automatically reclosing breakers** are used. After tripping, an automatic mechanism operates to reclose the breaker. If the short circuit still exists, the breaker cannot reclose. The breaker attempts to reclose two or three times and then if the short circuit still exists it remains permanently locked out.

**Metal-clad switch gears** are highly developed pieces of equipment that combine buses, circuit breakers, disconnecting devices, controlling devices, current and potential transformers, instruments, meters, and interlocking devices, all assembled at the factory as a single unit in a compact steel enclosing structure. Such equipment may comprise truck-type circuit breakers, assembled as a unit, each housed in a separate steel compartment and mounted on a small truck to facilitate removal for inspection and servicing. The equipment is interlocked to prevent mistakes in operation and in the removal of the unit; the removal of the unit breaks all electrical connections by suitable disconnecting switches in the rear of the compartment, and all metal parts are grounded. This design provides compactness, simplicity, ease of inspection, and safety to the operator.

**High-voltage circuit breakers** can be oil type, in which the contacts open under **oil, air-blast** type, in which the arc is extinguished by a powerful blast of air directed through an orifice across the arc and into an arc chute, $H_2S$ type, or vacuum contact type. The tripping of high-voltage circuit breakers is initiated by an abnormal current acting through the secondary of a current transformer on an inverse-time relay in which the time of closing the relay contacts is an inverse time function of the current; i.e., the greater the current the shorter the time of closing. The breaker is tripped by a dc tripping coil, the dc circuit being closed by the relay contacts. Modern circuit breakers should open the circuit within 3 cycles from the time of the closing of the relay contacts.

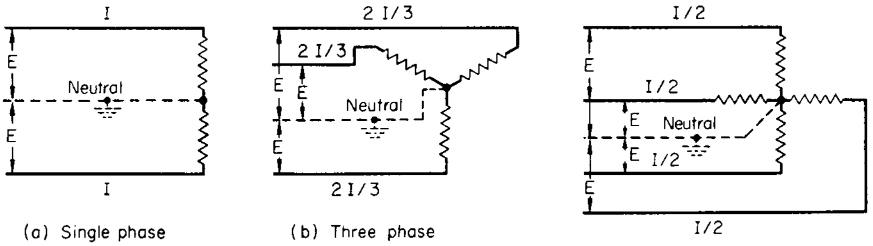
**Vacuum circuit breakers** have received wide acceptance in all fields in recent years, both for indoor work and for outdoor applications. Indoor breakers are available up to 40 kV and interrupting capacities up to 2.5 GVA. Outdoor breakers are available in ratings up to that of the EHV (extra-high voltage 765-kV three-pole breaker capable of interrupting 55 GVA, or 40,000-A symmetrical current. Its operating rating is 3,000 A, 765 kV. The arc is extinguished in a vacuum. Switching stations, gas-insulated and operating at 550 kV, are also in use.

## POWER TRANSMISSION

Power for long-distance transmission is usually generated at 6,600, 13,200, and 18,000 V and is stepped up to the transmission voltage by $\Delta$-Y-connected transformers. The transmission voltage is roughly 1,000 V/mi. Preferred or standard transmission voltages are 22, 33, 44, 66, 110, 132, 154, 220, 287, 330, 500, and 765 kV. High-voltage lines across country are located on private rights of way. When they reach urban areas, the power must be carried underground to the substations which must be located near the load centers in the thickly settled districts. In many cases it is possible to go directly to underground cables since these are now practicable up to 345 kV between three-phase line conductors (200 kV to ground). High-voltage cables are expensive in both first cost and maintenance, and it may be more economical to step down the voltage before transmitting the power by underground cables. Within a city, alternating current may be distributed from a substation at 13,200, 6,600, or 2,300 V, being stepped down to 600, 480, and 240 V, three-phase for power and 240 to 120 V single-phase three-wire for lights, by transformers at the consumers' premises. **Direct current** at 1,200 or 600 V for railways, 230 to 115 V for lighting and power, is supplied by motor-generator sets, synchronous converters, and rectifiers. **Constant current** for series street-lighting systems is obtained through constant-current transformers.

### Transmission Systems

Power is almost always transmitted three-phase. The following fundamental relations apply to any transmission system. The weight of conductor required to transmit power by any given system with a given percentage power loss varies directly with the power, directly as the square of the distance, and inversely as the square of the voltage. The cross-sectional area of the conductors with a given percentage power



(a) Single phase
P = 2EI
R ohms, ea. condr.

(b) Three phase
P = 2EI
3/2 R ohms, ea. condr.

(c) Four phase
P = 2EI
2 R ohms, ea. condr.

**Fig. 15.1.80** Three equivalent symmetrical transmission, or distribution, systems. (*a*) Single-phase; (*b*) three-phase; (*c*) four-phase.

loss varies directly with the power, directly with the distance, and inversely as the square of the voltage.

For two systems of the same length transmitting the same power at different voltages and with the same power loss for both systems, the cross-sectional area and weight of the conductors will vary inversely as the square of the voltages. The foregoing relations between the cross section or weight of the conductor and transmission distance and voltage hold for all systems, whether dc, single-phase, three-phase, or four-phase. With the power, distance, and power loss fixed, all symmetrical systems having equal voltages to neutral require equal weights of conductor. Thus, the three symmetrical systems shown in Fig. 15.1.80 all deliver the same power, have the same power loss and equal voltages to neutral, and the transmission distances are all assumed to be equal. They all require the same weight of conductor since the weights are inversely proportional to all resistances. (No actual neutral conductor is used.) The respective power losses are (1) $2I^2R$ W; (2) $3(2I/3)^2(3R/2) = 2I^2R$ W; (3) $4(I/2)^2(2R) = 2I^2R$ W, which are all equal.

**Size of Transmission Conductor** Kelvin's law states, "The most economical area of conductor is that for which the annual cost of energy wasted is equal to the interest on that portion of the capital outlay which can be considered proportional to the weight of copper used." In Fig. 15.1.81 are shown the annual interest cost, the annual cost of $I^2R$ loss, and the total cost as functions of circular mils cross section for both typical overhead conductors and three-conductor cables. Note that the total-cost curves have very flat minimums, and usually other factors such as the character of the load and the voltage regulation, are taken into consideration.

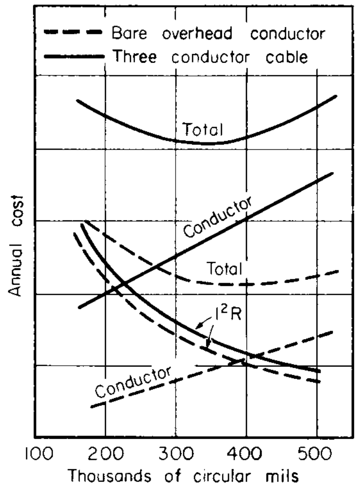


**Fig. 15.1.81** Most economical sizes of overhead and underground conductors.

In addition to resistance, overhead power lines have inductive reactance to alternating currents. The inductive reactance

$$X = 2\pi f\{80 + 741.1 \log [(D - r)/r]\}\ 10^{-6} \quad \Omega/\text{conductor mile} \qquad (15.1.126)$$

where $f$ = frequency, $D$ = distance between centers of conductors (in), and $r$ their radius (in). Table 15.1.16 gives the inductive reactance per mile at 60 Hz and the resistance of stranded and solid copper conductor. (See Table 15.1.20.)

Any **symmetrical system** having $n$ conductors can be divided into $n$ equal single-phase systems, each consisting of one wire and a return circuit of zero impedance and each having as its voltage the system voltage to neutral.

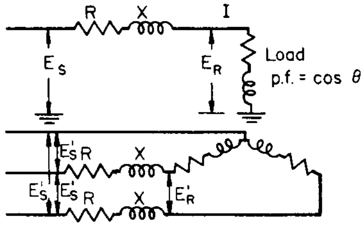


**Fig. 15.1.82** Three-phase power system.

Figure 15.1.82 shows a symmetrical three-phase system, with one phase detached. The load or received voltage between line conductors is $E'_R$ so that the receiver voltage to *neutral* is $E_R = E'_R/\sqrt{3}$V. The current is $I$ A, the load power factor is cos $\theta$, and the line resistance and reactance are $R$ and $X$ Ω per wire, and the sending-end voltage is $E_S$. The phasor diagram is shown in Fig. 15.1.83 (compare with Fig. 15.1.63). Its solution is

$$E_S = \sqrt{(E_R \cos\theta + IR)^2 + (E_R \sin\theta + IX)^2} \qquad (15.1.127)$$

[see Eq. (15.1.101)].

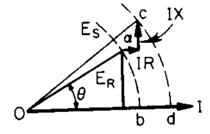


**Fig. 15.1.83** Phasor diagram for a power line.

Figure 15.1.84 (Mershon diagram) shows the right-hand portion of Fig. 15.1.83 plotted to large scale, the arc 00 corresponding to the arc *ab* (Fig. 15.1.83). The abscissa 0 (Fig. 15.1.84) corresponds to point *b* (Fig. 15.1.83) and is the load voltage $E_R$ taken as 100 percent. The concentric circular arcs 0–40 are given in percentage of $E_R$. To find the sending-

**Table 15.1.16 Resistance and Inductive Reactance per Single Conductor**

| Hard-drawn copper, stranded | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 60 Hz | | | | | | | | | | | | |
| | | | | Spacing, ft | | | | | | | | | | | | |
| Size, cir mils or AWG | No. of strands | OD, in | Resistance, Ω/mi | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 10 | 12 | 15 | 20 | 30 |
| 500,000 | 37 | 0.814 | 0.1130 | 0.443 | 0.527 | 0.576 | 0.611 | 0.638 | 0.660 | 0.679 | 0.695 | 0.722 | 0.745 | 0.772 | 0.807 | 0.856 |
| 400,000 | 19 | 0.725 | 0.1426 | 0.458 | 0.542 | 0.591 | 0.626 | 0.653 | 0.675 | 0.694 | 0.710 | 0.737 | 0.760 | 0.787 | 0.822 | 0.871 |
| 300,000 | 19 | 0.628 | 0.1900 | 0.476 | 0.560 | 0.609 | 0.644 | 0.671 | 0.693 | 0.712 | 0.728 | 0.755 | 0.778 | 0.805 | 0.840 | 0.889 |
| 250,000 | 19 | 0.574 | 0.2278 | 0.487 | 0.571 | 0.620 | 0.655 | 0.682 | 0.704 | 0.723 | 0.739 | 0.766 | 0.789 | 0.816 | 0.851 | 0.900 |
| 0000 | 19 | 0.528 | 0.2690 | 0.497 | 0.581 | 0.630 | 0.665 | 0.692 | 0.714 | 0.733 | 0.749 | 0.776 | 0.799 | 0.826 | 0.861 | 0.917 |
| 000 | 7 | 0.464 | 0.339 | 0.518 | 0.602 | 0.651 | 0.686 | 0.713 | 0.735 | 0.754 | 0.770 | 0.797 | 0.820 | 0.847 | 0.882 | 0.931 |
| 00 | 7 | 0.414 | 0.428 | 0.532 | 0.616 | 0.665 | 0.700 | 0.727 | 0.749 | 0.768 | 0.784 | 0.811 | 0.834 | 0.861 | 0.896 | 0.945 |
| 0 | 7 | 0.368 | 0.538 | 0.546 | 0.630 | 0.679 | 0.714 | 0.741 | 0.763 | 0.782 | 0.798 | 0.825 | 0.848 | 0.875 | 0.910 | 0.959 |
| Hard-drawn copper, solid | | | | | | | | | | | | | | | | |
| 0000 | — | 0.4600 | 0.264 | 0.510 | 0.594 | 0.643 | 0.678 | 0.705 | 0.727 | 0.746 | 0.762 | 0.789 | 0.812 | 0.839 | 0.874 | 0.923 |
| 000 | — | 0.4096 | 0.333 | 0.524 | 0.608 | 0.657 | 0.692 | 0.719 | 0.741 | 0.760 | 0.776 | 0.803 | 0.826 | 0.853 | 0.888 | 0.937 |
| 00 | — | 0.3648 | 0.420 | 0.538 | 0.622 | 0.671 | 0.706 | 0.733 | 0.755 | 0.774 | 0.790 | 0.817 | 0.840 | 0.867 | 0.902 | 0.951 |
| 0 | — | 0.3249 | 0.528 | 0.552 | 0.636 | 0.685 | 0.720 | 0.747 | 0.769 | 0.788 | 0.804 | 0.831 | 0.854 | 0.881 | 0.916 | 0.965 |
| 1 | — | 0.2893 | 0.665 | 0.566 | 0.650 | 0.699 | 0.734 | 0.761 | 0.783 | 0.802 | 0.818 | 0.845 | 0.868 | 0.895 | 0.930 | 0.979 |

end voltage $E_S$ for any power factor cos $\theta$, compute first the resistance drop $IR$ and the reactance drop $IX$ in percentage of $E_R$. Then follow the ordinate corresponding to the load power factor to the inner arc 00 (*a*, Fig. 15.1.83). Lay off the percentage $IR$ drop horizontally to the right, and the percentage $IX$ drop vertically upward. The arc at which the $IX$ drop terminates (*c*, Fig. 15.1.83) when added to 100 percent gives the sending-end voltage $E_S$ in percent of the load voltage $E_R$.

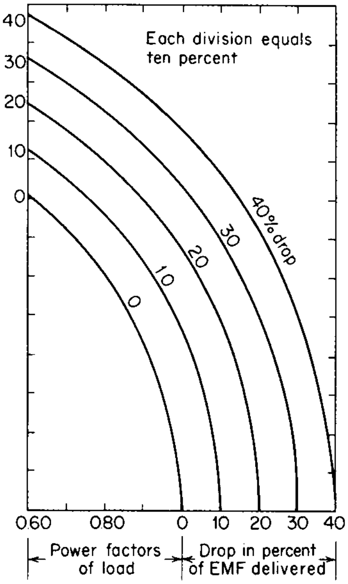


**Fig. 15.1.84** Mershon diagram for determining voltage drop in power lines.

EXAMPLE. Let it be desired to transmit 20,000 kW three-phase 80 percent power factor lagging current, a distance of 60 mi. The voltage at the receiving end is 66,000 V, 60 Hz and the line loss must not exceed 10 percent of the power delivered. The conductor spacing must be 7 ft (84 in). Determine the sending-end voltage and the actual efficiency. $I = 20{,}000{,}000/(66{,}000 \times 0.80 \times \sqrt{3}) = 218.8$ A. $3 \times 218.8^2 \times R' = 0.10 \times 20{,}000{,}000$. $R' = 13.9\ \Omega = 0.232\ \Omega$/mi. By referring to Table 13.1.16, 250,000 cir mils copper having a resistance of 0.2278 Ω/mi may be used. The total resistance $R = 60 \times 0.2278 = 13.67\ \Omega$. The reactance $X = 60 \times 0.723 = 43.38\ \Omega$. The volts to neutral at the load, $E_R = 66{,}000/\sqrt{3} = 38{,}100$ V. cos $\theta = 0.80$; sin $\theta = 0.60$. Using Eq. (15.1.127), $E_S = \{[(38{,}100 \times 0.80) + (218.8 \times 13.67)]^2 + [(38{,}100 \times 0.60) + (218.8 \times 43.38)]^2\}^{1/2} = 46{,}500$ V to neutral or $\sqrt{3} \times 46{,}500 = 80{,}500$ between lines at the sending end. The line loss is $3(218.8)^2 \times 13.67 = 1{,}963$ kW. The efficiency $\eta = 20{,}000/(20{,}000 + 1{,}963) = 0.911$, or 91.1 percent. This same line is solved by means of the Mershon diagram as follows. Let $E_R = 38{,}100\ \text{V} = 100$ percent. $IR = 218.8 \times 13.67 = 2{,}991\ \text{V} = 7.85$ percent. $IX = 218.8 \times 43.38 = 9{,}490\ \text{V} = 24.9$ percent. Follow the 0.80 power-factor ordinate (Fig. 15.1.84) to its intersection with the arc 00; from this point go 7.85 percent horizontally to the right and then 24.9 percent vertically. (These percentages are measured on the horizontal scale.) This last distance terminates on the 22.5 percent arc. The sending-end voltage to neutral is then $1.225 \times 38{,}100 = 46{,}500$ V, so that the sending-end voltage between line conductors is $E'_S = 46{,}500\sqrt{3} = 80{,}530$ V.

In Table 15.1.16 the spacing is the distance between the centers of the two conductors of a single-phase system or the distance between the centers of each pair of conductors of a three-phase system if they are equally spaced. If they are not equally spaced, the geometric mean distance (*GMD*) is used, where $GMD = \sqrt[3]{D_1 D_2 D_3}$ (Fig. 15.1.85*a*). With the flat horizontal spacing shown in Fig. 15.1.85*b*, $GMD = \sqrt[3]{2D^3} = 1.26D$.

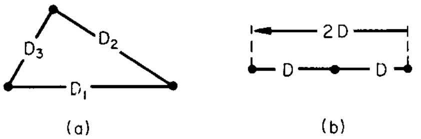


**Fig. 15.1.85** Unequal spacing of three-phase conductors. (*a*) GMD = $(D_1 D_2 D_3)^{1/3}$; (*b*) flat horizontal spacing; GMD = 1.26 *D*.

In addition to copper, aluminum cable steel-reinforced (ACSR), Table 15.1.17, is used for transmission conductor. For the same resistance it is lighter than copper, and with high voltages the larger diameter reduces corona loss.

Until 1966, 345 kV was the highest operating voltage in the United States. The first 500 kV system put into operation (1966) was a 350-mi transmission loop of the Virginia Electric and Power Company; the longest transmission distance was 170 mi. The towers, about 94 ft high,

**Table 15.1.17 Properties of Aluminum Cable Steel-Reinforced (ACSR)**

| Cir mils or AWG | | No. of wires | | | Cross section, in² | | | Ω/mi of single conductor at 25°C | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | 200 A | | 600 A | |
| Aluminum | Copper equivalent | Aluminum | Steel | OD, in | Aluminum | Total | Total lb/mi | 0 A dc | 25 Hz | 60 Hz | 25 Hz | 60 Hz |
| 1,590,000 | 1,000,000 | 54 | 19 | 1.545 | 1.249 | 1.4071 | 10,777 | 0.0587 | 0.0589 | 0.0594 | 0.0592 | 0.0607 |
| 1,431,000 | 900,000 | 54 | 19 | 1.465 | 1.124 | 1.2664 | 9,699 | 0.0652 | 0.0654 | 0.0659 | 0.0657 | 0.0671 |
| 1,272,000 | 800,000 | 54 | 19 | 1.382 | 0.9990 | 1.1256 | 8,621 | 0.0734 | 0.0736 | 0.0742 | 0.0738 | 0.0752 |
| 1,192,500 | 750,000 | 54 | 19 | 1.338 | 0.9366 | 1.0553 | 8,082 | 0.0783 | 0.0785 | 0.0791 | 0.0787 | 0.0801 |
| 1,113,000 | 700,000 | 54 | 19 | 1.293 | 0.8741 | 0.9850 | 7,544 | 0.0839 | 0.0841 | 0.0848 | 0.0843 | 0.0857 |
| 1,033,500 | 650,000 | 54 | 7 | 1.246 | 0.8117 | 0.9170 | 7,019 | 0.0903 | 0.0906 | 0.0913 | 0.0908 | 0.0922 |
| 954,000 | 600,000 | 54 | 7 | 1.196 | 0.7493 | 0.8464 | 6,479 | 0.0979 | 0.0980 | 0.0985 | 0.0983 | 0.0997 |
| 874,500 | 550,000 | 54 | 7 | 1.146 | 0.6868 | 0.7759 | 5,940 | 0.107 | 0.107 | 0.108 | 0.107 | 0.109 |
| 795,000 | 500,000 | 26 | 7 | 1.108 | 0.6244 | 0.7261 | 5,770 | 0.117 | 0.117 | 0.117 | 0.117 | 0.117 |
| 715,500 | 450,000 | 54 | 7 | 1.036 | 0.5620 | 0.6348 | 4,859 | 0.131 | 0.131 | 0.133 | 0.131 | 0.133 |
| 636,000 | 400,000 | 54 | 7 | 0.977 | 0.4995 | 0.5642 | 4,319 | 0.147 | 0.147 | 0.149 | 0.147 | 0.149 |
| 556,500 | 350,000 | 26 | 7 | 0.927 | 0.4371 | 0.5083 | 4,039 | 0.168 | 0.168 | 0.168 | 0.168 | 0.168 |
| 477,000 | 300,000 | 26 | 7 | 0.858 | 0.3746 | 0.4357 | 3,462 | 0.196 | 0.196 | 0.196 | 0.196 | 0.196 |
| 397,500 | 250,000 | 26 | 7 | 0.783 | 0.3122 | 0.3630 | 2,885 | 0.235 | 0.235 | 0.235 | 0.235 | 0.235 |
| 336,400 | 0000 | 26 | 7 | 0.721 | 0.2642 | 0.3073 | 2,442 | 0.278 | 0.278 | 0.278 | 0.278 | 0.278 |
| 266,800 | 000 | 26 | 7 | 0.642 | 0.2095 | 0.2367 | 1,936 | 0.350 | 0.350 | 0.350 | 0.350 | 0.350 |
| 0000 | 00 | 6 | 1 | 0.563 | 0.1662 | 0.1939 | 1,542 | 0.441 | 0.443 | 0.446 | 0.447 | 0.464 |
| 000 | 0 | 6 | 1 | 0.502 | 0.1318 | 0.1537 | 1,223 | 0.556 | 0.557 | 0.561 | 0.562 | 0.579 |
| 00 | 1 | 6 | 1 | 0.447 | 0.1045 | 0.1219 | 970 | 0.702 | 0.703 | 0.707 | 0.706 | 0.718 |
| 0 | 2 | 6 | 1 | 0.398 | 0.0829 | 0.0967 | 769 | 0.885 | 0.885 | 0.889 | 0.887 | 0.893 |

SOURCE: Aluminum Co. of America.

are of corrosion-resistant steel, and the conductors are 61-strand cables of aluminum alloy, rather than the usual aluminum cable with a steel core (ACSR). The conductor diameter is 1.65 in with two ''bundled'' conductors per phase and 18-in spacing. The standard span is 1,600 ft, the conductor spacing is flat with 30-ft spacing between phase-conductor centers, and the minimum clearance to ground is 34 to 39 ft. To maintain a minimum clearance of 11 ft to the towers and 30 ft spacing between phases, vee insulator strings, each consisting of twenty-four 10-in disks, are used with each phase. The highest EHV system in North American is the 765-kV system in the midwest region of the United States. A dc transmission line on the west coast of the United States operating at ± 450 kV is transmitting power in bulk more than 800 miles.

**High-voltage dc transmission** has a greater potential for savings and a greater ability to transmit large blocks of power longer distances than has three-phase transmission. For the same crest voltage there is a saving of 50 percent in the weight of the conductor. Because of the power stability limit due to inductive and capacitive effects (inherent with ac transmission), the ability to transmit large blocks of power long distances has not kept pace with power developments, even at the present highest ac transmission voltage of 765 kV. With direct current there is no such power stability limit.

Where cables are necessary, as under water, the capacitive charging current may, with alternating current become so large that it absorbs a large proportion, if not all, of the cable-carrying capability. For example, at 132 kV, three-phase (76 kV to ground), with a 500 MCM cable, at 36 mi, the charging current at 60 Hz is equal to the entire cable capability so that no capability remains for the load current. With direct current there is no charging current, only the negligible leakage current, and there are no ac dielectric losses. Furthermore, the dc voltage at which a given cable can operate is twice the ac voltage.

The high dc transmission voltage is obtained by converting the ac power voltage to direct current by means of mercury-arc rectifiers; at the receiving end of the line the dc voltage is inverted back to a power-frequency voltage by means of mercury-arc inverters. The maximum dc transmission voltage in use in the United States, as of 1994, is 500 kV.

Alternating to direct to alternating current is nonsynchronous transmission of electric power. It can be overhead or under the surface. In the early 1970s the problem of bulk electric-power transmission over high-voltage transmission lines above the surface developed the insistent discussion of land use and environmental cost.

While the maximum ac transmission voltage in use in the United States (1994) is 765 kV, ultrahigh voltage (UHV) is under consideration. Transmission voltages of 1,200 to 2,550 kV are being tested presently. The right-of-way requirements for power transmission are significantly reduced at higher voltages. For example, in one study the transmission of 7,500 MVA at 345 kV ac was found to require 14 circuits on a corridor 725 ft (221.5 m) wide, whereas a single 1,200-kV ac circuit of 7,500-MVA capacity would need a corridor 310 ft (91.5 m) wide.

Continuing research and development efforts may result in the development of more economic high-voltage underground transmission links. Sufficient bulk power transmission capability would permit **power wheeling,** i.e., the use of generating capacity to the east and west to serve a given locality as the earth revolves and the area of peak demand glides across the countryside.

**Corona** is a reddish-blue electrical discharge which occurs when the voltage-gradient in air exceeds 30 kV peak, 21.1 kV rms, at 76 cm pressure. This electrical discharge is caused by ionization of the air and becomes more or less concentrated at irregularities on the conductor surface and on the outer strands of stranded conductors. Corona is accompanied by a hissing sound; it produces ozone and, in the presence of moisture, nitrous acid. On high-voltage lines corona produces a substantial power loss, corrosion of the conductors, and radio and television interference. The fair-weather loss increases as the square of the voltage above a critical value $e_0$ and is greatly increased by fog, smoke, rainstorms, sleet, and snow (see Fig. 15.1.86). To reduce corona, the diameter of high-voltage conductors is increased to values much greater than would be required for the necessary conductance cross section. This is accomplished by the use of hollow, segmented conductors and by the use of aluminum cable, steel-reinforced (ACSR), which often has inner layers of jute to increase the diameter. In extra-high-voltage lines (400 kV and greater), corona is reduced by the use of bundled conductors in which each phase consists of two or three conductors spaced about 16 in (0.41 m) from one another.

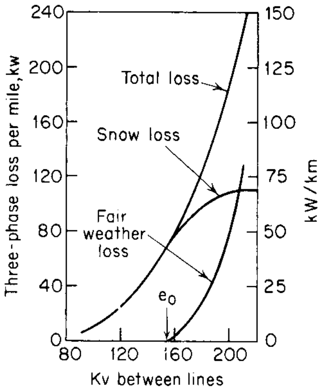


**Fig. 15.1.86** Corona loss with snowstorm.

### Underground Power Cables

Insulations for power cables include heat-resisting, low-water-absorptive synthetic rubber compounds, varnished cloth, impregnated paper, cross-linked polyethylene thermosetting compounds, and thermoplastics such as polyvinyl chloride (PVC) and polyethylene (PE) compounds (see Sec. 6).

Properly chosen **rubber-insulated cables** may be used in wet locations with a nonmetallic jacket for protective covering instead of a metallic sheath. Commonly used jackets are flame-resisting, such as neoprene and PVC. Such cables are relatively light in weight, easy to train in ducts and manholes, and easily spliced. When distribution voltages exceed 2,000 V phase to phase, an ozone-resisting type of compound is required. Such rubber insulation may be used in cables carrying up to 28,000 V between lines in three-phase grounded systems. The insulation wall will be thicker than with varnished cloth, polyethylene, ethylene propylene rubber, or paper.

**Varnished-cloth cables** are made by applying varnish-treated closely woven cloth in the form of tapes, helically, to the metallic conductor. Simultaneously a viscous compound is applied between layers which fills in any voids at laps in the taping and imparts flexibility when the cable is bent by permitting movement of one tape upon another. This type of insulation has higher dielectric loss than impregnated paper but is suitable for the transmission of power up to 28,000 V between phases over short distances. Such insulated cables may be used in dry locations with flame-resisting fibrous braid, reinforced neoprene tape, or PVC jacket and are often further protected with an interlocked metallic tape armor; but in wet locations these cables should be protected by a continuous metallic sheath such as lead or aluminum. Since varnish-cloth-insulated cable has high ozone resistance, heat resistance, and impulse strength, it is well adapted for station or powerhouse wiring or for any service where the temperature is high or where there are sudden increases in voltage for short periods. Since the varnish is not affected by mineral oils, such cables make excellent leads for transformers and oil switches.

**PVC** is readily available in several fast, bright colors and is often chosen for color-coded multiconductor control cables. It has inherent flame and oil resistance, and as single conductor wire and cable with the proper wall thickness for a particular application, it usually does not need any outside protective covering. On account of its high dielectric constant and high power factor, its use is limited to low voltages, i.e., under 1,000 V, except for series lighting circuits.

**Table 15.1.18 Ampacities of Insulated Cables in Underground Raceways**

[Based on conductor temperature of 90°C, ambient earth temperature of 20°C, 100 percent load factor, thermal resistance (RHO) of 90, and three circuits in group]

| Conductor size, AWG or MCM | Copper | | | | Aluminum | | | |
|---|---|---|---|---|---|---|---|---|
| | 3-1/C cables per raceway | | 1-3/C cable per raceway | | 3-1/C cables per raceway | | 1-3/C cable per raceway | |
| | 2,001–5,000-V ampacity | 5,001–35,000-V ampacity | 2,001–5,000-V ampacity | 5,001–35,000-V ampacity | 2,001–5,000-V ampacity | 5,001–35,000-V ampacity | 2,001–5,000-V ampacity | 5,001–35,000-V ampacity |
| 8 | 56 | | 53 | | 44 | | 41 | |
| 6 | 73 | 77 | 69 | 75 | 57 | 60 | 54 | 59 |
| 4 | 95 | 99 | 89 | 97 | 74 | 77 | 70 | 75 |
| 2 | 125 | 130 | 115 | 125 | 96 | 100 | 90 | 100 |
| 1 | 140 | 145 | 135 | 140 | 110 | 110 | 105 | 110 |
| 1/0 | 160 | 165 | 150 | 160 | 125 | 125 | 120 | 125 |
| 2/0 | 185 | 185 | 170 | 185 | 145 | 145 | 135 | 140 |
| 3/0 | 210 | 210 | 195 | 205 | 160 | 165 | 155 | 160 |
| 4/0 | 235 | 240 | 225 | 230 | 185 | 185 | 175 | 180 |
| 250 | 260 | 260 | 245 | 255 | 205 | 200 | 190 | 200 |
| 350 | 315 | 310 | 295 | 305 | 245 | 245 | 230 | 240 |
| 500 | 375 | 370 | 355 | 360 | 295 | 290 | 280 | 285 |
| 750 | 460 | 440 | 430 | 430 | 370 | 355 | 345 | 350 |
| 1,000 | 525 | 495 | 485 | 485 | 425 | 405 | 400 | 400 |

NOTE: This is a general table. For other temperatures and installation conditions, see NFPA 70, 1993, National Electrical Code, Tables 77 through 80 and associated notes.

**Polyethylene,** because of its excellent electrical characteristics, first found use when it was adapted especially for high-frequency cables used in radio and radar circuits; for certain telephone, communication, and signal cables; and for submarine cables. Submarine telephone cables with built-in repeaters laid first in the Atlantic Ocean and then in the Pacific are insulated with polyethylene. Because of polyethylene's thermal characteristics, the standard maximum conductor operating temperature is 75°C. It is commonly used for power cables (including large use for underground residential distribution), with transmissions up to 15,000 V. Successful installations have been in service at 46 kV and some at 69 kV. The upper limit has not been reached, inasmuch as work is in progress on higher-voltage polyethylene power cables as a result of advancements in the art of compounding.

**Cross-linked polyethylene** is another insulation which is gaining in favor in the process field. For power cable insulations, the cross-linking process is most commonly obtained chemically. It converts polyethylene from a thermoplastic into a thermosetting material; the result is a compound with a unique combination of properties, including resistance to heat and oxidation, thus permitting an increase in maximum conductor operating temperature to 90°C. The service record with this compound has been good at voltages which have been gradually increased to 35 kV. Another thermosetting material, ethylene propylene rubber (EPR), has found wide acceptance in the 5- to 35-kV range.

**Impregnated-paper insulation** is used for very-high-voltage cables whose range has been extended to 345 kV. To eliminate the detrimental effects of moisture and to maintain proper impregnation of the paper, such cables must have a continuous metallic sheath such as lead or aluminum or be enclosed within a steel pipe; the operation of the cable depends absolutely on the integrity of that enclosure. In three-conductor belted-type cables the individual insulated conductors are surrounded by a belt or wall of impregnated paper over which the lead sheath is applied. When all three conductors are within one sheath, their inductive effects practically neutralize one another and eddy-current loss in the sheath is negligible. In the type-H cable, each of the individual conductors is surrounded with a perforated metallic covering, either aluminum foil backed with a paper tape or thin perforated metal tapes wound over the paper. All three conductors are then enclosed within the metal sheath. The metallic coverings being grounded electrically, each conductor acts as a single-conductor cable. This construction eliminates ''tangential'' stresses within the insulation and reduces pockets or voids. When paper tapes are wound on the conductor, impregnated with an oil or a petrolatum compound, and covered with a lead sheath, they are called **solid type**.

Three-conductor cables are now operating at 33,000 V, and single-conductor cables at 66,000 V between phases (38,000 V to ground). In New York and Chicago, special hollow-conductor oil-filled single-conductor cables are operating successfully at 132,000 V (76,000 V to ground). In France, cables are operating at 345 kV between conductors.

Other methods of installing underground cables are to draw them into steel pipes, usually without the sheaths, and to fill the pipes with oil under pressure (**oilstatic**) or **nitrogen** under 200 lb pressure. The ordinary medium-high-voltage underground cables are usually drawn into duct lines. With a straight run and ample clearance the length of cable between manholes may reach 600 to 1,000 ft. Ordinarily, the distance is more nearly 400 to 500 ft. With bends of small radius the distance must be further reduced.

**Cable ratings** are based on the permissible operating temperatures of the insulation and environmental installation conditions. See Table 15.1.18 for ampacities.

## POWER DISTRIBUTION

**Distribution Systems** The choice of the system of power distribution is determined by the type of power that is available and by the nature of the load. To transmit a given power over a given distance with a given power loss ($I^2R$), the weight of conductor varies inversely as the square of the voltage. Incandescent lamps will not operate economically at voltages much higher than 120 V; the most suitable voltages for dc motors are 230, 500, and 550 V; for ac motors, standard voltages are 230, 460, and 575 V, three-phase. When power for lighting is to be distributed in a district where the consumers are relatively far apart, alternating current is used, being distributed at high voltage (2,400, 4,160, 4,800, 6,900, and 13,800 V) and transformed at the consumer's premises, or by transformers on poles or located in manholes or vaults under the street or sidewalks, to 240/120 V three-wire for lighting and domestic customers, and to 208, 240, 480, and 600 volts, three-phase, for power.

The first central station power systems were built with dc generation and distribution. The economical transmission distance was short. Densely populated, downtown areas of cities were therefore the first sections to be served. Growth of electric service in the United States was phenomenal in the last two decades of the nineteenth century. After 1895 when ac generation was selected for the development of power from Niagara Falls, the expansion of dc distribution diminished. The economics overwhelmingly favored the new ac system.

Direct current service is still available in small pockets in some cities. In those cases, ac power is generated, transmitted, and distributed. The conversion to dc takes place in rectifiers installed in manholes near the load or in the building to be served. Some dc customers resist the change to ac service because of their need for motor speed control. Elevator and printing press drives and some cloth-cutting knives are examples of such needs. (See Low-Voltage AC Network.)

**Series Circuits** These **constant-current** circuits were widely used for **street lighting**. The voltage was automatically adjusted to match the number of lamps in series and maintain a constant current. With the advent of **HID lamps** and individual **photocells** on street lighting fixtures which require parallel circuitry, this system fell into disuse and is rarely seen.

**Parallel Circuits** **Power** is usually distributed at **constant potential,** and all the devices or receivers in the circuit are connected in parallel, giving a constant-potential system, Fig. 15.1.87*a*. If conductors of constant cross section are used and all the loads, $L_1$, $L_2$, etc., are operating, there will be a greater voltage *IR* drop per unit length of wire in the portion of the circuit *AB* and *CD* than in the other portions; also the voltage will not be the same for the different lamps but will decrease along the mains with distance from the generating end.

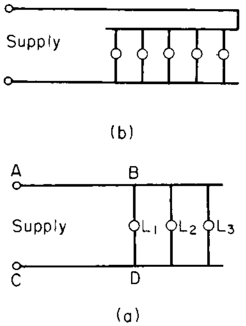


**Fig. 15.1.87** (*a*) Parallel circuit; (*b*) loop circuit.

**Loop Circuits** A more nearly equal voltage for each load is obtained in the loop system, Fig. 15.1.87*b*. The electrical distance from one generator terminal to the other through any receiver is the same as that through any other receiver, and the voltage at the receivers may be maintained more nearly equal, but at the expense of additional conductor material.

**Series-Parallel Circuit** For incandescent lamps the power must be at low voltage (115 V) and the voltage variations must be small. If the transmission distance is considerable or the loads are large, a large or perhaps prohibitive investment in conductor material would be necessary. In some special cases, lamps may be operated in groups of two in series as shown in Fig. 15.1.88. The transmitting voltage is thus doubled, and, for a given number of lamps, the current is halved, the permissible voltage drop (*IR*) in conductors doubled, the conductor resistance quadrupled, the weight of conductor material thus being reduced to 25 percent of that necessary for simple parallel operation.

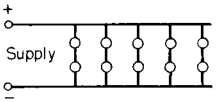


**Fig. 15.1.88** Series-parallel system.

**Three-Wire System** In the series-parallel system the loads must be used in pairs and both units of the pair must have the same power rating. To overcome these objections and at the same time to obtain the economy in conductor material of operating at higher voltage, the three-wire system is used. It consists merely of adding a third wire or neutral to the system of Fig. 15.1.88 as shown in Fig. 15.1.89.

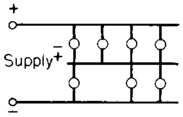


**Fig. 15.1.89** Three-wire system.

If the neutral wire is of the same cross section as the two outer wires, this system requires only 37.5 percent of the copper required by an equivalent two-wire system. Since the neutral ordinarily carries less current than the outers, it is usually smaller and the ratio of copper to that of the two-wire system is even less than 37.5 percent (see Table 15.1.19).

When the loads on each half of the system are equal, there will be no

**Table 15.1.19 Resistance and 60-Hz Reactance for Wires with Small Spacings, Ω, at 20°C**
(See also Table 15.1.16.)

| AWG and size of wire, cir mils | Resistance in 1,000 ft of line (2,000 ft of wire), copper | Reactance in 1,000 ft of line (2,000 ft of wire) at 60 Hz for the distance given in inches between centers of conductors | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | ½ | 1 | 2 | 3 | 4 | 5 | 6 | 9 | 12 | 18 | 24 |
| 14– 4,107 | 5.06 | 0.138 | 0.178 | 0.218 | 0.220 | 0.233 | 0.244 | 0.252 | 0.271 | 0.284 | 0.302 | |
| 12– 6,530 | 3.18 | 0.127 | 0.159 | 0.190 | 0.210 | 0.223 | 0.233 | 0.241 | 0.260 | 0.273 | 0.292 | |
| 10– 10,380 | 2.00 | 0.116 | 0.148 | 0.180 | 0.199 | 0.212 | 0.223 | 0.231 | 0.249 | 0.262 | 0.281 | |
| 8– 16,510 | 1.26 | 0.106 | 0.138 | 0.169 | 0.188 | 0.201 | 0.212 | 0.220 | 0.238 | 0.252 | 0.270 | 0.284 |
| 6– 26,250 | 0.790 | 0.095 | 0.127 | 0.158 | 0.178 | 0.190 | 0.201 | 0.209 | 0.228 | 0.241 | 0.260 | 0.272 |
| 4– 41,740 | 0.498 | 0.085 | 0.117 | 0.149 | 0.167 | 0.180 | 0.190 | 0.199 | 0.217 | 0.230 | 0.249 | 0.262 |
| 2– 66,370 | 0.312 | 0.074 | 0.106 | 0.138 | 0.156 | 0.169 | 0.180 | 0.188 | 0.206 | 0.220 | 0.238 | 0.252 |
| 1– 83,690 | 0.248 | 0.068 | 0.101 | 0.132 | 0.151 | 0.164 | 0.174 | 0.183 | 0.201 | 0.214 | 0.233 | 0.246 |
| 0–105,500 | 0.196 | 0.063 | 0.095 | 0.127 | 0.145 | 0.159 | 0.169 | 0.177 | 0.196 | 0.209 | 0.228 | 0.241 |
| 00–133,100 | 0.156 | 0.057 | 0.090 | 0.121 | 0.140 | 0.153 | 0.164 | 0.172 | 0.190 | 0.204 | 0.222 | 0.236 |
| 000–167,800 | 0.122 | 0.052 | 0.085 | 0.116 | 0.135 | 0.148 | 0.158 | 0.167 | 0.185 | 0.199 | 0.217 | 0.230 |
| 0000–211,600 | 0.098 | 0.046 | 0.079 | 0.111 | 0.130 | 0.143 | 0.153 | 0.161 | 0.180 | 0.193 | 0.212 | 0.225 |
| 250,000 | 0.085 | — | 0.075 | 0.106 | 0.125 | 0.139 | 0.148 | 0.157 | 0.175 | 0.189 | 0.207 | 0.220 |
| 300,000 | 0.075 | — | 0.071 | 0.103 | 0.120 | 0.134 | 0.144 | 0.153 | 0.171 | 0.185 | 0.203 | 0.217 |
| 350,000 | 0.061 | — | 0.067 | 0.099 | 0.188 | 0.128 | 0.141 | 0.149 | 0.168 | 0.182 | 0.200 | 0.213 |
| 400,000 | 0.052 | — | 0.064 | 0.096 | 0.114 | 0.127 | 0.138 | 0.146 | 0.165 | 0.178 | 0.197 | 0.209 |
| 500,000 | 0.042 | — | — | 0.090 | 0.109 | 0.122 | 0.133 | 0.141 | 0.160 | 0.172 | 0.192 | 0.202 |
| 600,000 | 0.035 | — | — | 0.087 | 0.106 | 0.118 | 0.128 | 0.137 | 0.155 | 0.169 | 0.187 | 0.200 |
| 700,000 | 0.030 | — | — | 0.083 | 0.102 | 0.114 | 0.125 | 0.133 | 0.152 | 0.165 | 0.184 | 0.197 |
| 800,000 | 0.026 | — | — | 0.080 | 0.099 | 0.112 | 0.122 | 0.130 | 0.148 | 0.162 | 0.181 | 0.194 |
| 900,000 | 0.024 | — | — | 0.077 | 0.096 | 0.109 | 0.119 | 0.127 | 0.146 | 0.159 | 0.178 | 0.191 |
| 1,000,000 | 0.022 | — | — | 0.075 | 0.094 | 0.106 | 0.117 | 0.125 | 0.144 | 0.158 | 0.176 | 0.188 |

NOTE: For other frequencies the reactance will be in direct proportion to the frequency.

current in the middle or neutral wire, and the condition is the same as that shown in Fig. 15.1.88. When the loads on the two sides are unequal, there will be a current in the neutral wire equal to the difference of the currents in the outside wires.

**AC Three-Wire Distribution** Practically all energy for lighting and small motor work is distributed at 1,150, 2,300, or 4,160 V ac to transformers which step down the voltage to 240 and 120 V for three-wire domestic and lighting systems as well as 208, 240, 480, and 600 volts, three-phase, for power. For the three-wire systems the transformers are so designed that the secondary or low-voltage winding will deliver power at 240 V, and the middle or neutral wire is obtained by connecting to the center or midpoint of this winding (see Figs. 15.1.90 and 15.1.91).

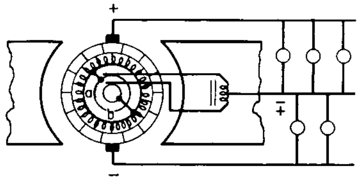


**Fig. 15.1.90** Three-wire generator.

**Disturbances** of utility power have been present since the inception of the electric utility industry; however, in the past equipment was much more forgiving and less affected. Present electronic data processing equipment is microprocessor-based and consequently requires a higher quality of ac power. Although the quality of utility power in the United States is very good, sensitive electronic equipment still needs to be protected against the adverse and damaging effects of transients, surges, and other power-system aberrations.

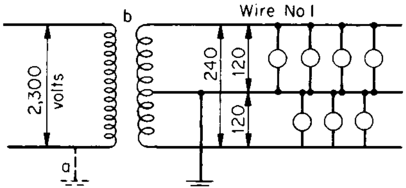


**Fig. 15.1.91** Three-wire 230/115-V ac system.

This has led to the development of technologies which condition power for use by this sensitive equipment. Power-enhancing devices (surge suppressors, isolation transformers, and line voltage regulators) modify the incoming waveform to mitigate some aberrations. Power-synthesizing devices (motor-generator sets, magnetic synthesizers, and uninterruptible power supplies) use the incoming power as a source of energy to generate a new, completely isolated waveform. Each type has advantages and limitations.

**Grounding** The neutral wire of the secondary circuit of the transformer should be grounded on the pole (or in the manhole) and at the service switch in the building supplied. If, as a result of a lightning stroke or a fault in the transformer insulation, the transformer primary circuit becomes grounded at *a* (Fig. 15.1.91) and the transformer insulation between primary and secondary windings is broken down at *b* and if there were no permanent ground connection in the secondary neutral wire, the potential of wire 1 would be raised 2,300 V above ground potential. This constitutes a very serious hazard to life for persons coming in contact with the 120 V system. The National Electrical Code requires the use of a ground wire not smaller than 8 AWG copper. With the neutral grounded (Fig. 15.1.91), voltages to ground on the secondary system cannot exceed 120 V. (See National Electrical Code 1991, Art. 250.)

**Feeders and Mains** Where power is supplied to a large district, improved voltage regulation is obtained by having **centers of distribution**. Power is supplied from the station bus at high voltage to the centers of distribution by large cables known as **feeders**. Power is distributed from the distribution centers to the consumers through the mains and transformed to a usable voltage at the user's site. As there are no loads connected to the feeders between the generating station and centers of distribution, the voltage at the latter points may be maintained constant. **Pilot wires** from the centers of distribution often run back to the station, allowing the operator or automatic controls to maintain constant voltage at the centers of distribution. This system provides a means of maintaining very close **voltage regulation** at the consumer's premises.

A common and economical method of supplying business and thickly settled districts with high load densities is to employ a 208/120-V, three-phase, four-wire **low-voltage ac network**. The network operates with 208 V between outer wires giving 120 V to neutral (Fig. 15.1.92). Motors are connected across the three outer wires operating at 208 V, three-phase. Lamp loads are connected between outer wires and the grounded neutral. The network is supplied directly from 13,800-V feeders by 13,800/208-V three-phase transformer units, usually located in manholes, vaults, or outdoor enclosures. This system thus eliminates the necessity for transformation in the substation. A large number of such units feed the network, so that the secondaries are all in parallel. Each transformer is provided with an overload reverse-energy circuit breaker (network protector), so that a feeder and its transformer are isolated if trouble develops in either. This system is flexible since units can be easily added or removed in accordance with the rapid changes in local loads that occur particularly in downtown business districts.

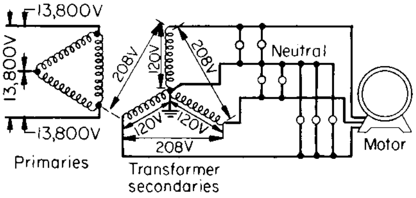


**Fig. 15.1.92** 208/120-V secondary network (single unit) showing voltages.

**Voltage Drops** In ac distribution systems the voltage drop from transformer to consumer in lighting mains should not exceed 2 percent in first-class systems, so that the lamps along the mains can all operate at nearly the same voltage and the annoying flicker of lamps may not occur with the switching of appliances. This may require a much larger conductor than the most economical size. In transmission lines and in feeders where there are no intermediate loads and where means of regulating the voltage are provided, the drop is not limited to the low values that are necessary with mains and the matter of economy may be given consideration.

## WIRING CALCULATIONS

These calculations can be used for dc, and for ac if the reactance can be neglected. The determination of the proper size of conductor is influenced by a number of factors. Except for short distances, the minimum size of conductor shown in Table 15.1.21, which is based on the maximum permissible current for each type of insulation, cannot be used; the size of conductor must be larger so that the voltage drop $IR$ shall not be too great. With branch circuits supplying an incandescent-lamp load, this drop should not be more than a small percentage of the voltage between wires. The National Electrical Code 1993 requires that conductors for feeders, i.e., from the service equipment to the final branch circuit overcurrent device, be sized to prevent (1) a voltage drop of more than 3 percent at the farthest outlet of power, heating, and lighting loads or combinations thereof, and (2) a maximum voltage drop on combined feeders and branch circuits to the farthest outlet of more than 5 percent.

The resistance of 1 cir mil · ft of commercial copper may be taken as 10.8 Ω. The resistance of a copper conductor may be expressed as $R = 10.8l/A$, where $l$ = length, ft and $A$ = area, cir mils. If the length is expressed in terms of the transmission distance $d$ (since the two wires are usually run parallel), the voltage drop $IR$ to the end of the circuit is

$$e = 21.6Id/A \qquad (15.1.128)$$

and the size of conductor in circular mils necessary to give the permissible voltage drop $e$ is

$$A = 21.6Id/e \qquad (15.1.129)$$

If $e$ is expressed as a percentage $x$ of the voltage $E$ between conductors, then

$$A = 2{,}160Id/xE \qquad (15.1.130)$$

EXAMPLE. Determine the size of conductor to supply power to a 10-hp, 220-V dc motor 500 ft from the switchboard with 5 V drop. Assume a motor efficiency of 86 percent. The motor will then require a current of (10 × 746)/(0.86 × 220) = 39.4 A. From Eq. (15.1.129), $A = 21.6 \times 39.4 \times 500/5 = 85{,}100$ cir mils. The next largest wire is no. 0 AWG.

The calculation of the size conductor for three-wire circuits is made in practically the same manner. With a balanced circuit there is no current in the neutral wire, and the current in each outside wire will be equal to one-half the sum of the currents taken by all the receiving devices connected between neutral and outside wires plus the sum of the currents taken by the receivers connected between the outside wires. Using this total current and neglecting the neutral wire, make calculations for the size of the outside wires by means of Eq. (15.1.129). The neutral wire should have the same cross section as the outside wires in interior wiring.

EXAMPLE. Determine the size wire which should be used for the three-wire main of Fig. 15.1.93. Allowable drop is 3 V and the distance to the load center 40 ft; circuit loaded with two groups of receivers each taking 60 A connected between the neutral and the outside wires, and one group of receivers taking 20 A connected across the outside wires.

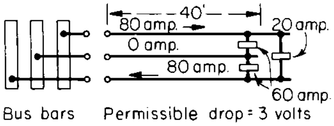


**Fig. 15.1.93** Three-wire 230/115-V main.

*Solution:* load = (60 + 60)/2 + 20 = 80 A. Substituting in Eq. (15.1.129), cir mils = $21.6Id/e = 21.6 \times 80 \times 40/3 = 23{,}030$ cir mils.

From Tables 15.1.19 and 15.1.21, no. 6 wire, which has a cross section of 26,250 cir mils, is the next size larger. This size of wire would satisfy the voltage-drop requirements, but rubber-insulated no. 6 has a safe carrying capacity of but 55 A. The current in the circuit is 80 A. Therefore, rubber-insulated wire no. 3, which has a carrying capacity of 80 A, should be used. The neutral wire should be the same size as the outside wires.

See also examples in the National Electrical Code 1993.

**Wiring calculations for ac circuits** require some consideration of power factor, reactance, and skin effect. Skin effect becomes pronounced only when very large conductors are used for alternating current. For interior wiring, conductors larger than 700,000 cir mils should not be used, and many prefer not to use conductors larger than 300,000 cir mils. Should the required copper cross section exceed these values, a number of conductors may be operated in parallel.

For voltages under 5,000 the effect of line capacitance may be neglected. With ordinary single-phase interior wiring, where the effect of the line reactance may be neglected and where the power factor of the load (incandescent lamps) is nearly 100 percent, the calculations are made the same as for dc circuits. Three-wire ac circuits of ordinary length with incandescent lamp loads are also determined in the same manner. When the load is other than incandescent lamps, it is necessary to know the power factor of the load in order to make calculations. When the exact power factor cannot be accurately determined, the following approximate values may be used: incandescent lamps, 0.95 to 1.00; lamps and motors, 0.75 to 0.85; motors 0.5 to 0.80. Equation (15.1.131) gives the value of current in a single-phase circuit. See also Table 15.1.25.

$$I = (P \times 1{,}000)/(E \times \text{pf}) \qquad (15.1.131)$$

where $I$ = current, A; $P$ = kW; $E$ = load voltage; and pf = power factor of the load. The size of conductor is then determined by substituting this value of $I$ in Eq. (15.1.129) or (15.1.130).

**For three-phase three-wire ac circuits** the current per wire

$$I = 1{,}000P/\sqrt{3}E\text{pf} = 580P/E\text{pf} \qquad (15.1.132)$$

Computations are usually made of voltage drop **per wire** (see Fig. 15.1.94). Hence, if reactance can be neglected, the conductor cross section in cir mils is one-half that given by Eq. (15.1.129). That is,

$$A = 10.8Id/e \qquad \text{cir mils} \qquad (15.1.133)$$

where $e$ in Eq. (15.1.133) is the voltage drop per wire. The voltage drop between any two wires is $\sqrt{3}e$. The percent voltage drop should be in terms of the voltage to **neutral**. That is, percent drop = $[e/(E/\sqrt{3})]100 = [\sqrt{3}e/E]100$ (see Fig. 15.1.82).

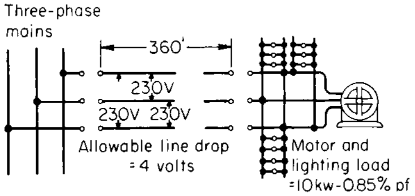


**Fig. 15.1.94** Three-phase lamp and induction motor load.

EXAMPLE. In Fig. 15.1.94, load 10 kW; voltage of circuit 230; power factor 0.85; distance 360 ft; allowable drop per wire 4 V. Substituting in Eq. (15.1.132) $I = (580 \times 10)/(230 \times 0.85) = 29.7$ A. Substituting in Eq. (15.1.133), $A = 10.8 \times 29.7 \times 360/4 = 28{,}900$ cir mils.

The next larger commercially available standard-size wire (see Table 15.1.19) is 41,700 cir mils corresponding to AWG no. 4. From Table 15.1.21 this will carry 70 A with rubber insulation, and is therefore ample in section for 29.7 A. Three no. 4 wires would be used for this circuit.

From Table 15.1.19 the resistance of 1,000 ft of no. 4 copper wire is 0.249 Ω. Hence, the voltage drop per conductor, $e = 29.7 \times (360/1{,}000)0.249 = 2.66$ V. Percent voltage drop = $\sqrt{3} \times 2.66/230 = 2.00$ percent.

Where all the wires of a circuit, two wires for a single-phase circuit, four wires for a four-phase circuit (see Fig. 15.1.32 and Fig. 15.1.80*c*), and three wires for a three-phase circuit, are carried in the same conduit or where the wires are separated less than 1 in between centers, the effect of line (inductive) reactance may ordinarily be neglected. Where circuit conductors are large and widely separated from one another and the circuits are long, the inductive reactance may increase the voltage drop by a considerable amount over that due to resistance alone. Such problems are treated using $IR$ and $IX$ phasors. Line reactance decreases somewhat as the size of wire increases and decreases as the distance between wires decreases.

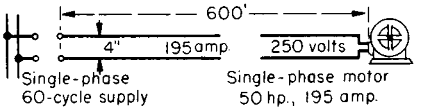


**Fig. 15.1.95** Single-phase induction motor load on branch circuit.

EXAMPLE. Determine the size of wire necessary for the branch to the 50-hp, 60-Hz, 250-V single-phase induction motor of Fig. 15.1.95. The name-plate rating of the motor is 195 A, and its full-load power factor is 0.85. The wires are run open and separated 4 in; length of circuit, 600 ft. Assume the line drop must not exceed 7 percent, or 0.07 × 250 = 17.5 V. The point made by this example is emphasized by the assumption of an outsize motor.

*Solution.* To ascertain approximately the size of conductor, substitute in Eq. (15.1.129) giving cir mils = 21.6 × 195 × 600/17.5 = 144,400. Referring to

Table 15.1.19, the next larger size wire is no. 000 or 167,800 cir mils. This size would be ample if there were no line reactance. In order to allow for reactance drop, a larger conductor is selected and the corresponding voltage drop determined. Inasmuch as this is a motor branch, the code rules require that the carrying capacity be sufficient for a 25 percent overload. Therefore the conductor should be capable of carrying 195 × 1.25 = 244 A. From Table 15.1.21, a 350,000-cir mil conductor rubber-insulated cable would be required to carry 244 A. Resistance drop (see Table 15.1.19), $IR = 195 \times 0.061 \times 0.6 = 7.14$ V. $7.14/250 = 2.86$ percent. From Table 15.1.19, $X = 0.128 \times 0.6 = 0.0768\ \Omega$. $IX = 195 \times 0.768 = 14.98$ V. $14.98/250 = 5.99$ percent. Using the Mershon diagram (Fig. 15.1.84), follow the ordinate corresponding to power factor, 0.85, until it intersects the smallest circle. From this point, lay off horizontally the percentage resistance drop, 2.86. From this last point, lay off vertically the percentage reactance drop 5.99. This last point lies about on the 6.0 percent circle, showing that with 195 amp the difference between the sending-end and receiving-end voltages is 0.06 × 250 = 15.0 V, which is within the specified limits.

Also Eq. (15.1.127) may be used. $\cos\theta = 0.85$; $\sin\theta = 0.527$.

$$E_s = \{[(250 \times 0.85) + 7.14]^2 + [(250 \times 0.527) + 14.98]^2\}^{1/2} = 264.3 \text{ V}$$

$$264.3/250 = 105.7 \text{ percent}$$

In the calculation of three-phase three-wire circuits where line reactance must be considered, the method found above under Power Transmission may be used. The system is considered as being three single-phase systems having a ground return the resistance and inductance of which are zero, and the voltages are equal to the line voltages divided by $\sqrt{3}$. When the three conductors are spaced unequally, the value of GMD given in Fig. 15.1.85 should be used in Tables 15.1.16 and 15.1.19. (When the value of resistance or reactance per 1,000 ft of **conductor** is desired, the values in Table 15.1.19 should be divided by 2.)

The National Electrical Code of 1993 specifies that the size of conductors for branch circuits should be such that the voltage drop will not exceed 3 percent to the farthest outlet for power, heating, lighting, or combination thereof, requiring further that the total voltage drop for feeders and branch circuits should not exceed 5 percent overall. For examples of calculations for interior wiring, see National Electrical Code of 1993 (Chap. 9).

## INTERIOR WIRING

**Interior wiring requirements are based,** for the most part, on the **National Electrical Code** (NEC), which has been adopted by the National Fire Protection Association, American National Standards Institute (ANSI), and the Occupational Safety and Health Act (OSHA).

The Occupational Safety and Health Act of 1970 (OSHA) made the National Electrical Code a national standard. Conformance with the NEC became a requirement in most commercial, industrial, agricultural, etc., establishments in the United States. Some localities may not accept NEC standards. In those cases, local rules must be followed.

NEC authority starts at the point where the connections are made to the conductor of the **service drop** (overhead) or **lateral** (underground) from the electricity supply system. The **service equipment** must have a rating not less than the load to be carried (computed according to NEC methods). Service equipment is defined as the necessary equipment, such as circuit breakers or fused switches and accompanying accessories. This equipment must be located near the point of entrance of supply conductors to a building or other structure or an otherwise defined area. Service equipment is intended to be the main control and means of cutoff of the supply.

**Service-entrance conductors** connect the electricity supply to the service equipment. Service-entrance conductors running along the exterior or entering a building or other structure may be installed (1) as separate conductors, (2) in approved cables, (3) as cable bus, or (4) enclosed in rigid conduit. Also, for voltages less than 600 V, the conductors may be installed in electrical metallic tubing, wireways, auxiliary gutters, or busways. Service-entrance cables which are exposed to physical damage from awnings, swinging signs, coal chutes, etc., must be of the protected type or be protected by conduit, electrical metallic tubing, etc. Service heads must be raintight. Thermoplastic or rubber insulation is required in overhead services. A grounded conductor may be bare. If exposed to the weather or embedded in masonry, raceways must be raintight and arranged to drain. Underground service raceway or duct entering from an underground distribution system must be sealed with a suitable compound (spare ducts, also).

NEC rules permit **multiple service** to a building for various reasons, such as: (1) fire pumps, (2) emergency light and power, (3) multiple occupancy, (4) when the calculated load is greater than 3,000 A, (5) when the building extends over a large area, and (6) where different voltages, frequencies, number of phases, or classes of use are required.

Ordinary service drops (overhead) and lateral (underground) must be large enough to carry the load but not smaller than no. 8 copper or no. 6 aluminum. As an exception, for installations to supply only limited loads of a single branch circuit, such as small polyphase power, etc., service drops must not be smaller than no. 12 hard-drawn copper or equivalent, and service laterals must be not smaller than no. 12 copper or no. 10 aluminum.

The phrase **large enough to carry the load** requires elaboration. The various conductors of public-utility electric-supply systems are sized according to the calculations and decisions of the personnel of the specific public utility supplying the service drop or lateral. At the load end of the drop or lateral, the NEC rules apply, and from that point on into the consumer's premises, NEC rules are the governing authority. There is a discontinuity at this point in the calculation of combined load demand for electricity and allowable current (ampacity) of conductors, cables, etc. This discontinuity in calculations results from the fact that the utility company operates locally, whereas the NEC is a set of national standards and therefore cannot readily allow for regional differences in electrical coincident demand, ambient temperature, etc. The NEC's aim is the assurance of an electrically ''safe'' human environment. This will be fostered by following the NEC rules.

Service-entrance cables are conductor assemblies which bear the type codes **SE** (for overhead services) and **USE** (for underground services). Under specified conditions, these cables may also be used for interior feeder and branch-circuit wiring.

The service-entrance equipment must have the **capability of safely interrupting** the current resulting from a short circuit at its terminals. **Available short-circuit current** is the term given to the maximum current that the power system can deliver through a given circuit to any negligible-impedance short circuit applied at a given point. (This value can be in terms of symmetrical or asymmetrical, momentary or clearing current, as specified.)

In most instances, the available short-circuit current is limited by the impedance of the last transformer in the supply system. **Large power users,** however, must become aware of changes in the electricity supply system which, because of growth of system capacity or any other reason, would increase the short-circuit current available to their service-entrance equipment. If this current is too great, explosive failure can result.

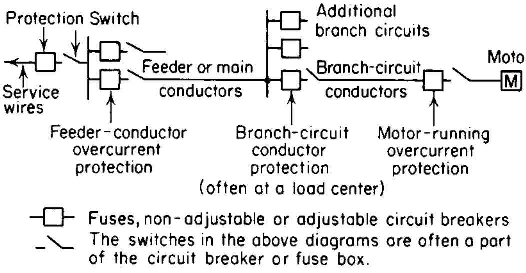


**Fig. 15.1.96** Motor and wiring protection.

Kilowatthour and sometimes demand-metering equipment are connected to the service-entrance conductors. Proceeding toward the utilization equipment, the power-supply system fans out into feeders and branch circuits (see Fig. 15.1.96). Each of the feeders, i.e., a run of untapped conductor or cable, is connected to the supply through a switch and fuses or a circuit breaker. At a point, usually near that portion of the electrical loads which are to be supplied, a **panel box** or perhaps a **load-center assembly** of switching and/or control equipment is installed. From this panel box or load-center assembly, circuits radiate; i.e., circuits are installed to extend into the area being served to connect electrical machinery or devices or make available electric receptacles connected to the source of electric power.

Each feeder and each branch circuit will have its own **over-current protection** and **disconnect** means in the form of a fuse and switch combination or a circuit breaker.

There is a provision in the NEC 1993 rules for the following types of feeder and branch circuit wiring:

**1. Open Wiring on Insulators** (NEC 1993, Art. 320). This wiring method uses approved cleats, knobs, tubes, and flexible tubing for the protection and support of insulated conductors run on or in buildings and not concealed by the building structure. It is permitted only in industrial or agricultural establishments.

**2. Concealed Knob-and-Tube Work** (NEC 1993, Art. 324). Concealed knob-and-tube work may be used in the hollow spaces of walls and ceilings. It may be used only for the extension of existing facilities.

**3. Flat Conductor Cable, Type FCC** (NEC 1993, Art. 328). Type FCC cable may be installed under carpet squares. It may not be used outdoors or in wet locations, in corrosive or hazardous areas, or in residential, school, or hospital buildings.

**4. Mineral-Insulated Metal-Sheathed Cable, Type MI** (NEC 1993, Art. 330). Type MI cable contains one or more electrical conductors insulated with a highly compressed refractory mineral insulation and enclosed in a liquid- and gastight metallic tube sheath. Appropriate approved fittings must be used with it. It may be used for services, feeders, and branch circuits either exposed or concealed and dry or wet. It may be used in Class I, II, or III hazardous locations. It may be used for under-plaster extensions and embedded in plaster finish or brick or other masonry. It may be used where exposed to weather or continuous moisture, for underground runs and embedded in masonry, concrete or fill, in buildings in the course of construction or where exposed to oil, gasoline, or other conditions. If the environment would cause destruction of the sheath, it must be protected by suitable materials.

**5. Power and Control Tray Cable** (NEC 1993, Art. 340). Type TC cable is a factory assembly of two or more insulated conductors with or without associated bare or covered-grounding conductors under a nonmetallic sheath, approved for installation in cable trays, in raceways, or where supported by messenger wire.

**6. Metal-Clad Cable, Type MC and AC Series** (NEC 1993, Art. 333 and 334). These are metal-clad cables, i.e., an assembly of insulated conductors in a flexible metal enclosure. Type MC are power cables and in the range up to 600 V are made in conductor sizes of no. 4 and larger for copper and no. 2 and larger for aluminum. Type AC are branch and feeder cables with armor of flexible metal tape. All AC types except ACL have an internal bonding strip of copper or aluminum in intimate contact with the armor for its entire length. Metal-clad branch circuit cable was formerly called BX. Metal-clad cables may generally be installed where not subject to physical damage, for feeders and branch circuits in exposed or concealed work, with qualifications for wet locations, direct burial in concrete, etc. The use of Type AC cable is prohibited (1) in motion-picture studios, (2) in theaters and assembly halls, (3) in hazardous locations, (4) where exposed to corrosive fumes or vapors, (5) on cranes or hoists except where flexible connections to motors, etc., are required, (6) in storage-battery rooms, (7) in hoistways or on elevators except (*i*) between risers and limit switches, interlocks, operating buttons, and similar devices in hoistways and in escalators and moving walkways and (*ii*) short runs on elevator cars, where free from oil, and if securely fastened in place, or (8) in commercial garages in hazardous locations. Type ACL (lead-covered) shall not be used for direct burial in the earth.

**7. Nonmetallic-Sheathed Cable, Types NM and NMC** (NEC 1993, Art. 336). These are assemblies of two more insulated conductors (nos. 14 through 2 for copper, nos. 12 through 2 for aluminum) having an outer sheath of moisture-resistant, flame-retardant, nonmetallic material. In addition to the insulated conductors, the cable may have an approved size of uninsulated or bare conductor for grounding purposes only. The outer covering of NMC cable is flame retardant and corrosion resistant. The use of this type of cable, commonly called **Nomex,** is permitted in one- or two-family dwellings, multifamily dwellings, and other structures provided that such structures do not exceed three floors above grade.

**8. Shielded Nonmetallic-Sheathed Cable, Type SNM** (NEC 1993, Art. 337). Type SNM is a factory-assembled cable consisting of two or more insulated conductors (nos. 14 through 2 copper and nos. 12 through 2 aluminum) in an extruded core of moisture-resistant material, covered with an overlapping spiral metal tape and wire shield and jacketed with an extruded moisture-, flame-, corrosion-, fungus-, and sunlight-resistant material. This cable is to be used (1) under appropriate ambient-temperature conditions and (2) in continuous rigid-cable support or in raceways. It can be used in some hazardous locations as defined by the NEC.

**9. Service Entrance Cable, Types SE and USE** (NEC 1993, Art. 338). These cables, containing one or more individually insulated conductors, are primarily used for electric services. Type SE has a flame-retardant, moisture-resistant covering and is not required to have built-in protection against mechanical abuse. Type USE is recognized for use underground. It has a moisture-resistant covering, but not necessarily a flame-retardant one. Like the SE cable, USE cable is not required to have inherent protection against mechanical abuse. Under specified conditions, SE and USE cables can be used for feeders and branch circuits.

**10. Underground Feeder and Branch-Circuit Cable, Type UF** (NEC 1993, Art. 339). This cable is made in sizes 14 through 4/0, and the insulated conductors are Types TW, RHW, and others approved for the purpose. As in the NM cable, the UF type may contain an approved size of uninsulated or bare conductor for grounding purposes only. The outer jacket of this cable shall be flame-retardant, moisture-resistant, fungus-resistant, corrosive-resistant, and suitable for direct burial in the ground.

**11. Other Installation Practices.** The NEC details rules for nonmetallic circuit extensions and underplaster extensions. It also provides detailed rules for installation of electrical wiring in (*a*) rigid metal conduit (which may be used for all atmospheric conditions and locations with due regard to corrosion protection and choice of fittings), (*b*) rigid nonmetallic conduit (which is essentially corrosion-proof), in electrical metallic tubing (which is lighter-weight than rigid metal conduit), (*c*) flexible metal conduit, (*d*) liquidtight flexible metal conduit, (*e*) surface raceways, (*f*) underfloor raceways, (*g*) multioutlet assemblies, (*h*) cellular metal floor raceways, (*i*) structural raceways, (*j*) cellular concrete floor raceways, (*k*) wireways (sheet-metal troughs with hinged or removable covers), (*l*) flat, Type FC, cable assemblies installed in a surface metal raceway (Type FC cable contains three or four no. 10 special stranded copper wires), (*m*) busways, and (*n*) cable-bus. Busways and cable-bus installations are permitted for exposed work only.

In all installation work, only approved outlets, switch and junction boxes, fittings, terminal strips, and dead-end caps shall be used, and they are to be used in an approved fashion (see NEC 1993, Art. 370).

**Table 15.1.20 Wire Table for Standard Annealed Copper at 20°C in SI Units**

| AWG size | Diameter, mm | kgf/km | m/Ω | Area, mm$^2$ |
|---|---|---|---|---|
| 14 | 1.628 | 18.50 | 120.7 | 2.08 |
| 12 | 2.053 | 29.42 | 191.9 | 3.31 |
| 10 | 2.588 | 46.77 | 305.1 | 5.261 |
| 8 | 3.264 | 74.37 | 485.2 | 8.367 |
| 6 | 4.115 | 118.2 | 771.5 | 13.30 |
| 4 | 5.189 | 188.0 | 1227 | 21.15 |
| 2 | 6.544 | 299.0 | 1951 | 33.62 |
| 1 | 7.348 | 377.0 | 2460 | 42.41 |
| 0 | 8.252 | 475.4 | 3102 | 53.49 |
| 00 | 9.266 | 599.5 | 3911 | 67.43 |
| 000 | 10.40 | 755.9 | 4932 | 85.01 |
| 0000 | 11.68 | 935.2 | 6219 | 107.2 |

Table 15.1.20 relates AWG wire sizes to metric units. Table 15.1.21 lists the allowable ampacities of copper and aluminum conductors. Table 15.1.22 lists various conductor insulation systems approved by the 1993 NEC for conductors used in interior wiring. Dimensions and allowable fill of conduit and tubing are listed in Table 15.1.23. Table 15.1.24 lists the cross-sectional area of various insulated conductors. For installations not covered by the tables presented here, review the 1993 NEC. Estimated full-load currents of motors can be taken from Table 15.1.25.

**Switching Arrangements** Small quick-break switches must be set in or on a metal box or fitting and may be of the push, tumbler, or rotary type. The following types of switches are used to control lighting circuits: (1) single-pole, (2) double-pole, (3) three-point or three-way, (4) four-way, in combination with three-way switches to control lights from three or more stations, (5) electrolier.

In all metallic protecting systems, such as conduit, armored cable, or metal raceways, joints and splices in conductors must be made only in junction boxes or other proper fittings; therefore, these fittings can be located only in accessible places and never concealed in partitions. Splices or joints in the wire must never be in the conduit piping, raceway, or metallic tubing itself, for the splices may become a source of trouble as a result of corrosion or grounding if water should enter the conduit.

All conductors of an ac system must be placed in the same metallic casing so that their resultant magnetic field is nearly zero. If this is not done, eddy currents are set up causing heating and excessive loss. With single conductors in a casing, an excessive reactance drop may result.

**Service wires** are the conductors that bring the electric power into a building and should enter the building as near as possible to the service switch, so that when the switch is open all the electrical conductors and equipment inside the building will be dead. The service wires must be rubber- or thermoplastic-covered from the point of support on the outside of the building to the service switch or cutout and must be no. 6 wire or larger except for installations consisting of two-wire branch circuits where no. 8 wire may be permitted. A minimum of 100-A three-wire service is recommended for all single-family residences.

**Table 15.1.21 Allowable Ampacities of Insulated Conductors**

(Not more than three conductors in conduit. Based on ambient air temperature of 40°C.)

| | Temperature rating of insulation, °C | | | | | |
|---|---|---|---|---|---|---|
| | Copper | | | Aluminum | | |
| | 60 | 75 | 90 | 60 | 75 | 90 |
| Conductor size: AWG or MCM | Types TW, UF | Types RH, RHW, THW, THWN, XHHW, USE, ZW | Types SA, AVB, FEP, FEPB, THHN, RHH, XHHW* | Types TW, UF | Types RH, RHW THW, THWN, XHHW, USE | Types SA, AVB, THHN, RHH, XHHW* |
| 14 | 18† | 22† | 25† | — | — | — |
| 12 | 23† | 28† | 32† | 18† | 22† | 26† |
| 10 | 29† | 37† | 42† | 23† | 29† | 34† |
| 8 | 36 | 48 | 55 | 28 | 37 | 43 |
| 6 | 50 | 64 | 75 | 37 | 50 | 58 |
| 4 | 65 | 83 | 97 | 50 | 65 | 76 |
| 3 | 76 | 98 | 114 | 59 | 76 | 89 |
| 2 | 87 | 112 | 130 | 68 | 87 | 102 |
| 1 | 104 | 134 | 156 | 81 | 104 | 122 |
| 0 | 119 | 153 | 179 | 93 | 119 | 139 |
| 00 | 135 | 175 | 204 | 106 | 137 | 159 |
| 000 | 160 | 207 | 242 | 125 | 162 | 189 |
| 0000 | 184 | 238 | 278 | 144 | 186 | 217 |
| 250 | 210 | 271 | 317 | 165 | 213 | 249 |
| 300 | 232 | 300 | 351 | 183 | 236 | 276 |
| 350 | 254 | 328 | 384 | 201 | 259 | 303 |
| 400 | 274 | 354 | 415 | 218 | 281 | 329 |
| 500 | 314 | 407 | 477 | 252 | 326 | 381 |
| 600 | 345 | 448 | 525 | 280 | 362 | 424 |
| 700 | 376 | 489 | 574 | 308 | 399 | 467 |
| 750 | 392 | 509 | 598 | 322 | 417 | 488 |
| 800 | 403 | 524 | 616 | 334 | 432 | 506 |
| 900 | 426 | 555 | 653 | 357 | 463 | 542 |
| 1,000 | 499 | 585 | 689 | 380 | 493 | 578 |
| Ambient temp., °C | For ambient temperatures other than 40°C, multiply the ampacities shown above by the appropriate factors shown below. | | | | | |
| 21–35 | 1.32 | 1.20 | 1.14 | 1.32 | 1.20 | 1.14 |
| 26–30 | 1.22 | 1.13 | 1.10 | 1.22 | 1.13 | 1.10 |
| 31–35 | 1.12 | 1.07 | 1.05 | 1.12 | 1.07 | 1.05 |
| 36–40 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 41–45 | 0.87 | 0.93 | 0.95 | 0.87 | 0.93 | 0.95 |
| 46–50 | 0.71 | 0.85 | 0.89 | 0.71 | 0.85 | 0.89 |
| 51–55 | 0.50 | 0.76 | 0.84 | 0.50 | 0.76 | 0.84 |
| 56–60 | — | 0.65 | 0.77 | — | 0.65 | 0.77 |
| 61–70 | — | 0.38 | 0.63 | — | 0.38 | 0.63 |
| 71–80 | — | — | 0.45 | — | — | 0.45 |

* For dry locations only, rated 75°C for wet locations.

† Overcurrent protection shall not exceed 15 A for no. 14 copper and no. 12 aluminum, 20 A for no. 12 copper, 25 A for no. 10 aluminum, and 30 A for no. 10 copper.

NOTE: This is a general table. For other installation conditions, see NFPA 70-1994 National Electric Code®, Article 310.

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**Table 15.1.22 Conductor Type and Application**

| Type letter | Insulation, trade name (see NEC 1984, Art. 310 for complete information) | Environment | Outer covering[a] |
|---|---|---|---|
| Max operating temperature = 60°C (140°F) | | | |
| TW | Moisture-resistant thermoplastic | Dry and wet | None |
| TF | Thermoplastic-covered, solid or 7-strand | [c,d] | None |
| TFF | Thermoplastic-covered, flexible stranding | [c,d] | None |
| MTW | Moisture-, heat-, and oil-resistant thermoplastic machine-tool wiring (NFPA Stand. 79, NEC 1975, Art. 670) | Wet | None or nylon |
| UF | Moisture-resistant, underground feeder | Dry and wet | None |
| Max operating temperature = 75°C (167°F) | | | |
| RH | Heat-resistant rubber | Dry | 1,2 |
| RHW | Moisture- and heat-resistant rubber[e] | Dry and wet | 1,2 |
| THW | Moisture- and heat-resistant thermoplastic | Dry and wet | None |
| THWN | Moisture- and heat-resistant thermoplastic | Dry and wet | Nylon |
| XHHW | Moisture- and heat-resistant cross-linked polymer | Wet | None |
| RFH-1 and 2 | Heat-resistant rubber-covered solid or 7-strand | [b–d] | None |
| FFH-1 and 2 | Heat-resistant rubber-covered flexible stranding | [b–d] | None |
| UF | Moisture-resistant and heat-resistant | Dry and wet | None |
| USE | Heat- and moisture-resistant | Dry and wet | 4 |
| ZW | Modified ethylene tetrafluoroethylene | Wet | None |
| Max operating temperature = 85°C (185°F) | | | |
| MI | Mineral-insulated (metal-sheathed) | Dry and wet | Copper |
| Max operating temperature = 90°C (194°F) | | | |
| RHH | Heat-resistant rubber | Dry | 1,2 |
| THHN | Heat-resistant thermoplastic | Dry | Nylon |
| THW | Moisture- and heat-resistant thermoplastic | *f* | None |
| XHHW | Moisture- and heat-resistant cross-linked synthetic polymer | Dry | None |
| FEP | Fluorinated ethylene propylene | Dry | None |
| FEPB | Fluorinated ethylene propylene | Dry | 3 |
| TFN | Heat-resistant thermoplastic covered, solid or 7-strand | [c,d] | Nylon |
| TFFN | Heat-resistant thermplastic flexible stranding | | Nylon |
| MTW | Moisture-, heat-, and oil-resistant thermoplastic machine-tool wiring (NFPA Stand. 79, NEC 1975, Art. 670) | Dry | None or nylon |
| SA | Silicone asbestos | Dry | Asbestos or glass |
| Max operating temperature = 150°C (302°F) | | | |
| Z, ZW | Modified ethylene tetrafluoroethylene | Dry | None |
| Max operating temperature = 200°C (392°F) | | | |
| FEP, FEPB | Fluorinated ethylene propylene | Dry | None |
| | Special applications | | 3 |
| PF, PGF | Fluorinated ethylene propylene | [c,d] | None or glass braid |
| PFA | Perfluoroalkoxy | Dry | None |
| SF-2 | Silicone rubber, solid or 7-strand | [c,d] | Nonmetallic |
| Max operating temperature = 250°C (482°F) | | | |
| MI | Mineral-insulated (metal-sheathed), for special applications | Dry and wet | Copper |
| TFE | Extruded polytetrafluoroethylene, only for leads within apparatus or within raceways connected to apparatus, or as open wiring (silver or nickel-coated copper only) | Dry | None |
| PFAH | Perfluoroalkoxy (special application) | Dry | None |
| PTF | Extruded polytetrafluoroethylene, solid or 7-strand (silver or nickel-coated copper only) | [c,d] | None |

[a] 1: Moisture-resistant, flame-retardant nonmetallic; 2: outer covering not required when rubber insulation has been specifically approved for the purpose; 3: no. 14-8 glass braid, no. 6-2 asbestos braid; 4: moisture-resistant nonmetallic.

[b] Limited to 300 V.

[c] No. 18 and no. 16 conductor for remote controls, low-energy power, low-voltage power, and signal circuits; NEC 1975 Sec. 725-16, Sec. 760-16.

[d] Fixture wire no. 18-16.

[e] For over 2,000 V, the insulation shall be ozone-resistant.

[f] Special applications within electric discharge lighting equipment. Limited to 1,000 V open-circuit volts or less.

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**Table 15.1.23 Dimensions and Allowable Fill of Conduit and Tubing**

| | | | Allowable fill, in$^2$ of conductors (not lead-covered) | | |
|---|---|---|---|---|---|
| Trade size, in | ID, in | Area, in$^2$ | One conductor, 53% fill | Two conductors, 31% fill | Over two conductors,* 40% fill |
| ½ | 0.622 | 0.30 | 0.16 | 0.09 | 0.12 |
| ¾ | 0.824 | 0.53 | 0.28 | 0.16 | 0.21 |
| 1 | 1.049 | 0.86 | 0.46 | 0.27 | 0.34 |
| 1¼ | 1.380 | 1.50 | 0.80 | 0.47 | 0.60 |
| 1½ | 1.610 | 2.04 | 1.08 | 0.63 | 0.82 |
| 2 | 2.067 | 3.36 | 1.78 | 1.04 | 1.34 |
| 2½ | 2.469 | 4.79 | 2.54 | 1.43 | 1.92 |
| 3 | 3.068 | 7.38 | 3.91 | 2.29 | 2.95 |
| 3½ | 3.548 | 9.90 | 5.25 | 3.07 | 3.96 |
| 4 | 4.026 | 12.72 | 6.74 | 3.94 | 5.09 |
| 4½ | 4.506 | 15.94 | 8.45 | 4.94 | 6.38 |
| 5 | 5.047 | 20.00 | 10.60 | 6.20 | 8.00 |
| 6 | 6.065 | 28.89 | 15.31 | 8.96 | 11.56 |

* For conductor derating with more than three conductors see NEC 1993, Art. 310.

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Generally, when the conductors from overhead lines enter a building, the wires are encased in rigid conduit equipped with a weather cap or a service entrance cable (type ASE armored or SE type, unarmored) may be attached directly to the building wall. The inner end of the service enters a metal service cabinet in which the service fuses and switch are located. Service conductors may also terminate at an air-break or oil-immersed switch in a metal case or on a panel board which is accessible to qualified persons only.

All underground service wires must be connected to the interior wiring through a blade of the service switch or circuit breaker and be fused or automatically interrupted at the service switch. A service switch controlling a three-wire dc, a single-phase or four-wire three-phase system having a grounded neutral wire does not need to open that conductor.

The single-line diagram, Fig. 15.1.96, indicates a simplified interior arrangement of circuits and the necessary protection of the conductors and terminal load. Where a reduction is made in the wire size a protective device shall be installed to limit the conductor current to a safe value. Large motors and other terminal loads should also have overcurrent protection.

The maximum permissible fuse ratings and the setting of the protective devices for starting and for running protection of motors are given in Table 15.1.26.

**Grounding** of direct- and alternating-current systems of 300 V and

**Table 15.1.24 Nominal Cross-Sectional Area of Rubber-Covered and Plastic-Covered Conductors**

| | Size, AWG | | | | | |
|---|---|---|---|---|---|---|
| | 18 | 16 | 14 | 12 | 10 | 8 |
| Type | Cross-sectional area, in$^2$ | | | | | |
| RFH-2 | 0.0167 | 0.0196 | (fixture wire) | | | |
| SF-2 | 0.0167 | 0.0196 | 0.0230 | (fixture wire) | | |
| RH | — | — | 0.0230 | 0.0278 | 0.0460 | 0.0854 |
| RHH, RHW | — | — | 0.0327 | 0.0384 | 0.0460 | 0.0854 |
| RHH, RHW (without outer covering) | — | — | 0.0206 | 0.0251 | 0.0311 | 0.0598 |
| THW | — | — | 0.0206 | 0.0251 | 0.0311 | 0.0598 |
| TW, RUH | — | — | 0.0135 | 0.0172 | 0.0224 | 0.0471 |
| TF | 0.0088 | 0.0109 | — | — | — | — |
| THWN, THHN | — | — | 0.0087 | 0.0117 | 0.0184 | 0.0373 |
| TFN | 0.0064 | 0.0079 | — | — | — | — |
| FEPB, Z, ZF, ZFF | — | — | 0.0087 | 0.0115 | 0.0159 | 0.0272 |
| FEP, TFE | — | — | 0.0087 | 0.0115 | 0.0159 | 0.0333 |
| PTF | 0.0052 | 0.0066 | 0.0087 | — | — | — |
| XHHW | — | — | 0.0131 | 0.0167 | 0.0216 | 0.0456 |

| | Size, AWG | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 6 | 4 | 3 | 2 | 1 | 1/0 | 2/0 | 3/0 | 4/0 |
| | Cross-sectional area, in$^2$ | | | | | | | | |
| RH, RHH,* RHW* | 0.1238 | 0.1605 | 0.1817 | 0.2067 | 0.2715 | 0.3107 | 0.3578 | 0.4151 | 0.4840 |
| RUH | 0.0819 | 0.1087 | 0.1263 | 0.1473 | — | — | — | — | — |
| TW, THW | 0.0819 | 0.1087 | 0.1263 | 0.1473 | 0.2027 | 0.2367 | 0.2781 | 0.3288 | 0.3904 |
| TFE | 0.0467 | 0.0669 | 0.0803 | 0.0973 | 0.1385 | 0.1676 | 0.1974 | 0.2436 | 0.2999 |
| FEPB, ZF, ZFF | 0.0716 | 0.0962 | 0.1122 | 0.1316 | — | — | — | — | — |
| FEP | 0.0467 | 0.0669 | 0.0803 | 0.0973 | — | — | — | — | — |
| THHN, THWN | 0.0519 | 0.0845 | 0.0995 | 0.1182 | 0.1590 | 0.1893 | 0.2265 | 0.2715 | 0.3278 |
| XHHW | 0.0625 | 0.0845 | 0.0995 | 0.1182 | 0.1590 | 0.1893 | 0.2265 | 0.2715 | 0.3278 |
| Z | 0.0716 | 0.0962 | 0.1122 | 0.1320 | 0.1385 | 0.1676 | 0.1948 | 0.2463 | 0.3000 |

| | Size, MCM | | | | | |
|---|---|---|---|---|---|---|
| | 250 | 500 | 750 | 1000 | 1500 | 2000 |
| | Cross-sectional area, in$^2$ | | | | | |
| RH, RHH,* RHW* | 0.5917 | 0.9834 | 1.4082 | 1.7531 | 2.5475 | 3.2079 |
| TW, T, THW | 0.4877 | 0.8316 | 1.2252 | 1.5482 | 2.2748 | 2.9013 |
| THHN, THWN | 0.4026 | 0.7163 | 1.0623 | 1.3623 | — | — |
| XHHW | 0.4026 | 0.7163 | 1.0936 | 1.3893 | 2.0612 | 2.6590 |

* RHH and RHW without covering have the same dimension as THW.

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NOTE: For general branch and feeder circuits the minimum conductor size is 14. Sizes 14 to 8 are solid wire. Sizes 6 and larger are stranded.

**Table 15.1.25 Approximate Full-Load Currents of Motors,* A**
(See NEC 1993 for more complete information.)

| | Three-phase ac motors squirrel-cage and wound-rotor induction types | | | | Synchronous type, unity power factor | | | | Single-phase ac motors | | DC motors† | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| hp | 230 V | 460 V | 575 V | 2,300 V | 230 V | 460 V | 575 V | 2,300 V | 115 V‡ | 230 V‡ | 120 V | 240 V |
| ½ | 2 | 1 | 0.8 | — | — | — | — | — | 9.8 | 4.9 | 5.4 | 2.7 |
| ¾ | 2.8 | 1.4 | 1.1 | — | — | — | — | — | 13.8 | 6.9 | 7.6 | 3.8 |
| 1 | 3.6 | 1.8 | 1.4 | — | — | — | — | — | 16 | 8 | 9.5 | 4.7 |
| 1½ | 5.2 | 2.6 | 2.1 | — | — | — | — | — | 20 | 10 | 13.2 | 6.6 |
| 2 | 6.8 | 3.4 | 2.7 | — | — | — | — | — | 24 | 12 | 17 | 8.5 |
| 3 | 9.6 | 4.8 | 3.9 | — | — | — | — | — | 34 | 17 | 25 | 12.2 |
| 5 | 15.2 | 7.6 | 6.1 | — | — | — | — | — | 56 | 28 | 40 | 20 |
| 7½ | 22 | 11 | 9 | — | — | — | — | — | 80 | 40 | 58 | 29 |
| 10 | 28 | 14 | 11 | — | — | — | — | — | 100 | 50 | 76 | 38 |
| 15 | 42 | 21 | 17 | — | — | — | — | — | — | — | — | 55 |
| 20 | 54 | 27 | 22 | — | — | — | — | — | — | — | — | 72 |
| 25 | 68 | 34 | 27 | — | 53 | 26 | 21 | — | — | — | — | 89 |
| 30 | 80 | 40 | 32 | — | 63 | 32 | 26 | — | — | — | — | 106 |
| 40 | 104 | 52 | 41 | — | 83 | 41 | 33 | — | — | — | — | 140 |
| 50 | 130 | 65 | 52 | — | 104 | 52 | 42 | — | — | — | — | 173 |
| 60 | 154 | 77 | 62 | 16 | 123 | 61 | 49 | 12 | — | — | — | 206 |
| 75 | 192 | 96 | 77 | 20 | 155 | 78 | 62 | 15 | — | — | — | 255 |
| 100 | 248 | 124 | 99 | 26 | 202 | 101 | 81 | 20 | — | — | — | 341 |
| 125 | 312 | 156 | 125 | 31 | 253 | 126 | 101 | 25 | — | — | — | 425 |
| 150 | 360 | 180 | 144 | 37 | 302 | 151 | 121 | 30 | — | — | — | 506 |
| 200 | 480 | 240 | 192 | 49 | 400 | 201 | 161 | 40 | — | — | — | 675 |

* The values of current are for motors running at speeds customary for belted motors and motors having normal torque characteristics. Use name-plate data for low-speed, high-torque, or multispeed motors. For synchronous motors of 0.8 pf multiply the above amperes by 1.25, at 0.9 pf by 1.1. The motor voltages listed are rated voltages. Respective nominal system voltages would be 220 to 240, 440 to 480, and 550 to 600 V. For full-load currents of 208-V motors, multiply the above amperes by 1.10; for 200-V motors, multiply by 1.15.

† Ampere values are for motors running at base speed.

‡ Rated voltage. Nominal system voltages are 120 and 240.

**Table 15.1.26 Maximum Rating or Setting of Motor Branch-Circuit Protective Devices and Starting-Inrush Code Letters**

| | Percent of full-load current | | | |
|---|---|---|---|---|
| Type of motor | Non-time delay fuse | Dual-element (time delay) fuse | Instantaneous breaker | Time-limit breaker |
| Single-phase, all types, no code letter | 300 | 175 | 700 | 250 |
| AC motors: single-phase, polyphase squirrel-cage, or synchronous with full-voltage, resistor, or reactor starting: | | | | |
| No code letter | 300 | 175 | 700 | 250 |
| F–V | 300 | 175 | 700 | 250 |
| B–E | 250 | 175 | 700 | 200 |
| A | 150 | 150 | 700 | 150 |
| AC squirrel-cage or synchronous motors with autotransformer starting: | | | | |
| Not more than 30 A | | | | |
| No code letter | 250 | 175 | 700 | 200 |
| More than 30 A | | | | |
| No code letter | 200 | 175 | 700 | 200 |
| F–V | 250 | 175 | 700 | 200 |
| B–E | 200 | 175 | 700 | 200 |
| A | 150 | 150 | 700 | 150 |
| High reactance squirrel-cage: | | | | |
| Not more than 30 A | | | | |
| No code letter | 250 | 175 | 700 | 250 |
| More than 30 A | | | | |
| No code letter | 200 | 175 | 700 | 200 |
| Wound rotor, no code letter | 150 | 150 | 700 | 150 |
| DC motors: | | | | |
| No more than 50 hp | | | | |
| No code letter | 150 | 150 | 250 | 150 |
| More than 50 hp | | | | |
| No code letter | 150 | 150 | 175 | 150 |
| Low-torque, low-speed (450 r/min or lower) synchronous motors which start unloaded | 200 | 200 | 200 | 200 |

| Code letter | kVA/hp with locked rotor |
|---|---|
| A | 0–3.14 |
| B | 3.15–3.54 |
| C | 3.55–3.99 |
| D | 4.0–4.49 |
| E | 4.5–4.99 |
| F | 5.0–5.59 |
| G | 5.6–6.29 |
| H | 6.3–7.09 |
| J | 7.1–7.99 |
| K | 8.0–8.99 |
| L | 9.0–9.99 |
| M | 10.0–11.19 |
| N | 11.2–12.49 |
| P | 12.5–13.99 |
| R | 14.0–15.99 |
| S | 16.0–17.99 |
| T | 18.0–19.99 |
| U | 20.0–22.39 |
| V | 22.4 and up |

SOURCE: NEC 1993, Tables 430-152 and 430-7(*b*). Reprinted with permission from NFPA 70-1993, National Electrical Code®, Copyright © 1992, National Fire Protection Association, Quincy, less is usually required. Inside a building the **grounded conductor** (one of the two conductors in two-wire system and the **neutral conductor** in a three-wire or a four-wire system) should have a **white or natural gray covering** throughout to distinguish it from the ungrounded conductors. This identified grounded conductor must not be fused or be opened unless the other conductors are opened simultaneously. **Green wires** only shall be used for grounding electrical equipment, such as motors, as well as conduits, armor, boxes, and such metallic enclosures. Four-wire circuits have **black, white, red, and blue** conductors or alphanumeric identification.

DC systems need be grounded only at the generating stations because the grounded wire is electrically connected to one of the conductors in all the circuits throughout the system. In ac systems, since one section can be insulated from the other by a transformer, each section of 300 V or under is grounded at the individual services. The conductor grounding the ac system should not be less than no. 8 copper wire and must be without a joint or a splice and run from the supply side of the service switch.

The service conduit that protects the service wires on the outside of the building must be grounded by a wire at least as large as no. 8, run directly to ground.

The entire metallic system surrounding the conductors must be at ground potential. It is only necessary to ground the metallic system, including motors and other equipment, at one point, provided that each section makes a good electrical connection with the next.

Since January 1, 1973, **ground-fault circuit interrupters** have been required by the NEC in some areas for personnel protection from line-to-ground electrical shock. Such circuit interrupters are required by the 1984 NEC in branch circuits supplying certain areas in residences, hotels and motels, health-care facilities, marinas and boat yards, mobile homes and recreational vehicles, swimming pools, and construction sites. The 1984 or subsequent code should be carefully reviewed for exact requirements.

Ground-fault circuit protection may be used at other locations and, if so used, will provide additional protection against line-to-ground shock hazard.

Ground fault-circuit interrupters monitor the current in the two conductors of a circuit. These two currents should be equal. If they are not equal, some current is leaking to ground, indicating a line to ground fault. If the difference between the two currents is 5 mA or more, the ground-fault circuit interrupter will automatically disconnect the faulted circuit in about 0.025 s.

**Overload Protection** A fuse or circuit breaker must be provided in all ungrounded conductors. Induction motors are usually protected by overload or thermal relays operating as automatic circuit breakers. To protect wiring properly, an automatic cutout must be installed at every point where a change is made in the size of the wire. Fuses or circuit breakers should not be placed either in a grounded line or in a ground wire. (See Fig. 15.1.96.)

**Fuses, cutout bases,** and **switches** are manufactured and change sizes, as follows: Edison plug (125 V only), 0 to 30 A; spring-clip cartridge (ferrule contact), 0 to 30, 31 to 60 A; knife-blade cartridge type, 61 to 100, 101 to 200, 201 to 400, 401 to 600 A; for 601 A and larger, knife-blade cartridge type with equal-size fuses in parallel may be used except for the protection of a branch motor circuit where a circuit breaker can be installed.

Since the rating of a fuse is only about 90 percent of the current that it will carry indefinitely, and since it may also take a few minutes before the heat due to slightly excessive current would be sufficient to melt the fuse wire and hence open the circuit, insulation may be permanently damaged if the fuses are larger than the current-carrying capacities given by Table 15.1.21.

**Demand Calculations for Building Feeder Sizes** The **demand factor** or **demand** is the ratio of maximum demand to the total connected load. This depends on the type of building, whether hotel, theater, factory, etc. The demand factor for any particular class of installation decreases as the floor area increases. Values of demand factors are found in the 1993 NEC Art. 220.

**Load centers** are panels or cabinets which act as distribution centers and which are supplied by feeder or main conductors, and from which the current to several branch circuits is taken. In each branch circuit there is usually a small combined switch and circuit breaker. Load centers for widely different types of circuits such as single-phase two-wire, single-phase three-wire, and three-phase are readily obtainable from several manufacturers.

## RESISTOR MATERIALS

For use in rheostats, electric furnaces, ovens, heaters, and many electrical appliances, a resistor material with high melting point and high resistivity which does not disintegrate or corrode at high temperatures is necessary. These requirements are met by the nickel-chromium and nickel-chromium-iron alloys. For electrical instruments and measuring apparatus, the resistor material should have high resistivity, low temperature coefficient, and, for many uses, low thermoelectric power against copper. The properties of resistor materials are given in Table 15.1.27. Most of these materials are available in ribbon as well as in wire form. Cast-iron and steel wire are efficient and economical resistor materials for many uses, such as power-absorbing rheostats and motor starters and controllers. (See also Sec. 6.)

**Advance** has a low temperature coefficient and is useful in many types of measuring instrument and precision equipment. Because of its high

**Table 15.1.27 Properties of Metals, Alloys, and Resistor Materials**

| | | | | Resistivity | | | | |
|---|---|---|---|---|---|---|---|---|
| Material | Composition | Sp gr | Microhms-cm at 20°C | Ohms cir-mil-ft at 20°C | Temp coef of resistance per deg C | Temp range, °C | Max safe working temp, °C | Approx melting point, °C |
| Advance | Cu 0.55; Ni 0.45 | 8.9 | 48.4 | 294 | ± 0.00002 | 20–100 | 500 | 1210 |
| Comet | Ni 0.30; Cr 0.05; Fe 0.65 | 8.15 | 95 | 570 | 0.00088 | 20–500 | 600 | 1480 |
| Bronze, commercial | Cu; Zn | 8.7 | 4.2 | 25 | 0.0020 | 0–100 | — | 1040 |
| Hytemco-Balco | Ni 0.50; Fe 0.50 | 8.46 | 20 | 120 | 0.0045 | 20–100 | 600 | 1425 |
| Kanthal A | Al 0.055; Cr 0.22; Co 0.055; Fe 0.72 | 7.1 | 145 | 870 | 0.00002 | 0–500 | 1330 | 1510 |
| Magno | Ni 0.955; Mn 0.045 | 8.75 | 20 | 120 | 0.0036 | 20–100 | 400 | 1435 |
| Manganin | Cu 0.84; Mn 0.12; Ni 0.04 | 8.19 | 48.2 | 290 | ± 0.000015 | 15–35 | 100 | 1020 |
| Monel metal | Ni 0.67; Cu 0.28 | 8.9 | 42.6 | 256 | 0.0001 | 0–100 | 425 | 1350 |
| Nichrome | Ni 0.60; Fe 0.25; Cr 0.15 | 8.247 | 112 | 675 | 0.00017 | 20–100 | 930 | 1350 |
| Nichrome V | Ni 0.80; Cr 0.20 | 8.412 | 108 | 650 | 0.00013 | 20–100 | 1100 | 1400 |
| Nickel, pure | Ni 0.99 | 8.9 | 10 | 60 | 0.0050 | 0–100 | 400 | 1450 |
| Platinum | Pt | 21.45 | 10.616 | 63.80 | 0.003 | 0–100 | 1200 | 1773 |
| Silver | Ag | 10.5 | 1.622 | 9.755 | 0.00361 | 0–100 | 650 | 960 |
| Tungsten | W | 19.3 | 5.523 | 33.22 | 0.0045 | — | * | 3410 |

* Tungsten subject to rapid oxidation in air above 150°C.

thermoelectric power to copper, it is valuable for thermoelements and pyrometers. It is noncorrosive and is used to a large extent in industrial and radio rheostats. **Hytemco** is a nickel-iron alloy characterized by a high temperature coefficient and is used advantageously where self-regulation is required as in immersion heaters and heater pads. **Magno** is a manganese-nickel alloy used in the manufacture of incandescent lamps and radio tubes. **Manganin** is a copper-manganese-nickel alloy which, because of its very low temperature coefficient and its low thermal emf with respect to copper, is very valuable for high-precision electrical measuring apparatus. It is used for the resistance units in bridges, for shunts, multipliers, and similar measuring devices. **Nichrome V** is a nickel-chromium alloy free from iron, is noncorrosive, nonmagnetic, withstands high temperatures, and has high resistivity. It is recommended as material for heating elements in electric furnaces, hot-water heaters, ranges, radiant heaters, and high-grade electrical appliances. **Kanthal** is used for heating applications where higher operating temperatures are required than for Nichrome. Mechanically, it is less workable than Nichrome. **Platinum** is used in specialized heating applications where very high temperatures are required. **Tungsten** may be used in very high temperature ovens with an inert atmosphere. **Pure nickel** is used to satisfy the high requirements in the fabrication of radio tubes, such as the elimination of all gases and impurities in the metal parts. It also has other uses such as in incandescent lamps, for combustion boats, laboratory accessories, and resistance thermometers.

**Carbon** withstands high temperatures and has high resistance; its temperature coefficient is negative; it will safely carry about 125 A/in$^2$. Amorphous carbon has a resistivity of 3,800 and 4,100 $\mu\Omega \cdot$cm, retort carbon about 720 $\mu\Omega \cdot$cm, and graphite about 812 $\mu\Omega \cdot$cm. The properties of any particular kind of carbon depend on the temperature at which it was fired. Carbon for rheostats may best be used in the form of compression rheostats. **Silicon carbide** is used to manufacture heating rods that will safely operate at 1,650°C (3,000°F) surface temperature. It has a negative coefficient of resistance up to 650°C, after which it is positive. It must be mechanically protected because of inherent brittleness.

## MAGNETS

A **permanent magnet** is one that retains a considerable amount of magnetism indefinitely. Permanent magnets are used in electrical instruments, telephone receivers, loudspeakers, magnetos, tachometers, magnetic chucks, motors, and for many purposes where a constant magnetic field or a constant source of magnetism is desired. The magnetic material should have high retentivity, a high remanence, and a high coercive force (see Fig. 15.1.8). These properties are usually found with hardened steel and its alloys and also in ceramic permanent magnet materials.

Since permanent magnets must operate on the molecular mmf imparted to them when magnetized, they must necessarily operate on the portion *CDO* of the hysteresis loop (see Fig. 15.1.8). The area *CDO* is proportional to the **stored energy** within the magnet and is a criterion of its usefulness as a permanent-magnetic material. In the left half of Fig. 15.1.97 are given the *B-H* characteristics of several permanent-magnetic materials; these include 5 to 6 percent tungsten steel (curve 1); 3½ percent chrome magnet steel (curve 2); cobalt magnet steel, containing 16 to 36 percent cobalt and 5 to 9 percent chromium and in some alloys tungsten (curve 3); and the carbon-free aluminum-nickel-cobalt-steel alloys called Alnico. There are many grades of Alnico; the characteristics of three of them are shown by curves 4, 5, 6. Their composition is as follows:

| Curve | Alnico no. | Composition, percent | | | | | |
|---|---|---|---|---|---|---|---|
| | | Al | Ni | Co | Cu | Ti | Fe |
| 4 | 5 | 8 | 14 | 24 | 3 | . . . | 51 |
| 5 | 6 | 8 | 14 | 24 | 3 | 1.25 | 49.75 |
| 6 | 12 | 6 | 18 | 35 | . . . | 8.0 | 33 |

All the Alnicos can be made by the sand or the precision-casting (lost-wax) process, but the most satisfactory method is by the sintering process.

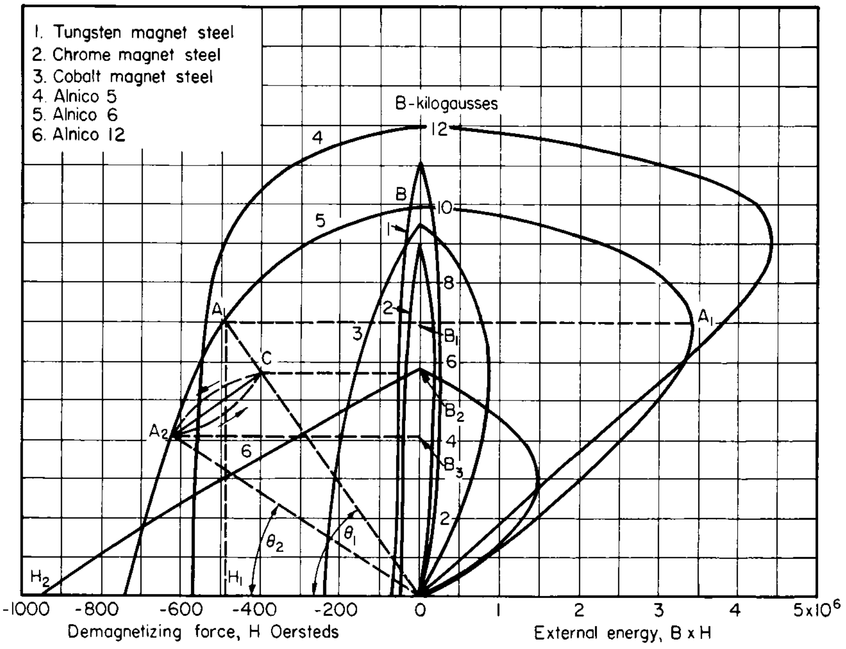


**Fig. 15.1.97** Characteristics of permanent magnet materials.

If the alloys are held in a magnetic field during heat-treatment, a **magnet grain** is established and the magnetic properties in the direction of the field are greatly increased. The alloys are hard, can be formed only by casting or sintering, and cannot be machined except by grinding.

The curves in the right half of Fig. 15.1.97 are ‘‘external energy’’ curves and give the product of $B$ and $H$. The optimum point of operation is at the point of maximum energy as is indicated at $A_1$ on curve 5.

Considering curve 5, if the magnetic circuit remained closed, the magnet would operate at point $B$. To utilize the flux, an air gap must be introduced. The air gap acts as a demagnetizing force, $H_1$ $(= B_1A_1)$, and the magnet operates at point $A_1$ on the $HB$ curve. The line $OA_1$ is called the *air-gap line* and its slope is given by tan $\theta_1 = B_1/H_1$ where $H_1 = B_g l_g / l_m$ and $B_1/B_g = A_g/A_m$, where $B_g$ = flux density in gap, T; $l_g$ = length of gap, m; $l_m$ = length of magnet, m; $A_g$, $A_m$ = areas of the gap and magnet, m$^2$.

If the air gap is lengthened, the magnet will operate at $A_2$ corresponding to a lesser flux density $B_3$ and the new air-gap line is $OA_2$. If the gap is now closed to its original value, the magnet will not return to operation at point $A_1$ but will operate at some point $C$ on the line $OA_1$. If the air gap is varied between the two foregoing values, the magnet will operate along the **minor hysteresis loop** $A_2C$. Return to point $A_1$ can be accomplished only by remagnetizing and coming back down the curve from $B$ to $A_1$.

Alnico magnets corresponding to curves 4 and 5 are best adapted to operation with short air gaps, since the introduction of a long air gap will demagnetize the magnet materially. On the other hand, a magnet with a long air gap will operate most satisfactorily on curve 6 on account of the high coercive force $H_2$. With change in the length of the air gap, the operation will be essentially along that curve and the magnet will lose little of its original magnetization.

There are several other grades of Alnico with characteristics between curves 4, 5, and 6. Ceramic PM materials have a very large coercive force.

The steels for permanent magnets are cut in strips, heated to a red-hot temperature, and forged into shape, usually in a ‘‘bulldozer.’’ If they are to be machined, they are cooled in mica dust to prevent air hardening. They are then ground, tumbled, and tempered. Alnico and ceramic types are cast and then finish-ground.

Permanent magnets are magnetized either by placing them over a bus bar carrying a large direct current, by placing them across the poles of a powerful electromagnet, or by an ampere-turn pulse.

Unless permanent magnets are subjected to artificial aging, they gradually weaken until after a long period they become stabilized usually at from 85 to 90 percent of their initial strength. With magnets for electrical instruments, where a constant field strength is imperative, artificial aging is accomplished by mechanical vibration or by immersion in oil at 250°F for a period of a few hours.

In an **electromagnet** the magnetic field is produced by an electric current. The core is usually made of soft iron or mild steel because, the permeability being higher, a stronger magnetic field may be obtained. Also since the retentivity is low, there is little trouble due to the sticking of armatures when the circuit is opened. Electromagnets may have the form of simple solenoids, iron-clad solenoids, plunger electromagnets, electromagnets with external armatures, and lifting magnets, which are circular in form with a flat holding surface.

A **solenoid** is a winding of insulated conductor and is wound helically; the direction of winding may be either right or left. A **portative electromagnet** is one designed only for holding material brought in contact with it. A **tractive electromagnet** is one designed to exert a force on the load through some distance and thus do work. The **range** of an electromagnet is the distance through which the plunger will perform work when the winding is energized. For long range of operation, the plunger type of tractive magnet is best suited, for the length of core is governed practically by the range of action desired, and the area of the core is determined by the pull. **Solenoid and plunger** is a solenoid provided with a movable iron rod or bar called a plunger. When the coil is energized, the iron rod becomes magnetized and the mutual action of the field in the solenoid on the poles created on the plunger causes the plunger to move within the solenoid. This force becomes zero only when the magnetic centers of the plunger and solenoid coincide. If the load is attached to the plunger, work will be done until the force to be overcome is equal to the force that the solenoid exerts on the plunger. When the iron of the plunger is not saturated, the strength of magnetic field in the solenoid and the induced poles are both proportional to the exciting current, so that the pull varies as the **current squared**. When the plunger becomes highly saturated, the pull varies almost **directly** with the current.

The **maximum uniform pull** occurs when the end of the plunger is at the center of the solenoid and is equal to

$$F = CAnI/l \qquad \text{lb} \qquad (15.1.134)$$

where $A$ = cross-sectional area of plunger, in$^2$; $n$ = number of turns; $I$ = current, A; $l$ = length of the solenoid, in; and $C$ = pull, (lb/in$^2$)/(A-turn/in). $C$ depends on the proportions of the coil, the degree of saturation, the length, and the physical and chemical purity of the plunger. Table 15.1.28 gives values of $C$ for several different solenoids.

Curve 1, Fig. 15.1.98, shows the characteristic pull of an open-magnetic circuit solenoid, 12 in long, having 10,000 A-turns or 833 A-turns/in.

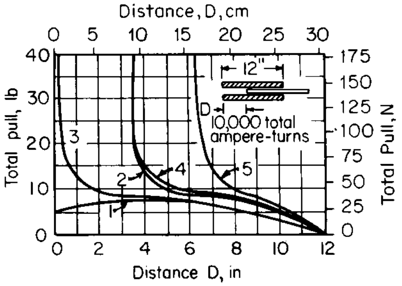


**Fig. 15.1.98** Pull on solenoid with plunger. (1) Coil and plunger; (2) coil and plunger with stop; (3) iron-clad coil and plunger; (4) and (5) same as (3) with different lengths of stop.

When a **strong pull** is desired at the end of the stroke, a stop may be used as shown in Fig. 15.1.99. Curve 2, Fig. 15.1.98, shows the pull obtained by adding a stop to the plunger. It will be noted that, except when the end of the plunger is near the stop, the stop adds little to the

**Table 15.1.28 Maximum Pull per Square Inch of Core for Solenoids with Open Magnetic Circuit**

| Length of coil $l$, in | Length of plunger, in | Core area $A$, in$^2$ | Total ampere-turns $I \times n$ | Max pull $P$, psi | $1{,}000 \times C$ |
|---|---|---|---|---|---|
| 6 | Long | 1.0 | 15,900 | 22.4 | 9.0 |
| 9 | Long | 1.0 | 11,330 | 11.5 | 9.1 |
| 9 | Long | 1.0 | 14,200 | 14.6 | 9.2 |
| 10 | 10 | 2.76 | 40,000 | 40.2 | 10.0 |
| 10 | 10 | 2.76 | 60,000 | 61.6 | 10.3 |
| 10 | 10 | 2.76 | 80,000 | 80.8 | 10.1 |
| 12 | Long | 1.0 | 11,200 | 8.75 | 9.4 |
| 12 | Long | 1.0 | 20,500 | 16.75 | 9.8 |
| 18 | 36 | 1.0 | 18,200 | 9.8 | 9.7 |
| 18 | 36 | 1.0 | 41,000 | 22.5 | 9.8 |
| 18 | 18 | 1.0 | 18,200 | 9.8 | 9.7 |
| 18 | 18 | 1.0 | 41,000 | 22.5 | 9.8 |

SOURCE: From data by Underhill, *Elec. World*, 45, 1906, pp. 796, 881.

solenoid pull. The pull is made up of two components: one due to the attraction between plunger and winding, the other to the attraction between plunger and stop. The equation for the pull is

$$P = AIn[(In/l_a^2 C_1^2) + (C/l)] \qquad (15.1.135)$$

where $A$ = area of the core, in$^2$; $n$ = number of turns; $l_a$ = length of gap between core and stop; and $C$, $C_1$ = constants. At the beginning of the stroke the second member of the equation is predominant, and at the end of the stroke the first member represents practically the entire pull. Approximate values of $C$ and $C_1$ are $C_1 = 2{,}660$ (for $l$ greater than $10d$), $C = 0.0096$, where $d$ is the diameter of the plunger, in. In SI units

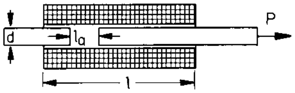


**Fig. 15.1.99** Solenoid with stop.

$$P = 1.7512AnI\left(\frac{2.54nI}{l_a^2 C_1^2} + \frac{C}{l}\right) \quad \text{N} \qquad (15.1.135a)$$

where A is in cm$^2$, $l$ and $l_a$ in cm, and the pull $P$ in N. All other quantities are unchanged.

The **range of uniform** pull can be extended by the use of conical ends of stop and plunger, as shown in Fig. 15.1.100. A stronger magnet mechanically can be obtained by using an iron-clad solenoid, Fig. 15.1.101, in which an iron return path is provided for the flux. Except for low flux densities and short air gaps the dimensions of the iron return path are of no practical importance, and the fact that an iron return path is used does not affect the pull curve except at short air gaps. This is illustrated in Fig. 15.1.98 where curves 3, 4, and 5 are typical pull curves for this same solenoid when it is made iron-clad, each curve corresponding to a different position of the stop.

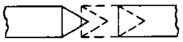


**Fig. 15.1.100** Conical plunger and stop.

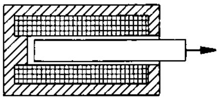


**Fig. 15.1.101** Iron-clad solenoid.

Mechanical jar at the end of the stroke may be prevented by leaving the end of the solenoid open. The plunger then comes to equilibrium when its middle is at the middle of the winding, thus providing a magnetic cushion effect. Electromagnets with external armatures are best adapted for **short-range** work, and the best type is the horseshoe magnet. The pull for short-range magnets is expressed by the equation

$$F = B^2A/72{,}134{,}000 \quad \text{lb} \qquad (15.1.136)$$

where $B$ = flux density, Mx/in$^2$, and $A$ = area of the core, in$^2$.

In SI units

$$F = 397{,}840B^2A \quad \text{N} \qquad (15.1.136a)$$

where the flux density $B$ is in Wb/m$^2$; $A$ = area, m$^2$; and $F$ = force, N.

A greater holding power is obtained if the surfaces of the armature and core are not machined to an absolutely smooth contact surface. If the surface is slightly irregular, the area of contact $A$ is reduced but the flux density $B$ is increased approximately in proportion (if the iron is being operated below saturation) and the pull is increased since it varies as the square of the density $B$. Nonmagnetic stops should be used if it is desired that the armature may be released readily when the current is interrupted.

**Lifting magnets** are of the portative type in that their function is merely to hold the load. The actual lifting is performed by the hoisting apparatus. The magnet is almost toroidal in shape. The coil shield is of manganese steel which is very hard and thus resists wear and is practically nonmagnetic. The holding power is given by Eq. (15.1.136), where $A$ = area of holding surface, in$^2$. It is difficult to calculate accurately the holding force of a lifting magnet for it depends on the magnetic characteristics of the load, the area of contact, and the manner in which the load is applied.

**Rapid action** in a magnet can be obtained by reducing the time constant of the winding and by subdividing the metal parts to reduce induced currents which have a demagnetizing effect when the circuit is closed. The movement of the plunger through the winding causes the winding and its bobbin to be cut by a magnetic field; if the bobbin is of metal and not slotted longitudinally, it is a short-circuited turn linked by a changing magnetic field and hence currents are induced in it. These currents oppose the flux and hence reduce the pull during the transient period. They also cause some heating. Where it is found impossible to reduce the time constant sufficiently, an electromagnet designed for a voltage much lower than normal is often used. A resistor is connected in series which is short-circuited during the stroke of the plunger. At the completion of the stroke the plunger automatically opens the short circuit, reducing the current to a value which will not overheat the magnet under continuous operation. The extremely short time of overload produces very rapid action but does not injure the winding. The solenoids on many automatic motor-starting panels are designed in this manner.

When **slow action** is desired, it can be obtained by using solid cores and yoke and by using a heavy metallic spool or bobbin for the winding. A separate winding short-circuited on itself is also used to some extent.

**Sparking** at switch terminals may be reduced or eliminated by neutralizing the inductance of the winding. This is accomplished by winding a separate short-circuited coil with its wires parallel to those of the active winding. (This method can be used with dc magnets only.) This is not economical, since one-half the winding space is wasted. By connecting a capacitor across the switch terminals, the energy of the inductive discharge on opening the circuit may be absorbed. For the purpose of neutralizing the inductive discharge and causing a quick release, a small **reverse current** may be sent through the coil winding automatically on opening the circuit. Sleeves of tin, aluminum, or copper foil placed over the various layers of the winding absorb energy when the circuit is broken and reduce the energy dissipated at the switch terminals. This scheme can be used for dc magnets only. **Sticking** of the parts of the magnetic circuit due to residual magnetism may be prevented by the use of nonmagnetic stops. In the case of lifting magnets subjected to rough usage and hard blows (as in a steel works), these stops usually consist of plates of manganese steel, which are extremely hard and nonmagnetic.

**AC Tractive Magnets** Because of the iron losses due to eddy currents, the magnetic circuits of ac electromagnets should be composed of laminated iron or steel. The magnetic circuit of large magnets is usually built up of thin sheets of sheet metal held together by means of suitable clamps. Small cores of circular cross section usually consist of a bundle of soft iron wires. Since the iron losses increase with the flux density, it is not advisable to operate at as high a density as with direct current. The current instead of being limited by the resistance of the winding is now determined almost entirely by the inductive reactance as the resistance is small. With the removal of the load the current rises to high values. The pull of ac magnets is nearly constant irrespective of the length of air gap.

In a **single-phase magnet** the pull varies from zero to a maximum and back to zero twice every cycle, which may cause considerable chattering of the armature against the stop. This may be prevented by the use of a spring or, in the case of a solenoid coil, by allowing the plunger to seek its position of equilibrium in the coil. **Chattering** may also be prevented by the use of a short-circuited winding or shading coil around one tip of the pole piece or by the use of polyphase. In a **two-phase magnet** the pull is constant and equal to the maximum instantaneous pull produced by one phase so long as the voltage is a sine function. In a **three-phase magnet** under the same conditions the pull is constant and equal to 1.5 times the maximum instantaneous pull of one phase. Should the load become greater than the minimum instantaneous pull, there will be chattering as in a single-phase magnet.

**Heating of Magnets** The lifting capacity of an electromagnet is limited by the permissible current-carrying capacity of the winding, which, in turn, is dependent on the amount of heat energy that the winding can dissipate per unit time without exceeding a given temperature rise. **Enamels, synthetic varnishes,** and **thermoplastic wire insulations** are available to allow a wide variety of temperature rises.

**Design of Exciting Coil** Let $n$ = number of turns, $l$ = mean length of turn, in ($l = 2\pi r$, where $r$ is the mean radius, in), $A$ = cross section of wire, cir mils. The resistance of 1 cir mil · ft of copper is practically 12 Ω at 60°C, or 1 Ω/cir mil · in. Hence the resistance, $R = nl/A$ Ω; the current, $I = EA/nl$; the ampere-turns, $nI = EA/l$; the power to be dissipated, $P = E^2A/nl$ W. From the foregoing equations the cross section of wire and the number of turns can be calculated.

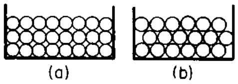


**Fig. 15.1.102** Winding space factor.

**Space Factor of Winding** Space factor of a coil is the ratio of the space occupied by the conductor to the total volume of the coil or winding. Only in the theoretical case of uninsulated square or rectangular conductor may the space factor be 100 percent. For wire of circular section with insulation of negligible thickness, wound as shown in Fig. 15.1.102*a*, the space factor will be 78.5 percent. When the turns of wire are ''bedded,'' as shown in Fig. 15.1.102*b* (the case in most windings, particularly with smaller wires), there is a theoretical gain of about 7 percent in space factor. Experiments have shown that in most cases this gain is about neutralized in practice by the flattening out of the insulation of the wire due to the tension used in winding. When wound in a haphazard manner, the space factors of magnet wires vary according to size, substantially as follows:

| | Double cotton covered | | | | Single cotton covered | | | |
|---|---|---|---|---|---|---|---|---|
| Size, AWG | 0 | 5 | 10 | 15 | 20 | 25 | 30 | 35 |
| Space factor, % | 60 | 53.8 | 45.5 | 35.1 | 32.2 | 32 | 25.7 | 16 |

**Magnet wire** is usually a soft insulated annealed copper wire of high conductivity. It can be obtained in square, rectangular, and circular section, but the round or cylindrical wire is used almost entirely in the smaller sizes. Ribbons are frequently used in the larger sizes. **Aluminum** has been used at times. A number of different varnish or enamel insulating compounds are available in different temperature classes, up to 220°C, the **temperature** rating and thickness for **dielectric strength** being dependent on the usage. Where **mechanical strength** is important and space is not at a premium, textile or paper insulation is used on the wires and later varnish impregnated for high dielectric strength. **Asbestos-covered** magnet wire is used where the temperature is high. It combines

**Table 15.1.29 Magnet-Wire Dimensions, Sizes 14 to 44 AWG**

| | | | | Single | | Heavy | |
|---|---|---|---|---|---|---|---|
| | Bare wire diameter, in | | | Minimum increase in diameter, in | Maximum overall diameter, in | Minimum increase in diameter, in | Maximum overall diameter, in |
| AWG | Minimum | Nominal | Maximum | | | | |
| 14 | 0.0635 | 0.0641 | 0.0644 | 0.0016 | 0.0666 | 0.0032 | 0.0682 |
| 15 | 0.0565 | 0.0571 | 0.0574 | 0.0015 | 0.0594 | 0.0030 | 0.0609 |
| 16 | 0.0503 | 0.0508 | 0.0511 | 0.0014 | 0.0531 | 0.0029 | 0.0545 |
| 17 | 0.0448 | 0.0453 | 0.0455 | 0.0014 | 0.0475 | 0.0028 | 0.0488 |
| 18 | 0.0399 | 0.0403 | 0.0405 | 0.0013 | 0.0424 | 0.0026 | 0.0437 |
| 19 | 0.0355 | 0.0359 | 0.0361 | 0.0012 | 0.0379 | 0.0025 | 0.0391 |
| 20 | 0.0317 | 0.0320 | 0.0322 | 0.0012 | 0.0339 | 0.0023 | 0.0351 |
| 21 | 0.0282 | 0.0285 | 0.0286 | 0.0011 | 0.0303 | 0.0022 | 0.0314 |
| 22 | 0.0250 | 0.0253 | 0.0254 | 0.0011 | 0.0270 | 0.0021 | 0.0281 |
| 23 | 0.0224 | 0.0226 | 0.0227 | 0.0010 | 0.0243 | 0.0020 | 0.0253 |
| 24 | 0.0199 | 0.0201 | 0.0202 | 0.0010 | 0.0217 | 0.0019 | 0.0227 |
| 25 | 0.0177 | 0.0179 | 0.0180 | 0.0009 | 0.0194 | 0.0018 | 0.0203 |
| 26 | 0.0157 | 0.0159 | 0.0160 | 0.0009 | 0.0173 | 0.0017 | 0.0182 |
| 27 | 0.0141 | 0.0142 | 0.0143 | 0.0008 | 0.0156 | 0.0016 | 0.0164 |
| 28 | 0.0125 | 0.0126 | 0.0127 | 0.0008 | 0.0140 | 0.0016 | 0.0147 |
| 29 | 0.0112 | 0.0113 | 0.0114 | 0.0007 | 0.0126 | 0.0015 | 0.0133 |
| 30 | 0.0099 | 0.0100 | 0.0101 | 0.0007 | 0.0112 | 0.0014 | 0.0119 |
| 31 | 0.0088 | 0.0089 | 0.0090 | 0.0006 | 0.0100 | 0.0013 | 0.0108 |
| 32 | 0.0079 | 0.0080 | 0.0081 | 0.0006 | 0.0091 | 0.0012 | 0.0098 |
| 33 | 0.0070 | 0.0071 | 0.0072 | 0.0005 | 0.0081 | 0.0011 | 0.0088 |
| 34 | 0.0062 | 0.0063 | 0.0064 | 0.0005 | 0.0072 | 0.0010 | 0.0078 |
| 35 | 0.0055 | 0.0056 | 0.0057 | 0.0004 | 0.0064 | 0.0009 | 0.0070 |
| 36 | 0.0049 | 0.0050 | 0.0051 | 0.0004 | 0.0058 | 0.0008 | 0.0063 |
| 37 | 0.0044 | 0.0045 | 0.0046 | 0.0003 | 0.0052 | 0.0008 | 0.0057 |
| 38 | 0.0039 | 0.0040 | 0.0041 | 0.0003 | 0.0047 | 0.0007 | 0.0051 |
| 39 | 0.0034 | 0.0035 | 0.0036 | 0.0002 | 0.0041 | 0.0006 | 0.0045 |
| 40 | 0.0030 | 0.0031 | 0.0032 | 0.0002 | 0.0037 | 0.0006 | 0.0040 |
| 41 | 0.0027 | 0.0028 | 0.0029 | 0.0002 | 0.0033 | 0.0005 | 0.0036 |
| 42 | 0.0024 | 0.0025 | 0.0026 | 0.0002 | 0.0030 | 0.0004 | 0.0032 |
| 43 | 0.0021 | 0.0022 | 0.0023 | 0.0002 | 0.0026 | 0.0004 | 0.0029 |
| 44 | 0.0019 | 0.0020 | 0.0021 | 0.0001 | 0.0024 | 0.0004 | 0.0027 |

SOURCE: ''Standard Handbook for Electrical Engineers,'' Fink and Carrol, McGraw-Hill, New York, 1968.

resistance to heat and abrasion, can resist mild acids, has good dielectric strength, and is fireproof.

Table 15.1.29 gives the diameters of magnet wire with the different types of insulation. For further data on electrical insulating materials, see Sec. 6.

## AUTOMOBILE SYSTEMS

### Automobile Ignition Systems

The ignition system in an automobile produces the spark which ignites the combustible mixture in the engine cylinders. This is accomplished by a high-voltage, or high-tension, spark between metal points in a spark plug. (A spark plug is an insulated bushing screwed into the cylinder head.) Spark plugs usually have porcelain insulation, but for some special uses, such as in airplane engines, mica may be used. There are two general sources for the energy necessary for ignition; one is the electrical system of the car which is maintained by the generator and the battery **(battery ignition),** and the other is a **magneto.** Battery ignition systems have traditionally operated electromechanically, using a spark coil, a high-voltage distributor, and low-voltage breaker points. Electronic ignition systems, working from the battery, became standard on U.S. cars in 1975. These vary in complexity from the use of a single transistor to reduce the current through the points to pointless systems triggered by magnetic pulses or interrupted light beams. Capacitor discharge into a pulse transformer is used in some systems to obtain the high voltage needed to fire the spark plugs.

**Battery ignition** is most widely used since it is simple, reliable, and low in cost, and the electrical system is a part of the car equipment. The high voltage for the spark is obtained from an ignition coil which consists of a primary coil of relatively few turns and a secondary coil of a large number of turns, both coils being wound on a common magnetic core consisting of either thin strips of iron or small iron wires. In a 6-V system the resistance of the primary coil is from 0.9 to 2 Ω and the inductance is from 5 to 10 mH. The number of secondary turns varies from 9,000 to 25,000, and the ratio of primary to secondary turns varies from 1 : 40 to 1 : 100.

The coil operates on the following principle. It stores energy in a magnetic field relatively slowly and then releases it suddenly. The power developed ($p = dw/dt$) is thus relatively large ($w$ = stored energy). The high emf $e_2$ which is required for the spark is induced by the sudden change in the flux $\phi$ in the core of the coil when the primary current is suddenly interrupted, $e_2 = -n_2(d\phi/dt)$, where $n_2$ is the number of secondary turns. For satisfactory ignition, peak voltages from 10 to 20 kV are desirable. Figure 15.1.103 shows the relation between the volts required to produce a spark and pressure with compressed air.

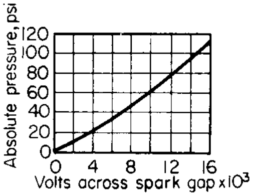


**Fig. 15.1.103** Pressure-voltage curve for spark plug.

A battery ignition system for a four-cylinder engine is shown diagrammatically in Fig. 15.1.104. The primary circuit supplied by the battery consists of the primary coil $P$ and a set of contacts, or ''points'' operated by a four-lobe cam, in series. In order to reduce arcing and burning of the contacts and to produce a sharp break in the current, a capacitor $C$ is connected across the contacts. The contacts, which are of pure tungsten, are operated by a four-lobe cam which is driven at one-half engine speed. A strong spring tends to keep the contacts closed.

In the Delco-Remy distributor (Fig. 15.1.105) two breaker arms are connected in parallel; one coil and one capacitor are used. One set of contacts is open when the other is just breaking but closes a few degrees after the break occurs. This closes the primary of the ignition coil immediately after the break and increases the time that the primary of the ignition coil is closed and permits the flux in the iron to reach its full value. The interrupter shown in Fig. 15.1.105 is designed for an eight-cylinder engine.

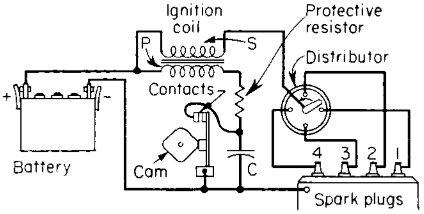


**Fig. 15.1.104** Battery-ignition system.

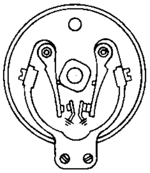


**Fig. 15.1.105** Delco-Remy eight-cylinder interrupter.

**Electronic ignition systems** have no problem operating at the required speed.

The spark should advance with increase in engine speed so as to allow for the time lag in the explosion. To take care of this **automatically** most timers are now equipped with centrifugally operated weights which advance the breaker cam with respect to the engine drive as the speed increases.

### Automobile Lighting and Starting Systems

Automobile lighting and starting systems initially operated at 6 V, but at present nearly all cars, except the smaller ones, operate at 12 V because larger engines, particularly V-8s, are now common and require more starting power. With 12 V, for the same power, the starting current is halved, and the effect of resistance in the leads, connections, and brushes is materially reduced. In some systems the positive side of the system is grounded, but more often the negative side is grounded.

A further development is the application of an **ac generator,** or alternator, combined with a rectifier as the generating unit rather than the usual dc generator. One advantage is the elimination of the commutator, made up of segments, which requires some maintenance due to the sparking and wear of the carbon brushes. With the alternator the dc field rotates, the brushes operating on smooth slip rings require almost no maintenance. Also, the system is greatly simplified by the fact that rectifiers are ''one-way'' devices, and the battery **cannot** deliver current back to the generator when its voltage drops below that of the battery. Thus, no cutout relay, such as is required with dc generators, is necessary. This ac development is the result of the development of reliable, low-cost germanium and silicon semiconductor rectifiers.

Figure 15.1.106 shows a schematic diagram of the Ford system (adapted initially to trucks). The generator stator is wound three-phase Y-connected, and the field is bipolar supplied with direct current through slip rings and brushes. The rectifier diodes are connected full-wave bridge circuit to supply the battery through the ammeter.

**Regulator** The function of the regulator is to control the generator current so that its value is adapted to the battery voltage which is related to the condition of charge of the battery (see Fig. 15.1.15). Thus, when the battery voltage drops (indicating a lowered condition of charge), the current should be increased, and, conversely, when the battery voltage increases (indicating a high condition of charge), the current should be decreased.

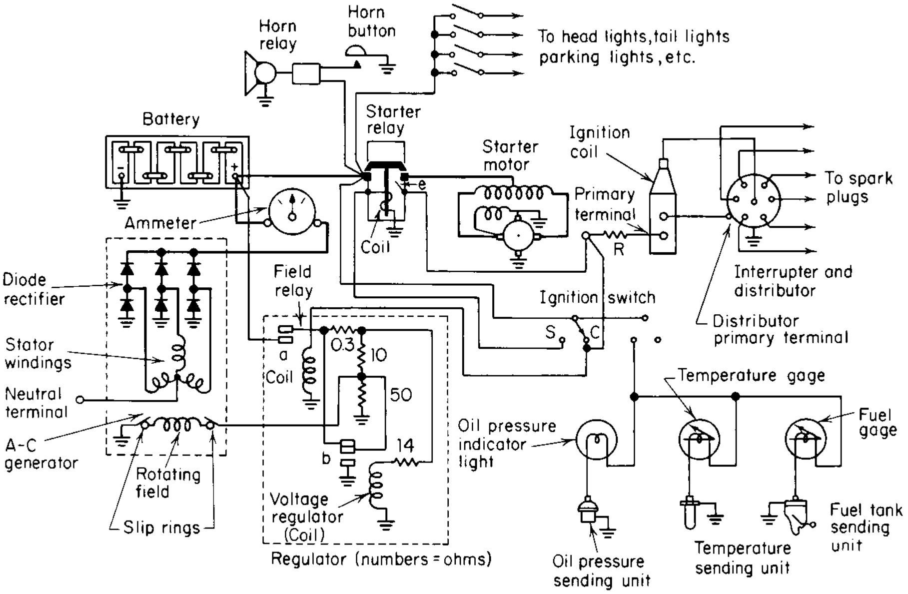


**Fig. 15.1.106** Schematic diagram of Ford lighting and starting system.

Neglecting for the moment the starting procedure, when the ignition switch is thrown to the normal ''on'' position at *c*, the coil actuating the field relay is connected to the battery + terminal and causes the relay contacts *a* to close. This energizes the regulator circuits, and, if the two upper voltage regulator contacts *b* are closed as shown, the rotating field of the alternator is connected directly to the battery + terminal, and the field current is then at its maximum value and produces a high generator voltage and large output current. At the same time the voltage regulator coil in series with the 0.3- and 14-Ω resistors is connected between the battery + terminal and ground. If the voltage of the battery rises owing to its higher condition of charge, the current to the voltage regulator coil increases, causing it to open the two upper contacts at *b*. Current from the battery now flows through the 0.3-Ω resistor and divides, some going through the 10-Ω resistor and dividing between the field and the 50-Ω resistor, and the remainder going to the voltage regulator coil. The current to the rotating field is thus reduced, causing the alternator output to be reduced. Because of the 0.3 Ω now in circuit, the current to the coil of the voltage regulator is reduced to such a value that it holds the center contact at *b* in the mid, or open, position. If the battery voltage rises to an even higher value, the regulator coil becomes strong enough to close the lower contacts at *b*; this short-circuits the field, reducing its current almost to zero, and thus reducing the alternator output to zero. On the other hand when the battery voltage drops, the foregoing sequence is reversed, and the contacts at *b* operate to increase the current to the alternator field.

As was mentioned earlier, the battery cannot supply current to the alternator because of the ''one-way'' characteristic of the rectifier. Thus, when the alternator voltage drops below that of the battery and even when the alternator stops running, its current automatically becomes zero. The alternator has a normal rectifier open-circuit voltage of about 14 V and a rating of 20 A.

**Starting** In most cases, for starting, the ignition key is turned far to the right and held there until the motor starts. Then, when the key is released, the ignition switch contacts assume a normal operating position. Thus, in Fig. 15.1.106, when the ignition-switch contact is in the starting position *S*, the starter relay coil becomes connected by a lead to the battery + terminal and thus becomes energized, closing the relay contacts. The starter motor is then connected to the battery to crank the engine. At the time that the contact closes it makes contact with a small metal brush *e* which connects the battery + terminal to the primary terminal of the ignition coil through the protective resistor *R*. After the motor starts, the ignition switch contacts spring to the normal operating position *C*, and the starter relay switch opens, thereby breaking contact with the small brush *e*. However, when contact *C* is closed, the ignition coil primary terminal is now connected through leads to the battery + terminal. The interrupter, the ignition coil, and the distributor now operate in the manner described earlier (see Fig. 15.1.104); the system shown in Fig. 15.1.106 is that for a six-cylinder engine.

The connection of **accessories** to the electric system is illustrated in Fig. 15.1.106 for the horn, head and other lights, and temperature and fuel gages.

### Magneto Ignition

**Principle of Magneto** A magneto is an electric generator in which the magnetic flux is provided by one or more permanent magnets. It is a self-contained unit and is used advantageously for ignition where a generator and a battery are not needed to supply power to other accessories. The design of magnetos was radically changed when Alnico, with its very high retentivity (Fig. 15.1.97), became available as a permanent-magnet material. One method of utilizing Alnico magnets is to insert the bar magnets in the frame of the magneto (Fig. 15.1.107). The rotor is a soft-iron bobbin. A primary winding of relatively few turns and a secondary winding of a relatively large number of turns are wound over the laminated yoke *Y*. The position of the rotor shown in (*a*) provides a low reluctance path for the magnetic flux of the left-hand mag-

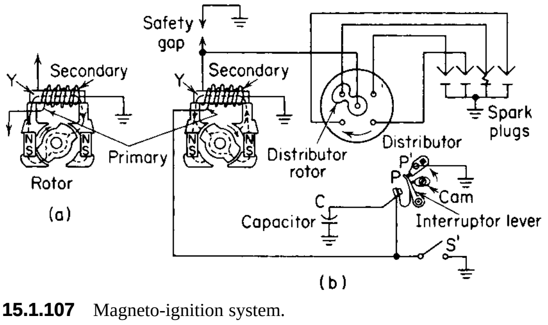


**Fig. 15.1.107** Magneto-ignition system.

net and a high reluctance path for the magnetic flux of the right-hand magnet so that the flux goes through the yoke from left to right as shown. When the rotor turns one-eighth of a revolution, it becomes horizontal; obviously, each of the magnets acts in opposition relative to the yoke, and the flux therein becomes zero. In (*b*), which also shows the external electrical connections, the rotor is shown as having turned one-fourth of a revolution, or 90°, from its position in (*a*).

The rotor now provides a low-reluctance path for the right-hand magnet and a high-reluctance path for the left-hand one. Thus the magnetic flux now goes through the yoke from right to left. It follows that in each 90° interval the flux in the yoke undergoes a complete reversal. It will be recognized that this is an **inductor** type of ac generator.

In the diagram in (*b*), one end each of the primary and of the secondary are grounded together. The other end of the primary is connected to an insulated interrupter lever having a contact point $P$. This makes intermittent contact with the grounded contact point $P'$. The contact point $P$ is actuated by a cam which is driven by the same shaft as the magneto rotor and is in a definite relation to it. A switch $S'$ is provided to ground and thus short-circuit the secondary when it is desired to stop the engine. A capacitor $C$ is connected between the point $P$ and ground to absorb the energy of the spark which occurs when the contacts open.

With the contacts closed, the primary is short-circuited, and the varying flux in the core produced by the rotation of the rotor induces an alternating current in the winding which in turn produces an alternating flux in the core. With the rotation of the rotor the current in the secondary rises cyclically to maximum values, and at these instants the cam causes the points $PP'$ to open suddenly, interrupting the current in the primary and thus causing a sudden collapse of the flux in the core. This induces a high-impulse emf in the secondary which is transmitted to the distributor and thence to the proper spark plug as shown.

On starting, the speed of the magneto may be so low that the emf is not sufficient to produce a hot spark. This difficulty can be met by impulse starting, in which the rotor is driven through a spring. During cranking the rotor is restrained from turning until the engine comes to the proper firing position, at which time the rotor is suddenly released. The energy stored in the spring produces a high, instantaneous, angular velocity to the rotor, resulting in a high emf and hot spark.

Inductor-type magnetos, having a large number of rotor poles and arranged differently from those shown in Fig. 15.1.107, are used for airplane-engine ignition. In another magneto design the rotor is a solid cylindrical Alnico magnet, permanently magnetized with an N and an S pole diametrically opposite. The frame is laminated, and there is a yoke with primary and secondary windings. When the rotor rotates, its N and S poles produce an alternating flux in the yoke which induces a short-circuit current in the primary winding and the method of producing the spark is then the same as with Fig. 15.1.107*b*.

### Miscellaneous Automobile Electronics Systems

The use of electronics on automobiles is expanding rapidly. **Microprocessors** are being installed to control many functions that were previously not controlled or poorly controlled.

**Air-fuel ratio** is controlled from sensing oxygen in the exhaust system. **Timing** is based on crankshaft position, acceleration, and engine temperature. **Air injection** into exhaust and recirculation of exhaust reduces emissions. **Knock** is prevented by stopping untimely detonations. **Diagnosis** of problems is performed. Car leveling and load matching are made by shock absorber adjustments. Wheel **spin** is prevented. **Transmission** controls provide improved efficiency. Operator interfaces are by **cathode ray tube, fluid crystal, vacuum fluorescent displays,** and **speech synthesis. Navigation aids** are in a rudimentary state.

# 15.2 ELECTRONICS

by Byron M. Jones

REFERENCES: ‘‘Reference Data for Radio Engineers,’’ Howard Sams & Co. ‘‘Transistor Manual,’’ General Electric Co. ‘‘SCR Manual,’’ General Electric Co. ‘‘The Semiconductor Data Book,’’ Motorola Inc. Fink, ‘‘Television Engineering,’’ McGraw-Hill. ‘‘Industrial Electronics Reference Book,’’ Wiley. Mano, ‘‘Digital and Logic Design,’’ Prentice-Hall. McNamara, ‘‘Technical Aspects of Data Communication,’’ Digital Press. Fletcher, ‘‘An Engineering Approach to Digital Design,’’ Prentice-Hall. ‘‘The TTL Data Book,’’ Texas Instruments, Inc. ‘‘1988 MOS Products Catalog,’’ American Microsystems, Inc. ‘‘1988 Linear Data Book,’’ National Semiconductor Corp. ‘‘CMOS Standard Cell Data Book,’’ Texas Instruments, Inc. ‘‘Power MOSFET Transistor Data,’’ Motorola, Inc. Franco, ‘‘Design with Operational Amplifiers and Analog Integrated Circuits,’’ McGraw-Hill. Soclof, ‘‘Applications of Analog Integrated Circuits,’’ Prentice-Hall. Gibson, ‘‘Computer Systems Concepts and Design,’’ Prentice-Hall. Sedra and Smith, ‘‘Microelectronic Circuits,’’ HRW Saunders. Millman and Grabel, ‘‘Microelectronics,’’ McGraw-Hill. Ghausi, ‘‘Electronic Devices and Circuits: Discrete and Integrated,’’ HRW Saunders. Savant, Roden, and Carpenter, ‘‘Electronic Design Circuits and Systems,’’ Benjamin Cummings. Stearns and Hush, ‘‘Digital Signal Analysis,’’ Prentice-Hall. Kassakian, Schlecht, and Verghese, ‘‘Principles of Power Electronics,’’ Addison Wesley. Yariv, ‘‘Optical Electronics,’’ HRW Saunders.

The subject of electronics can be approached from the standpoint of either the design of devices or the use of devices. The practicing mechanical engineer has little interest in designing devices, so the approach in this article will be to describe devices in terms of their external characteristics.

### Components

**Resistors, capacitors, reactors,** and **transformers** are described earlier in this section, along with basic circuit theory. These explanations are equally applicable to electronic circuits and hence are not repeated here. A description of additional components peculiar to electronic circuits follows.

A **rectifier,** or **diode,** is an electronic device which offers unequal resistance to forward and reverse current flow. Figure 15.2.1 shows the schematic symbol for a diode. The arrow beside the diode shows the direction of current flow. Current flow is taken to be the flow of positive charges, i.e., the arrow is counter to electron flow. Figure 15.2.2 shows typical forward and reverse volt-ampere characteristics. Notice that the scales for voltage and current are not the same for the first and third quadrants. This has been done so that both the forward and reverse characteristics can be shown on a single plot even though they differ by several orders of magnitude.

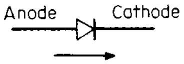


**Fig. 15.2.1** Diode schematic symbol.

**Diodes** are rated for forward current capacity and reverse voltage breakdown. They are manufactured with maximum current capabilities ranging from 0.05 A to more than 1,000 A. Reverse voltage breakdown varies from 50 V to more than 2,500 V. At rated forward current, the forward voltage drop varies between 0.7 and 1.5 V for silicon diodes. Although other materials are used for special-purpose devices, by far the most common semiconductor material is silicon. With a forward current of 1,000 A and a forward voltage drop of 1 V, there would be a power loss in the diode of 1,000 W (more than 1 hp). The basic diode package shown in Fig. 15.2.3 can dissipate about 20 W. To maintain an acceptable temperature in the diode, it is necessary to mount the diode on a **heat sink.** The manufacturer's recommendation should be followed very carefully to ensure good heat transfer and at the same time avoid fracturing the silicon chip inside the diode package.

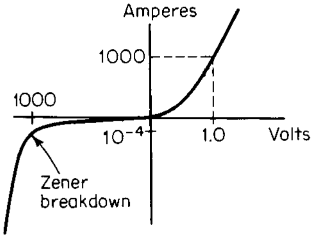


**Fig. 15.2.2** Diode forward-reverse characteristic.

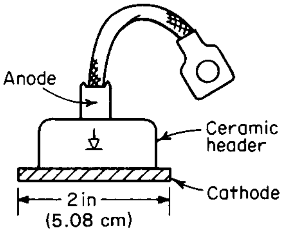


**Fig. 15.2.3** Physical diode package.

The selection of **fuses** or **circuit breakers** for the protection of **rectifiers** and rectifier circuitry requires more care than for other electronic devices. Diode failures as a result of circuit faults occur in a fraction of a millisecond. Special semiconductor fuses have been developed specifically for semiconductor circuits. Proper protective circuits must be provided for the protection of not only semiconductors but also the rest of the circuit and nearby personnel. Diodes and diode fuses have a short-circuit rating in amperes-squared-seconds ($I^2t$). As long as the $I^2t$ rating of the diode exceeds the $I^2t$ rating of its protective fuse, the diode and its associated circuitry will be protected. Circuit breakers may be used to protect diode circuits, but additional line impedance must be provided to limit the current while the circuit breaker clears. Circuit breakers do not interrupt the current when their contacts open. The fault is not cleared until the line voltage reverses at the end of the cycle of the applied voltage. This means that the **clearing time for a circuit breaker** is about ½ cycle of the ac input voltage. Diodes have a 1-cycle overcurrent rating which indicates the fault current the diode can carry for circuit breaker protection schemes. Line inductance is normally provided to limit fault currents for breaker protection. Often this inductance is in the form of leakage reactance in the transformer which supplies power to the diode circuit.

A **thyristor,** often called a **silicon-controlled rectifier (SCR),** is a rectifier which blocks current in both the forward and reverse directions. Conduction of current in the forward direction will occur when the anode is positive with respect to the cathode and when the gate is pulsed positive with respect to the cathode. Once the thyristor has begun to conduct, the gate pulse can return to 0 V or even go negative and the thyristor will continue to pass current. To stop the cathode-to-anode current, it is necessary to reverse the cathode-to-anode voltage. The thyristor will again be able to block both forward and reverse voltages until current flow is initiated by a gate pulse. The schematic symbol for an SCR is shown in Fig. 15.2.4. The physical packaging of thyristors is similar to that of rectifiers with similar ratings except, of course, that the thyristor must have an additional gate connection.

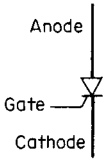


**Fig. 15.2.4** Thyristor schematic symbol.

The gate pulse required to fire an SCR is quite small compared with the anode voltage and current. Power gains in the range of $10^6$ to $10^9$ are easily obtained. In addition, the power loss in the thyristor is very low, compared with the power it controls, so that it is a very efficient power-controlling device. Efficiency in a thyristor power supply is usually 97 to 99 percent. When the thyristor blocks either forward or reverse current, the high voltage drop across the thyristor accompanies low current. When the thyristor is conducting forward current after having been fired by its gate pulse, the high anode current occurs with a forward voltage drop of about 1.5 V. Since high voltage and high current never occur simultaneously, the power dissipation in both the on and off states is low.

The thyristor is rated primarily on the basis of its forward-current capacity and its voltage-blocking capability. Devices are manufactured to have equal forward and reverse voltage-blocking capability. Like diodes, thyristors have $I^2t$ ratings and 1-cycle surge current ratings to allow design of protective circuits. In addition to these ratings, which the SCR shares in common with diodes, the SCR has many additional specifications. Because the thyristor is limited in part by its average current and in part by its rms current, forward-current capacity is a function of the duty cycle to which the device is subjected. Since the thyristor cannot regain its blocking ability until its anode voltage is reversed and remains reversed for a short time, this time must be specified. The time to regain blocking ability after the anode voltage has been reversed is called the **turn-off time**. Specifications are also given for minimum and maximum gate drive. If forward blocking voltage is reapplied too quickly, the SCR may fire with no applied gate voltage pulse. The maximum safe value of rate of reapplied voltage is called the $dv/dt$ rating of the SCR. When the gate pulse is applied, current begins to flow in the area immediately adjacent to the gate junction. Rather quickly, the current spreads across the entire cathode-junction area. In some circuits associated with the thyristor an extremely fast rate of rise of current may occur. In this event localized heating of the cathode may occur with a resulting immediate failure or in less extreme cases a slow degradation of the thyristor. The maximum rate of change of current for a thyristor is given by its $di/dt$ rating. Design for $di/dt$ and $dv/dt$ limits is not normally a problem at power-line frequencies of 50 and 60 Hz. These ratings become a design factor at frequencies of 500 Hz and greater. Table 15.2.1 lists typical thyristor characteristics.

A **triac** is a bilateral SCR. It blocks current in either direction until it receives a gate pulse. It can be used to control in ac circuits. Triacs are widely used for light dimmers and for the control of small universal ac motors. The triac must regain its blocking ability as the line voltage crosses through zero. This fact limits the use of triacs to 60 Hz and below.

A **transistor** is a semiconductor amplifier. The schematic symbol for a transistor is shown in Fig. 15.2.5. There are two types of transistors, *p-n-p* and *n-p-n*. Notice that the polarities of voltage applied to these devices are opposite. In many sizes matched *p-n-p* and *n-p-n* devices are available. The most common transistors have a collector dissipation rating of 150 to 600 mW. Collector to base breakdown voltage is 20 to 50 V. The amplification or gain of a transistor occurs because of two facts: (1) A small change in current in the base circuit causes a large

**Table 15.2.1 Typical Thyristor Characteristics**

| | Current, A | | | | | | |
|---|---|---|---|---|---|---|---|
| Voltage | rms | avg | $I^2t$, $A^2 \cdot s$ | 1-cycle surge, A | $di/dt$, A/$\mu$s | $dv/dt$, V/$\mu$s | Turn-off time, $\mu$s |
| 400 | 35 | 20 | 165 | 180 | 100 | 200 | 10 |
| 1,200 | 35 | 20 | 75 | 150 | 100 | 200 | 10 |
| 400 | 110 | 70 | 4,000 | 1,000 | 100 | 200 | 40 |
| 1,200 | 110 | 70 | 4,000 | 1,000 | 100 | 200 | 40 |
| 400 | 235 | 160 | 32,000 | 3,500 | 100 | 200 | 80 |
| 1,200 | 235 | 160 | 32,000 | 3,500 | 75 | 200 | 80 |
| 400 | 470 | 300 | 120,000 | 5,500 | 50 | 100 | 150 |
| 1,200 | 470 | 300 | 120,000 | 5,500 | 50 | 100 | 150 |

change in current in the collector and emitter leads. This current amplification is designated *hfe* on most transistor specification sheets. (2) A small change in base-to-emitter voltage can cause a large change in either the collector-to-base voltage or the collector-to-emitter voltage. Table 15.2.2 shows basic ratings for some typical transistors. There is a great profusion of transistor types so that the choice of type depends upon availability and cost as well as operating characteristics.

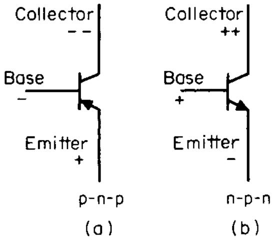


**Fig. 15.2.5** Transistor schematic symbol.

The gain of a transistor is independent of frequency over a wide range. At high frequency, the gain falls off. This cutoff frequency may be as low as 20 kHz for audio transistors or as high as 1 GHz for radio-frequency (rf) transistors.

The schematic symbols for the field effect transistor (FET) is shown in Fig. 15.2.6. The flow of current from source to drain is controlled by an electric field established in the device by the voltage applied between the gate and the drain. The effect of this field is to change the resistance of the transistor by altering its internal current path. The FET has an extremely high gate resistance ($10^{12}$ $\Omega$), and as a consequence, it is used for applications requiring high input impedance. Some FETs have been designed for high-frequency characteristics. The two basic constructions used for FETs are **bipolar junctions** and **metal oxide semiconductors**. The schematic symbols for each of these are shown in Fig. 15.2.6*a* and 15.2.6*b*. These are called JFETs and MOSFETs to distinguish between them. JFETs and MOSFETs are used as stand-alone devices and are also widely used in integrated circuits. (See below, this section.)

A MOSFET with higher current capacity is called a **power MOSFET**. Table 15.2.3 shows some typical characteristics for power MOSFETs. Power MOSFETs are somewhat more limited in maximum power than are thyristors. Circuits with multiple power MOSFETs are limited to about 20 kW. Thyristors are limited to about 1500 kW. As a point of interest, there are electric power applications in the hundreds of megawatts which incorporate massively series and parallel thyristors. An advantage of power MOSFETs is that they can be turned on and turned off by means of the gate-source voltage. Thus low-power electric control can turn the device on and off. Thyristors can be turned on only by their gate voltage. To turn a thyristor off it is necessary for its high-powered anode-to-cathode voltage to be reversed. This factor adds

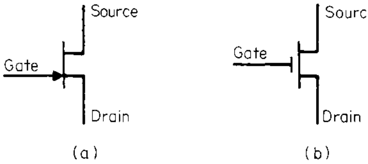


**Fig. 15.2.6** Field-effect transistor. (*a*) Bipolar junction type (JFET); (*b*) metal-oxide-semiconductor type (MOSFET).

**Table 15.2.3 Typical Power MOSFET Characteristics**

| Drain voltage | Device | Drain amperes | Power dissipation, W | Case type |
|---|---|---|---|---|
| 600 | MTH6N60 | 6.0 | 150 | TO-218 |
| 400 | MTH8N40 | 8.0 | 150 | TO-218 |
| 100 | MTH25N10 | 25 | 150 | TO-218 |
| 50 | MTH35N05 | 35 | 150 | TO-218 |
| 600 | MTP1N60 | 1.0 | 75 | TO-220 |
| 400 | MTP2N40 | 2.0 | 75 | TO-220 |
| 100 | MTP10N10 | 10 | 75 | TO-220 |
| 200 | MTE120N20 | 120 | 500 | 346-01 |
| 100 | MTE150N10 | 150 | 500 | 346-01 |
| 50 | MTE200N05 | 200 | 500 | 346-01 |

**Table 15.2.2 Typical Transistor Characteristics**

| JEDEC number | Type | Collector-emitter volts at breakdown, $BV_{CE}$ | Collector dissipation, $P_c(25°C)$ | Collector current, $I_c$ | Current gain, $h_{fe}$ |
|---|---|---|---|---|---|
| 2N3904 | *n-p-n* | 40 | 310 mW | 200 mA | 200 |
| 2N3906 | *p-n-p* | 40 | 310 mW | 200 mA | 200 |
| 2N3055 | *n-p-n* | 100 | 115 W | 15 A | 20 |
| 2N6275 | *n-p-n* | 120 | 250 W | 50 A | 30 |
| 2N5458 | JFET | 40 | 200 mW | 9 mA | * |
| 2N5486 | JFET | 25 | 200 mW | | † |

* JFET, current gain is not applicable.
† High-frequency JFET—up to 400 MHz.

complication to many thyristor circuits. Another power device which is similar to the power MOSFET is the **insulated gate-bipolar transistor (IGBT)**. This device is a **Darlington** combination of a MOSFET and a bipolar transistor (see Fig. 15.2.13). A low-power MOSFET first transistor drives the base of a second high-power bipolar transistor. These two transistors are integrated in a single case. The IGBT is applied in high-power devices which use high-frequency switching. IGBTs are available in ratings similar to thyristors (see Table 15.2.1), so they are power devices. The advantage of the IGBT is that it can be switched on and off by means of its gate. The advantage of an IGBT over a power MOSFET is that it can be made with higher power ratings.

The **unijunction** is a special-purpose semiconductor device. It is a pulse generator and widely used to fire thyristors and triacs as well as in timing circuits and waveshaping circuits. The schematic symbol for a unijunction is shown in Fig. 15.2.7. The device is essentially a silicon resistor. This resistor is connected to base 1 and base 2. The emitter is fastened to this resistor about halfway between bases 1 and 2. If a positive voltage is applied to base 2, and if the emitter and base 1 are at zero, the emitter junction is back-biased and no current flows in the emitter. If the emitter voltage is made increasingly positive, the emitter junction will become forward-biased. When this occurs, the resistance between base 1 and base 2 and between base 2 and the emitter suddenly switches to a very low value. This is a regenerative action, so that very fast and very energetic pulses can be generated with this device.

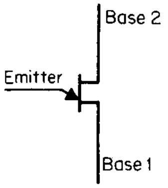


**Fig. 15.2.7** Unijunction.

Before the advent of semiconductors, electronic rectifiers and amplifiers were **vacuum tubes** or **gas-filled tubes**. Some use of these devices still remains. If an electrode is heated in a vacuum, it gives up surface electrons. If an electric field is established between this heated electrode and another electrode so that the electrons are attracted to the other electrode, a current will flow through the vacuum. Electrons flow from the heated cathode to the cold anode. If the polarity is reversed, since there are no free electrons around the anode, no current will flow. This, then, is a vacuum-tube rectifier. If a third electrode, called a **control grid,** is placed between the cathode and the anode, the flow of electrons from the cathode to the anode can be controlled. This is a basic vacuum-tube amplifier. Additional grids have been placed between the cathode and anode to further enhance certain characteristics of the vacuum tube. In addition, multiple anodes and cathodes have been enclosed in a single tube for special applications such as radio signal converters.

If an inert gas, such as neon or argon, is introduced into the vacuum, conduction can be initiated from a cold electrode. The breakdown voltage is relatively stable for given gas and gas pressure and is in the range of 50 to 200 V. The **nixie** display tube is such a device. This tube contains 10 cathodes shaped in the form of the numerals from 0 to 9. If one of these cathodes is made negative with respect to the anode in the tube, the gas in the tube glows around that cathode. In this way each of the 10 numerals can be made to glow when the appropriate electrode is energized.

An **ignitron** is a vapor-filled tube. It has a pool of liquid mercury in the bottom of the tube. Air is exhausted from the enclosure, leaving only mercury vapor, which comes from the pool at the bottom. If no current is flowing, this tube will block voltage whether the anode is plus or minus with respect to the mercury-pool cathode. A small rod called an **ignitor** can form a cathode spot on the pool of mercury when it is withdrawn from the pool. The ignitor is pulled out of the pool by an electromagnet. Once the cathode spot has been formed, electrons will continue to flow from the mercury-pool cathode to the anode until the anode-to-cathode voltage is reversed. The operation of an ignitron is very similar to that of a thyristor. The anode and cathode of each device perform similar functions. The ignitor and gate also perform similar functions. The thyristor is capable of operating at much higher frequencies than the ignitron and is much more efficient since the thyristor has 1.5 V forward drop and the ignitron has 15 V forward drop. The ignitron has an advantage over the thyristor in that it can carry extremely high overload currents without damage. For this reason ignitrons are often used as electronic ‘‘crowbars’’ which discharge electrical energy when a fault occurs in a circuit.

### Discrete-Component Circuits

Several common rectifier circuits are shown in Fig. 15.2.8. The waveforms shown in this figure assume no line reactance. The presence of line reactance will make a slight difference in the waveshapes and the conversion factors shown in Fig. 15.2.8. These waveshapes are equally applicable for loads which are pure resistive or resistive and inductive. In a resistive load the current flowing in the load has the same waveshape as the voltage applied to it. For inductive loads, the current waveshape will be smoother than the voltage applied. If the inductance is high enough, the ripple in the current may be indeterminantly small. An approximation of the ripple current can be calculated as follows:

$$I = \frac{E_{\mathrm{dc}}\,PCT}{200\pi fNL} \tag{15.2.1}$$

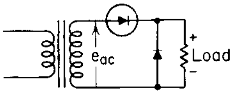
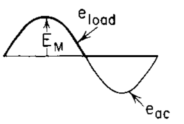
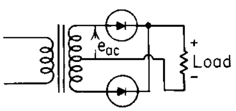
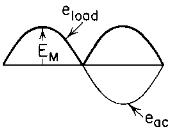
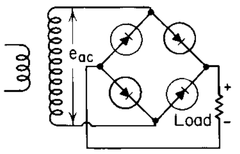
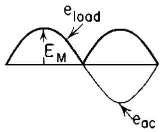
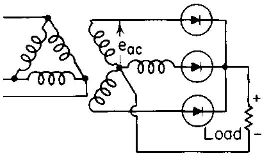
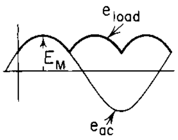
where $I$ = rms ripple current, $E_{\mathrm{dc}}$ = dc load voltage, $PCT$ = percent ripple from Fig. 15.2.8, $f$ = line frequency, $N$ = number of cycles of ripple frequency per cycle of line frequency, $L$ = equivalent series inductance in load. Equation (15.2.1) will always give a value of ripple higher than that calculated by more exact means, but this value is normally satisfactory for power-supply design.

Capacitance in the load leads to increased regulation. At light loads, the capacitor will tend to charge up to the peak value of the line voltage and remain there. This means that for either the single full-wave circuit or the single-phase bridge the dc output voltage would be 1.414 times the rms input voltage. As the size of the loading resistor is reduced, or as the size of the parallel load capacitor is reduced, the load voltage will more nearly follow the rectified line voltage and so the dc voltage will approach 0.9 times the rms input voltage for very heavy loads or for very small filter capacitors. One can see then that dc voltage may vary between 1.414 and 0.9 times line voltage due only to waveform changes when **capacitor filtering** is used.

Four different **thyristor rectifier circuits** are shown in Fig. 15.2.9. These circuits are equally suitable for resistive or inductive loads. It will be noted that the half-wave circuit for the thyristor has a rectifier across the load, as in Fig. 15.2.8. This diode is called a **freewheeling diode** because it freewheels and carries inductive load current when the thyristor is not conducting. Without this diode, it would not be possible to build up current in an inductive load. The gate-control circuitry is not shown in Fig. 15.2.9 in order to make the power circuit easier to see. Notice the location of the thyristors and rectifiers in the single-phase full-wave circuit. Constructed this way, the two diodes in series perform the function of a free-wheeling diode. The circuit can be built with a thyristor and rectifier interchanged. This would work for resistive loads but not for inductive loads. For the full three-phase bridge, a freewheeling diode is not required since the carryover from the firing of one SCR to the next does not carry through a large portion of the negative half cycle and therefore current can be built up in an inductive load.

**Capacitance** must be used with care **in thyristor circuits.** A capacitor directly across any of the circuits in Fig. 15.2.9 will immediately destroy the thyristors. When an SCR is fired directly into a capacitor with no series resistance, the resulting $di/dt$ in the thyristor causes extreme local heating in the device and a resultant failure. A sufficiently high series resistor prevents failure. An inductance in series with a capacitor must also be used with caution. The series inductance may cause the capacitor to ‘‘ring up.’’ Under this condition, the voltage across the capacitor can approach twice peak line voltage or 2.828 times rms line voltage.

The advantage of the thyristor circuits shown in Fig. 15.2.9 over the rectifier circuits is, of course, that the thyristor circuits provide variable output voltage. The output of the thyristor circuits depends upon the magnitude of the incoming line voltage and the phase angle at which the

| Type | Circuit | Output voltage waveform | $E_{dc}$ (avg) | Ripple fundamental frequency | % ripple | Peak inverse voltage |
|---|---|---|---|---|---|---|
| Half-wave 1ϕ |  |  | 0.318 $E_M$<br>0.45 $E_{ac}$ | F | 121 | 3.14 $E_{dc}$ |
| Full-wave 1ϕ |  |  | 0.636 $E_M$<br>0.9 $E_{ac}$ | 2F | 48 | 3.14 $E_{dc}$ |
| Bridge 1ϕ |  |  | 0.636 $E_M$<br>0.9 $E_{ac}$ | 2F | 48 | 1.57 $E_{dc}$ |
| Half-wave 3ϕ |  |  | 0.827 $E_M$<br>1.17 $E_{ac}$ | 3F | 18 | 2.09 $E_{dc}$ |

$E_M$ = maximum value of $e_{ac}$

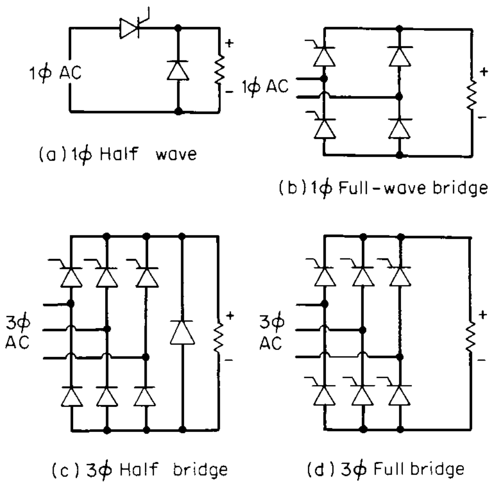
$E_{ac}$ = effective value of $e_{ac}$

$E_{dc}$ = average value of d-c load voltage

F = line frequency

% ripple = 100 x rms ripple/ $E_{dc}$

**Fig. 15.2.8** Comparison of rectifier circuits.



(a) 1ϕ Half wave

(b) 1ϕ Full-wave bridge

(c) 3ϕ Half bridge

(d) 3ϕ Full bridge

**Fig. 15.2.9** Basic thyristor circuits.

thyristors are fired. The control characteristic for the thyristor power supply is determined by the waveshape of the output voltage and also by the phase-shifting scheme used in the firing-control means for the thyristor. Practical and economic power supplies usually have control characteristics with some degree of nonlinearity. A representative characteristic is shown in Fig. 15.2.10. This control characteristic is usually given for nominal line voltage with the tacit understanding that variations in line voltage will cause approximately proportional changes in output voltage.

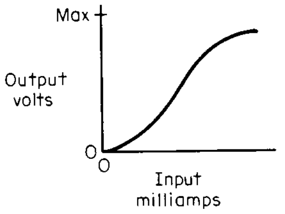


**Fig. 15.2.10** Thyristor control characteristic.

**Transistor amplifiers** can take many different forms. A complete discussion is beyond the scope of this handbook. The circuits described here illustrate basic principles. A basic **single-stage amplifier** is shown in Fig. 15.2.11. The transistor can be cut off by making the input terminal sufficiently negative. It can be saturated by making the input terminal sufficiently positive. In the linear range, the base of an *n-p-n* transistor will be 0.5 to 0.7 V positive with respect to the emitter. The collector voltage will vary from about 0.2 V to $V_c$ (20 V, typically). Note that there is a sign inversion of voltage between the base and the collector; i.e., when the base is made more positive, the collector becomes less positive. The resistors in this circuit serve the following functions. Resistor *R*1 limits the input current to the base of the transistor so that it is not harmed when the input signal overdrives. Resistors *R*2 and *R*3 establish the transistor's operating point with no input signal. Resistors *R*4 and *R*5 determine the voltage gain of the amplifier. Resistor *R*4 also serves to stabilize the zero-signal operating point, as established by resistors *R*2 and *R*3. Usual practice is to design single-stage gains of 10 to 20. Much higher gains are possible to achieve, but low gain levels permit the use of less expensive transistors and increase circuit reliability.

Figure 15.2.12 illustrates a basic **two-stage transistor amplifier** using complementary *n-p-n* and *p-n-p* transistors. Note that the first stage is identical to that shown in Fig. 15.2.11. This *n-p-n* stage drives the following *p-n-p* stage. Additional alternate *n-p-n* and *p-n-p* stages can be added until any desired overall amplifier gain is achieved.

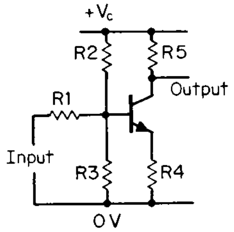


**Fig. 15.2.11** Single-stage amplifier.

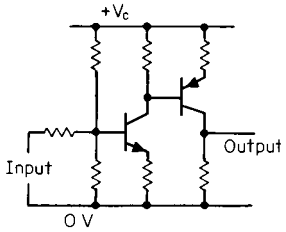


**Fig. 15.2.12** Two-stage amplifier.

Figure 15.2.13 shows the **Darlington** connection of transistors. The amplifier is used to obtain maximum current gain from two transistors.

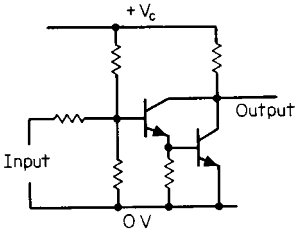


**Fig. 15.2.13** Darlington connection.

Assuming a base-to-collector current gain of 50 times for each transistor, this circuit will give an input-to-output current gain of 2,500. This high level of gain is not very stable if the ambient temperature changes, but in many cases this drift is tolerable.

Figure 15.2.14 shows a circuit developed specifically to minimize temperature drift and drift due to power supply voltage changes. The **differential amplifier** minimizes drift because of the balanced nature of the circuit. Whatever changes in one transistor tend to increase the output are compensated by reverse trends in the second transistor. The input signal does not affect both transistors in compensatory ways, of course, and so it is amplified. One way to look at a differential amplifier is that twice as many transistors are used for each stage of amplification to achieve compensation. For very low drift requirements, matched transistors are available. For the ultimate in differential amplifier performance, two matched transistors are encapsulated in a single unit. **Operational amplifiers** made with discrete components frequently use differential amplifiers to minimize drift and offset. The operational amplifier is a low-drift, high-gain amplifier designed for a wide range of control and instrumentation uses.

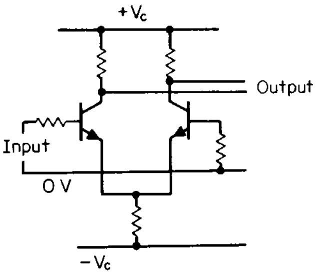


**Fig. 15.2.14** Differential amplifier.

**Oscillators** are circuits which provide a frequency output with no signal input. A portion of the collector signal is fed back to the base of the transistor. This feedback is amplified by the transistor and so maintains a sustained oscillation. The frequency of the oscillation is determined by parallel inductance and capacitance. The oscillatory circuit consisting of an inductance and a capacitance in parallel is called an *LC* **tank circuit.**

This frequency is approximately equal to

$$f = 1/2\pi\sqrt{CL} \tag{15.2.2}$$

where $f$ = frequency, Hz; $C$ = capacitance, F; $L$ = inductance, H. A 1-MHz oscillator might typically be designed with a 20-$\mu$H inductance in parallel with a 0.05-$\mu$F capacitor. The exact frequency will vary from the calculated value because of loading effects and stray inductance and capacitance. The **Colpitts** oscillator shown in Fig. 15.2.15 differs from the **Hartley** oscillator shown in Fig. 15.2.16 only in the way energy is fed back to the emitter. The Colpitts oscillator has a capacitive voltage divider in the resonant tank. The Hartley oscillator has an inductive voltage divider in the tank. The **crystal oscillator** shown in Fig. 15.2.17 has much greater frequency stability than the circuits in Figs. 15.2.15 and 15.2.16. Frequency stability of 1 part in $10^7$ is easily achieved with a crystal-controlled oscillator. If the oscillator is temperature-controlled by mounting it in a small temperature-controlled oven, the frequency stability can be increased to 1 part in $10^9$. The resonant *LC* tank in the collector circuit is tuned to approximately the crystal frequency. The crystal offers a low impedance at its resonant frequency. This pulls the collector-tank operating frequency to the crystal resonant frequency.

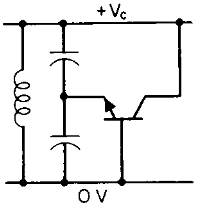


**Fig. 15.2.15** Colpitts oscillator.

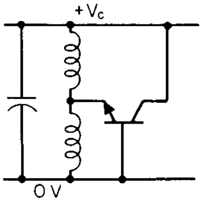


**Fig. 15.2.16** Hartley oscillator.

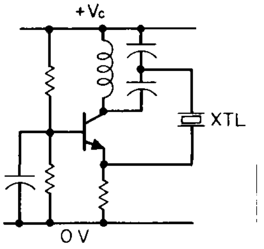


**Fig. 15.2.17** Crystal-controlled oscillator.

As the desired operating frequency becomes 500 MHz and greater, **resonant cavities** are used as tank circuits instead of discrete capacitors and inductors. A rough guide to the relationship between frequency and resonant-cavity size is the wavelength of the frequency

$$\lambda = 300 \times 10^6/f \qquad (15.2.3)$$

where $\lambda$ = wavelength, m; $300 \times 10^6$ = speed of light, m/s; $f$ = frequency, Hz. The resonant cavities will be smaller than indicated by Eq. (15.2.3) because in general the cavity is either one-half or one-fourth wavelength and also, in general, the electromagnetic wave velocity is less in a cavity than in free space.

The operating principles of these devices are beyond the scope of this article. There are many different kinds of **microwave tubes** including **klystrons, magnetrons,** and **traveling-wave** tubes. All these tubes employ moving electrons to excite a resonant cavity. These devices serve as either oscillators or amplifiers at microwave frequencies.

**Lasers** operate at a frequency of light of approximately 600 THz. This corresponds to a wavelength of 0.5 $\mu$m, or, the more usual measure of visual-light wavelength, $5 \times 10^3$ Å. Most laser oscillators are basically a variation of the Fabry-Perot etalon, or interferometer. High-power lasers may be gas, liquid, or ruby-based devices. High-power lasers are used for machining and surveying. A more recent device, invented in 1961, is the semiconductor laser. The semiconductor laser is constructed using gallium arsenide (GaAs) as the semiconductor material. These devices are quite small and can be controlled by means of field-effect transistors. The GaAs laser can be modulated (turned on and off) at a 10 GHz rate, making it ideal for modern fiber-optic communications.

Most light is disorganized insofar as the axis of vibration and the frequency of vibration are concerned. When radiation along different axes is attenuated, as with a polarizing screen, the light is said to be *polarized.* White light contains all visible frequencies. When white light is filtered, the remaining light is colored, or frequency-limited. A single color of light still contains a broad range of frequencies. Polarized, colored light is still so disorganized that it is difficult to focus the light energy into a narrow beam. Laser light is inherently a single-axis, single-frequency light. Lasers can be focused into an extremely narrow beam, making them very accurate cutting tools and surveying devices. Lasers are also widely used for high-speed, wide-frequency-band fiber-optic communications.

A radio wave consists of two parts, a **carrier,** and an information signal. The carrier is a steady high frequency. The information signal may be a voice signal, a video signal, or telemetry information. The carrier wave can be modulated by varying its amplitude or by varying its frequency. **Modulators** are circuits which impress the information signal onto the carrier. A **demodulator** is a circuit in the receiving apparatus which separates the information signal from the carrier. A simple amplitude modulator is shown in Fig. 15.2.18. The transistor is base-driven with the carrier input and emitter driven with the information signal. The modulated carrier wave appears at the collector of the transistor. An FM modulator is shown in Fig. 15.2.19. The carrier must be changed in frequency in response to the information signal input. This is accomplished by using a saturable ferrite core in the inductance of a Colpitts oscillator which is tuned to the carrier frequency. As the collector current in transistor $T1$ varies with the information signal, the saturation level in the ferrite core changes, which in turn varies the inductance of the winding in the tank circuit and alters the operating frequency of the oscillator.

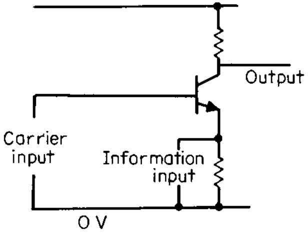


**Fig. 15.2.18** AM modulator.

The **demodulator** for an AM signal is shown in Fig. 15.2.20. The diode rectifies the carrier plus information signal so that the filtered voltage appearing across the capacitor is the information signal. Resistor $R2$ blocks the carrier signal so that the output contains only the information signal. An FM **demodulator** is shown in Fig. 15.2.21. In this circuit, the carrier plus information signal has a constant amplitude. The information is in the form of varying frequency in the carrier wave. If inductor $L1$ and capacitor $C1$ are tuned to near the carrier frequency but not exactly at resonance, the current through resistor $R1$ will vary as the carrier frequency shifts up and down. This will create an AM signal across resistor $R1$. The diode, resistors $R2$ and $R3$, and capacitor $C2$ demodulate this signal as in the circuit in Fig. 15.2.20.

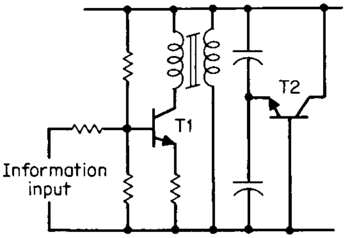


**Fig. 15.2.19** FM modulator.

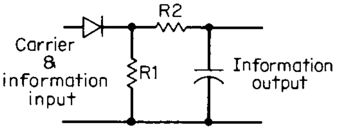


**Fig. 15.2.20** AM demodulator.

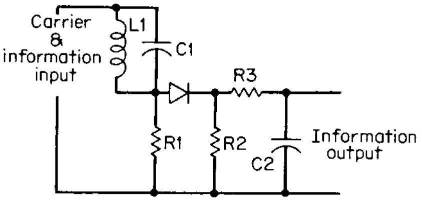


**Fig. 15.2.21** FM discriminator.

The waveform of the basic **electronic timing circuit** is shown in Fig. 15.2.22 along with a basic timing circuit. Switch $S1$ is closed from time $t1$ until time $t3$. During this time, the transistor shorts the capacitor and holds the capacitor at 0.2 V. When switch $S1$ is opened at time $t3$, the transistor ceases to conduct and the capacitor charges exponentially due to the current flow through resistor $R1$. Delay time can be measured to any point along this exponential charge. If the time is measured until time $t6$, the timing may vary due to small shifts in supply voltage or slight changes in the voltage-level detecting circuit. If time is measured until time $t4$, the voltage level will be easy to detect, but the obtainable time delay from time $t3$ to time $t4$ may not be large enough compared with the reset time $t1$ to $t2$. Considerations like these usually dictate detecting at time $t4$. If this time is at a voltage level which is 63 percent of $V_c$, the time from $t3$ to $t4$ is one time constant of $R1$ and $C$. This time can be calculated by

$$t = RC \qquad (15.2.4)$$

where $t$ = time, s; $R$ = resistance, Ω; $C$ = capacitance, F. A timing circuit with a 0.1-s delay can be constructed using a 0.1-$\mu$F capacitor and a 1.0-MΩ resistor.

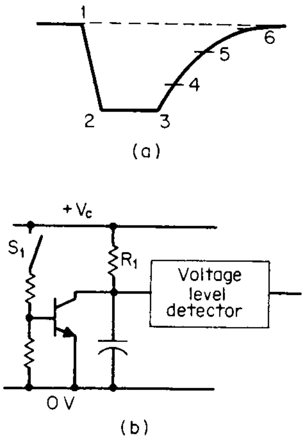


**Fig. 15.2.22** Basic timing circuit.

An improved timing circuit is shown in Fig. 15.2.23. In this circuit, the unijunction is used as a level detector, a pulse generator, and a reset means for the capacitor. The transistor is used as a constant current source for charging the timing capacitor. The current through the transistor is determined by resistors $R1$, $R2$, and $R3$. This current is adjustable by means of $R1$. When the charge on the capacitor reaches approximately 50 percent of $V_c$, the unijunction fires, discharging the capacitor and generating a pulse at the output. The discharged capacitor is then recharged by the transistor, and the cycle continues to repeat. The pulse rate of this circuit can be varied from one pulse per minute to many thousands of pulses per second.

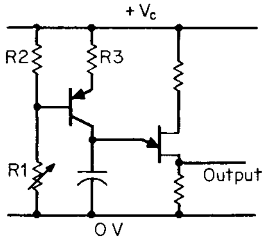


**Fig. 15.2.23** Improved timing circuit.

### Integrated Circuits

Table 15.2.4 lists some of the more common physical packages for discrete component and integrated semiconductor devices. Although discrete components are still used for electronic design, **integrated circuits (ICs)** are becoming predominant in almost all types of electronic equipment. Dimensions of common dual in-line pin (DIP) integrated-circuit devices are shown in Fig. 15.2.24. An IC costs far less than circuits made with discrete components. Integrated circuits can be classified in several different ways. One way to classify them is by complexity. **Small-scale integration (SSI), medium-scale integration (MSI), large-scale integration (LSI),** and **very large scale integration (VLSI)** refer to this kind of classification. The cost and availability of a particular IC are more dependent upon the size of the market for that device than on the level of its internal complexity. For this reason, the classification by circuit complexity is not as meaningful today as it once was. The literature still refers to these classifications, however. For the purpose of this text, ICs will be separated into two broad classes: linear ICs and digital ICs.

**Table 15.2.4 Semiconductor Physical Packaging**

| | |
|---|---|
| Signal devices | |
| Plastic | TO92 |
| Metal can | TO5, TO18, TO39 |
| Power devices | |
| Tab mount | TO127, TO218, TO220 |
| Diamond case | TO3, TO66 |
| Stud mount | |
| Flat base | |
| Flat pak (Hockey puck) | |
| Integrated circuits | |
| Dip (dual in-line pins) | (See Fig. 15.2.24) |
| Flat pack | |
| Chip carrier (50-mil centers) | |

| Number of pins | *W* | *P* | *L* | Approximate height |
|---|---|---|---|---|
| 64 | 0.8 | 0.1 | 3.3 | 0.24 |
| 40 | 0.6 | 0.1 | 2.0 | 0.2 |
| 28 | 0.6 | 0.1 | 1.4 | 0.2 |
| 24 | 0.6 | 0.1 | 1.3 | 0.2 |
| 22 | 0.4 | 0.1 | 1.1 | 0.2 |
| 20 | 0.3 | 0.1 | 1.0 | 0.2 |
| 18 | 0.3 | 0.1 | 0.9 | 0.2 |
| 16 | 0.3 | 0.1 | 0.87 | 0.2 |
| 14 | 0.3 | 0.1 | 0.78 | 0.2 |
| 8 | 0.3 | 0.1 | 0.4 | 0.2 |

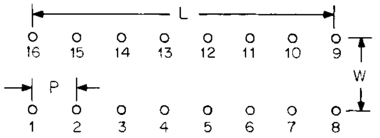


**Fig. 15.2.24** Approximate physical dimensions of dual in-line pin (DIP) integrated circuits. All dimensions are in inches. Dual in-line packages are made in three different constructions—molded plastic, cerdip, and ceramic.

The trend in IC development has been toward greatly increased complexity at significantly reduced cost. Present-day ICs are manufactured with internal spacings as low as 0.5 $\mu$m. The limitation of the contents of a single device is more often controlled by external connections than by internal space. For this reason, more and more complex combinations of circuits are being interconnected within a single device. There is also a tendency to accomplish functions digitally that were formerly done by analog means. Although these digital circuits are much more complex than their analog counterparts, the cost and reliability of ICs make the resulting digital circuit the preferred design. One can expect these trends will continue based on current technology. One can also anticipate further declines in price versus performance. It has been demonstrated again and again that digital IC designs are much more stable and reliable than analog designs.

For years, the complexity of large-scale integrated circuits doubled each year. This meant that, over a 10-year period, the complexity of a single device increased by $2^{10}$ times, or over 1000 times, and, over the period from 1960 to 1980 grew from one transistor on a chip to one million transistors on a chip. More recently the complexity increase has fallen off to only 1.7 times, or $1.7^{10}$, or over 200 times in a 10-year period. Manufacturers also have developed application-specific integrated circuits (ASICs). These devices allow a circuit designer to design integrated circuits almost as easily as printed board circuits.

### Linear Integrated Circuits

The basic building block for many linear ICs is the **operational amplifier**. Table 15.2.5 lists the basic characteristics for a few representative IC operational amplifiers. In most instances, an adequate design for an operational amplifier circuit can be made assuming an ''ideal'' operational amplifier. For an ideal operational amplifier, one assumes that it

**Table 15.2.5 Operational Amplifiers**

| Type | Purpose | Input bias current, nA | Input res., Ω | Supply voltage, V | Voltage gain | Unity-gain bandwidth, MHz |
|---|---|---|---|---|---|---|
| LM741 | General purpose | 500 | $2 \times 10^6$ | +20 | 25,000 | 1.0 |
| LM224 | Quad gen. purpose | 150 | $2 \times 10^6$ | 3 to 32 | 50,000 | 1.0 |
| LM255 | FET input | 0.1 | $10^{12}$ | +22 | 50,000 | 2.5 |
| LM444A | Quad FET input | 0.005 | $10^{12}$ | +22 | 50,000 | 1.0 |

has infinite gain and no voltage drop across its input terminals. In most designs, feedback is used to limit the gain of each operational amplifier. As long as the resulting closed-loop gain is much less than the open-loop gain of the operational amplifier, this assumption yields results that are within acceptable engineering accuracy. Operational amplifiers use a balanced input circuit which minimizes input voltage offset. Furthermore, specially designed operational amplifiers are available which have extremely low input offset voltage. The input voltage must be kept low because of temperature drift considerations. For these reasons, the assumption of zero input voltage, sometimes called a ''virtual ground,'' is justified. Figure 15.2.25 shows three operational amplifier circuits and the equations which describe their behavior. In this figure *S* is the **Laplace transform** variable. In these equations the input and output voltages are functions of *S*. The equations are written in the frequency domain. A simple transformation to steady variable-frequency behavior can be obtained by simply substituting cos *ωt* for the variable *S* wherever it appears in the equation. By varying *ω*, the frequency in radians per second, one can obtain the steady-state frequency response of the circuit.

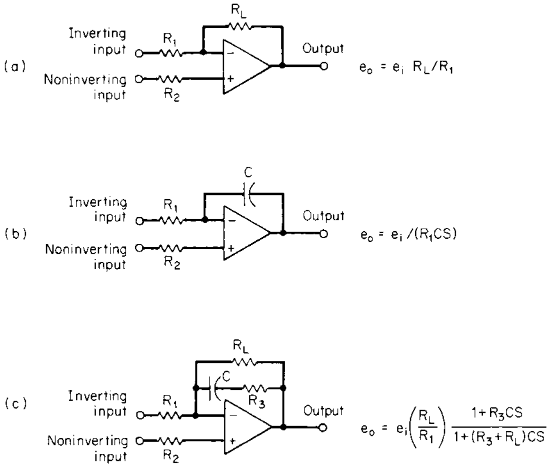


**Fig. 15.2.25** Operational amplifier circuits.

The operational amplifier circuits shown in Figs. 15.2.25, 15.2.26, 15.2.27, and 15.2.28, show only the signal wires. There are additional connections to a dc power supply, and in some instances, to stabilizing circuits and guard circuits. These connections have been omitted for conceptual clarity.

One of the most useful analog integrated circuits is the **difference amplifier**. This is a balanced input amplifier that is a fundamental component in instrumentation and control applications. The difference amplifier is shown in Fig. 15.2.26. This amplifier maximizes the voltage gain for $V_{\text{output}}/V_{\text{dif}}$, the **difference gain,** and minimizes the voltage gain for $V_{\text{output}}/V_{\text{CM}}$, the **common-mode gain**. There are two resistors in the circuit shown as $R1$ and two resistors shown as $R2$. The resistance values of the two $R1$ resistors are equal, and similarly the resistance values of the two $R2$ resistors are equal. The difference gain is given by

$$\frac{V_{\text{output}}}{V_{\text{dif}}} = -\frac{R2}{R1} \tag{15.2.5}$$

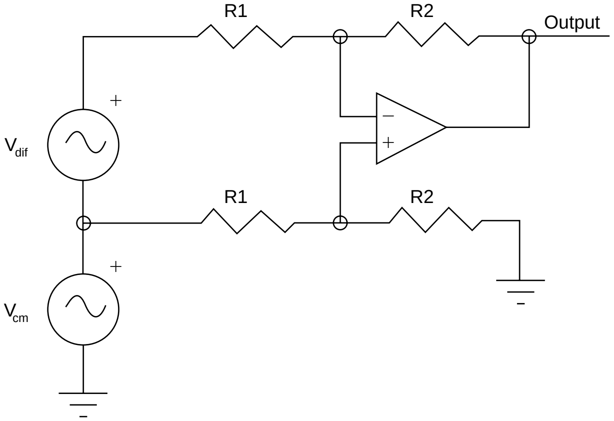


**Fig. 15.2.26** Difference amplifier.

The ratio of the common-mode gain to the difference gain is called the **common-mode rejection ratio (CMRR)**. In a well-designed difference amplifier, the CMRR is − 80 dB. Stated another way, the common mode gain is 10,000 times smaller than the difference gain. The difference amplifier is the most common input to instrumentation amplifiers and analog-to-digital converter circuits. Bridge-connected transducers have a common-mode voltage that is 100 times the difference voltage, or more. Such transducers require a difference amplifier. The common-mode gain is highly dependent on the matching of the $R1$ resistors and the $R2$ resistors. A 1 percent difference in these resistors causes the CMRR to be degraded to − 30 or − 40 dB.

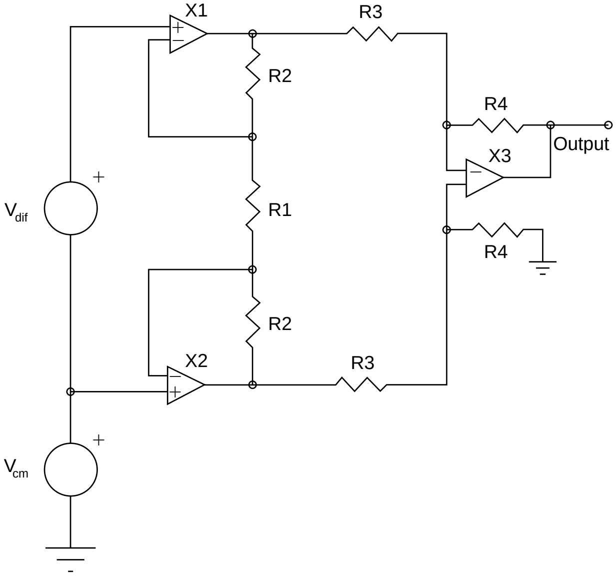


**Fig. 15.2.27** Instrumentation amplifier.

An **instrumentation amplifier** is a high-grade difference amplifier. Although there are many implementations of the instrumentation amplifier, the three op-amp circuit is quite common, and will illustrate this device. Figure 15.2.27 shows the three op-amp instrumentation amplifier. This is a two-stage amplifier. The first stage is composed of amplifiers $X1$ and $X2$ and resistors $R1$, $R2$, and $R2$. The second stage is composed of amplifier $X3$ and resistors $R3$, $R3$, $R4$, and $R4$. The CMRR is usually much lower for the instrumentation amplifier, typically $-120$ dB. The differential mode gain is much higher for the instrumentation amplifier. For stability and frequency response considerations, the difference gain of a normal difference amplifier is usually 10 or less. For the instrumentation amplifier, the difference gain is typically 1000. In the circuit shown in Fig. 15.2.27, the difference gain of the first stage is given by

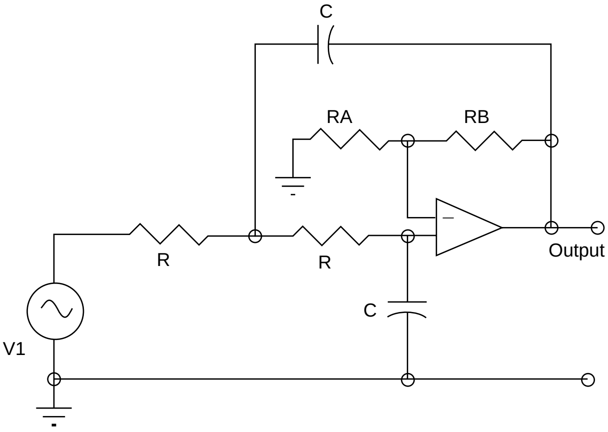


**Fig. 15.2.28** Modified Sallen-Key filter circuit.

$$\frac{V_{\text{internal}}}{V_{\text{dif}}} = \frac{(2 \times R2 + R1)}{R1} \tag{15.2.6}$$

The difference gain of the second is given by

$$\frac{V_{\text{output}}}{V_{\text{internal}}} = -\frac{R4}{R3} \tag{15.2.7}$$

The overall gain for the amplifier is the product of the individual stage gains. In the typical case the gain of the first stage is 100, and for the second stage is 10, giving an overall gain of 1,000. Integrated circuit instrumentation amplifiers are available which include all of the circuitry in Fig. 15.2.27. The resistors are matched so that the circuit designer does not have to contend with component matching.

A word about cost is in order. In 1994, high-grade operational amplifiers cost $0.50 for four op amps in a single IC chip, or about $0.125 for each amplifier. The instrumentation amplifier is somewhat more expensive, but can be obtained for less than $5.00.

Filtering of electronic signals is often required. A filter passes some frequencies and suppresses others. Filters may be classed as low pass, high pass, band pass, or band stop. Figure 15.2.28 shows a low-pass active filter circuit which is a modification of the Sallen-Key circuit. In this circuit, the two resistors labeled $R$ are matched and the two capacitors labeled $C$ are matched. The frequency response of this circuit is given by its transfer function:

$$\frac{V_{\text{output}}}{V_{\text{input}}} = \frac{1}{S^2 + \dfrac{\omega_N}{Q}S + \omega_N^2} \tag{15.2.8}$$

In this equation, $\omega_N$ is the resonant frequency of this circuit, in radians per second, and $Q$ is a quality factor that indicates the amount of amplitude increase at the resonant frequency. For the circuit shown in Fig. 15.2.28, $\omega_N$ is given by

$$\omega_N = \frac{1}{RC} \tag{15.2.9}$$

and $Q$ is given by

$$Q = \frac{1}{2 - (\text{RB}/\text{RA})} \tag{15.2.10}$$

The filter shown in Fig. 15.2.28 is a two-pole low-pass filter. Higher-order filters—four pole, six, etc.—can be constructed by cascading sections of two-pole filters. Thus, a six-pole low-pass filter would consist of three circuits of the configuration shown in the figure. The components *R, R, C, C,* RA, and RB would vary in each filter section.

Continuing with the low-pass filter, there are three common variations in filter response: Butterworth response, Chebychev response, and elliptical response. The Butterworth filter has no ripple in either the pass band or the stop band. The Chebychev filter has equal ripple variations in the pass band, but is flat in the stop band, and the elliptical filter has equal ripple variations in both the pass band and the stop band. There is a transition band of frequencies between the pass band and the stop band. The Butterworth filter has the greatest transition band. The Chebychev response has a sharper cutoff frequency characteristic than the Butterworth response, and the elliptical response has the sharpest transition from pass band to stop band. The circuits shown in Figs. 15.2.27 and 15.2.28 can be used to realize Butterworth and Chebychev filters. The elliptical filter requires a more complex circuit.

The high-pass filter can be formulated by substituting $1/S$ for $S$ in Eq. (15.2.8). The circuit configuration for a high-pass filter is shown in Fig. 15.2.29. Notice that only the position of the $R$s and $C$s have changed. In general, the values of $R$s, $C$s, RA, and RB will change for the high-frequency filter, so it would be inappropriate to design a low-pass filter and simply reverse the positions of the $R$s and $C$s.

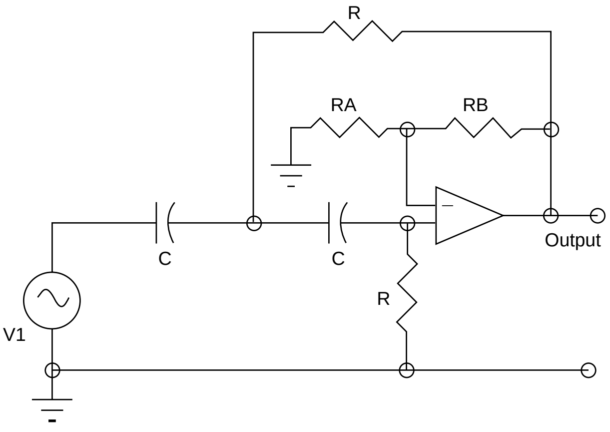
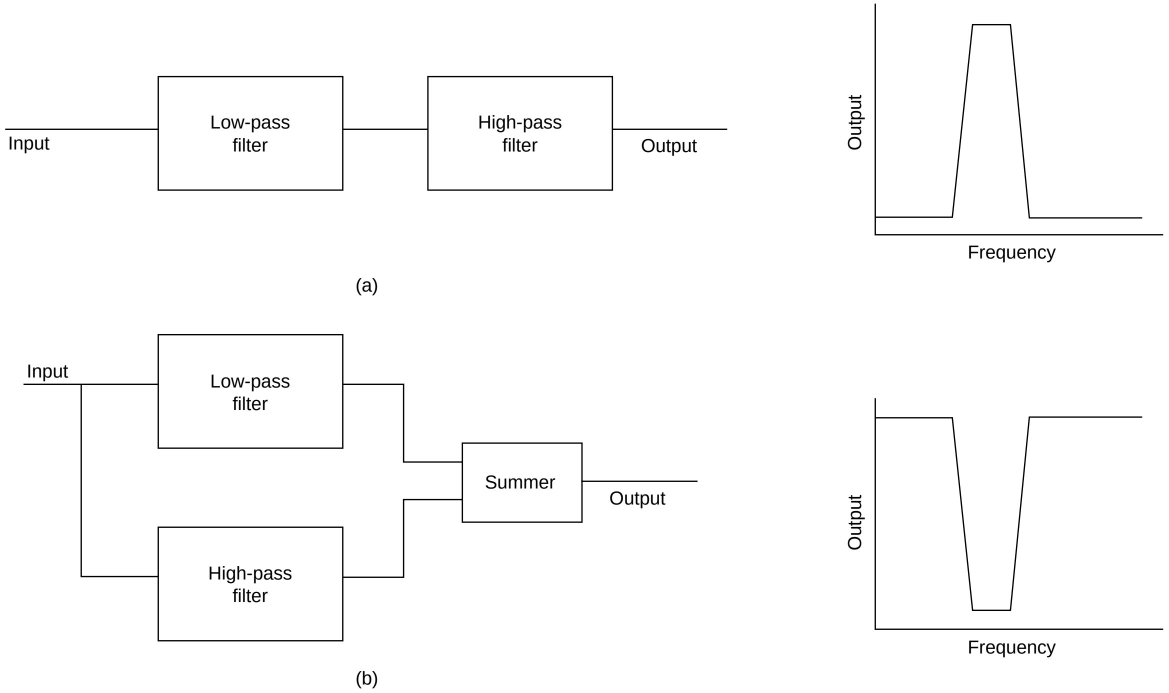


**Fig. 15.2.29** High-pass filter section.

Band-pass and band-stop filters can be made by combinations of low-pass and high-pass filter sections. Figure 15.2.30*a* shows the diagram configuration of filters to realize a band-pass filter. The low-pass filter would be designed for the high-frequency transition, and the high-pass filter would be designed for the low-frequency transition. Figure 15.2.30*b* shows the block diagram configuration for a band-stop filter. The band-stop filter and the low-pass filter would be designed for the low-frequency transition, and the high-pass filter would be designed for the high-frequency transition. Band-pass and band-stop filters may also be realized by means of special high-$Q$ circuits. A more complete discussion of filter technology can be found in the references at the beginning of this section.

Table 15.2.6 lists some typical linear ICs, most of which contain operational amplifiers with additional circuitry. The **voltage comparator**



(a)

(b)

**Fig. 15.2.30** (*a*) Band-pass and (*b*) band-stop filters.

is an operational amplifier that compares two input voltages, *V*1 and *V*2. Its output voltage is positive when *V*1 is greater than *V*2, and negative when *V*2 is greater than *V*1. The **sample-and-hold** circuit samples an analog input voltage at prescribed intervals, which are determined by an input clock pulse. Between clock pulses the circuit holds the sample voltage level. This circuit is useful in converting from an analog voltage to a digital number whose value is proportional to the analog voltage. An **analog-to-digital (A/D) converter** is a signal-converting device which changes several analog signals into digital signals. It consists of an input difference amplifier, an analog time multiplexer, a sample-and-hold amplifier, a digital decoder, and the necessary logic to interface with a digital computer. The A/D converter is programmable, in that a computer can set up the device for the requisite number of input channels and whether these input channels are differential inputs or single-ended inputs. The A/D converter typically takes eight differential analog input signals and converts them to 10-, 12-, or 16-bit digital signals. Typical A/D converters convert signals at a rate of 200,000 samples per second. Other types of A/D converters, such as flash converters, can convert over 10,000,000 samples per second.

A companion circuit to the A/D converter is the **digital-to-analog (D/A) converter,** which is used to convert from digital signals to analog signals. This is also a programmable device, but in general the D/A converter is less complex than is the A/D converter. **Voltage-regulators** and **voltage references** are electronic circuits which create precision dc voltage sources. The voltage reference is more precise than the voltage regulator. The **voltage-controlled oscillator** is a circuit which converts from a dc signal to a proportional ac frequency. The output of a voltage-controlled oscillator is usually a rectangular ac wave rather than a sine wave. The **NE555 timer/oscillator** is a general-purpose timer/oscillator which has been integrated into a single IC chip. It can function as a **monostable multivibrator,** a **free-running multivibrator,** or as a **synchronized multivibrator**. It can also be used as a **linear ramp generator,** or for time delay or sequential timing applications.

**Table 15.2.6 Linear Integrated-Circuit Devices**

Operational amplifier
Sample and hold
Analog-to-digital converter
Voltage regulator
Voltage-controlled oscillator
Voltage comparator
Digital-to-analog converter
Voltage reference
NE555 Timer/oscillator

Table 15.2.7 lists linear ICs that are used in audio, radio, and television circuits. The degree of complexity that can be incorporated in a single device is illustrated by the fact that a complete AM-FM radio circuit is available in a single IC device. The **phase-locked loop** is a device that is widely utilized for accurate frequency control. This device produces an output frequency that is set by a digital input. It is a highly accurate and stable circuit. This circuit is often used to demodulate FM radio waves.

Table 15.2.8 lists linear IC circuits that are used in telecommunications. These circuits include digital circuits within them and/or are used with digital devices. Whether these should be classed as linear ICs or

**Table 15.2.7 Audio, Radio, and Television Integrated-Circuit Devices**

Audio amplifier
Dolby filter circuit
Intermediate frequency circuit
TV chroma demodulator
Video-IF amplifier-detector
Tone-volume-balance circuit
Phase-locked loop (PLL)
AM-FM radio
Digital tuner

**Table 15.2.8 Telecommunication Integrated-Circuit Devices**

Radio-control transmitter-encoder
Radio-control receiver-decoder
Pulse-code modulator–coder-decoder (PCM CODEC)
Single-chip programmable signal processor
Touch-tone generators
Modulator-demodulator (modem)

digital ICs may be questioned. Several manufacturers include them in their linear device listings and not with their digital devices, and for this reason, they are listed here as linear devices. The radio-control **transmitter-encoder** and **receiver-decoder** provide a means of sending up to four control signals on a single radio-control frequency link. Each of the four channels can be either an on-off channel or a **pulse-width-modulated (PWM)** proportional channel. The **pulse-code modulator–coder-decoder (PWM CODEC)** is typical of a series of IC devices that have been designed to facilitate the design of digital-switched telephone circuits.

Integrated circuits are normally divided into two classes: linear or analog ICs and digital ICs. There are a few hybrid circuits which have both analog and digital characteristics. Some representative hybrid integrated circuits are listed in Table 15.2.9, and shown in Fig. 15.2.31. In the **superdiode,** there are two modes of operation. When the input signal is positive, the output of the op amp is negative, causing diode $D2$ to conduct and diode $D1$ to block current flow. When the input is negative, diode $D2$ blocks and diode $D1$ conducts. The output of the circuit is zero when the input is negative, and the output is proportional to the input when the input is positive. A normal diode has 0.5 to 1.0 V of forward voltage drop. This circuit is called a super diode because its switching point is at zero volts. There is a voltage inversion from input to output, but this can be reversed by means of an additional op-amp inverter following the super diode. The action of the circuit can be reversed by reversing diodes $D1$ and $D2$. The **limiter** circuit, shown in Fig. 15.2.31*b*, provides linear operation at low output voltages, either positive or negative, and neither diode is conducting. When the input voltage goes sufficiently negative, diode $D1$ begins to conduct, limiting the negative output of the op-amp. Similarly when the input goes sufficiently positive, diode $D2$ begins to conduct, limiting the positive output of the op-amp. The **Schmitt trigger** circuit, shown in Fig. 15.2.31*c*, has positive feedback to the op-amp, through resistors $R1$ and $R2$. If the amplifier output is initially negative, the output will not change until the input becomes as negative as the non-inverting terminal of the op-amp. When the input becomes slightly more negative, the op-amp output will suddenly switch from negative to positive due to the positive feedback. The op-amp will remain in this condition until the input becomes sufficiently positive, causing the op-amp to switch to a negative output.

The **dead-band** circuit is similar to the limiter circuit except that for input voltages around zero, there is no output voltage. Above a threshold input voltage, the output voltage is proportional to the input voltage. The logarithmic amplifier relies upon the fact that the voltage drop across a diode causes logarithmically varying current to flow through the diode. This relationship is remarkably true for current changes of $10^6$ to 1. The logarithmic amplifiers can have their outputs added together to effect a multiplication of the input signals.

### Digital Integrated Circuits

The basic circuit building block for digital ICs is the gate circuit. A gate is a switching amplifier that is designed to be either on or off. (By contrast, an operational amplifier is a proportional amplifier.) For 5-V logic levels, the gate switches to a 0 whenever its input falls below 0.8 V and to a 1 whenever its input exceeds 2.8 V. This arrangement ensures immunity to spurious noise impulses in both the 0 and the 1 state.

Several representative **transistor-transistor-logic (TTL) gates** are listed in Table 15.2.10. Gates can be combined to form logic devices of two fundamental kinds: combinational and sequential. In **combinational logic,** the output of a device changes whenever its input conditions change. The basic gate exemplifies this behavior.

A number of gates can be interconnected to form a **flip-flop** circuit. This is a bistable circuit that stays in a particular state, a 0 or a 1 state, until its ‘‘clock’’ input goes to a 1. At this time its output will stay in its present state or change to a new state depending upon its input just prior to the clock pulse. Its output will retain this information until the next time the clock goes to a 1. The flip-flop has memory, because it retains its output from one clock pulse to another. By connecting several flip-flops together, several sequential states can be defined permitting the design of a **sequential logic** circuit.

**Table 15.2.9 Hybrid Circuits**

| | |
|---|---|
| Superdiode | Limiters |
| Schmitt trigger circuits | Dead-band circuits |
| Switched-capacitor filters | Logarithmic amplifiers |

Table 15.2.11 shows three common flip-flops. The **truth table,** sometimes called a **state table,** shows the specification for the behavior of each circuit. The present output state of the flip-flop is designated $Q(t)$. The next output state is designated $Q(t + 1)$. In addition to the truth

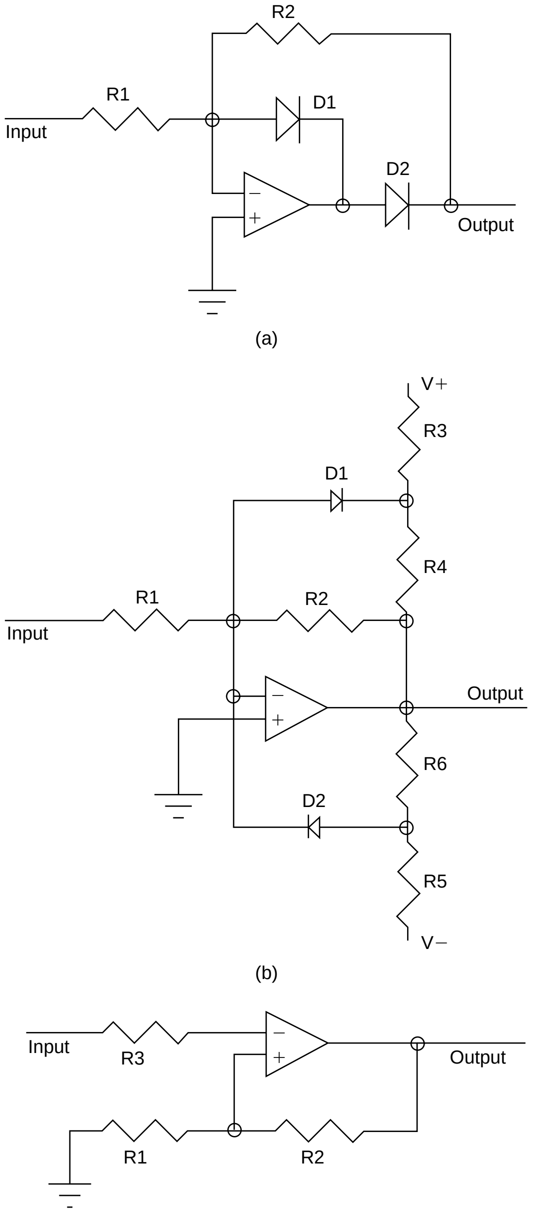


**Fig. 15.2.31** Hybrid circuits. (*a*) Superdiode circuit; (*b*) limiter circuit; (*c*) Schmitt trigger circuit.

**Table 15.2.10 Digital Integrated-Circuit Devices**

| Type 54/74* | No. circuits per device | No. inputs per device | Function |
|---|---|---|---|
| 00 | 4 | 2 | NAND gate |
| 02 | 4 | 2 | NOR gate |
| 04 | 6 | 1 | Inverter |
| 06 | 6 | 1 | Buffer |
| 08 | 4 | 2 | AND gate |
| 10 | 3 | 3 | NAND gate |
| 11 | 3 | 3 | AND gate |
| 13 | 2 | 4 | Schmitt trigger |
| 14 | 6 | 1 | Schmitt trigger |
| 20 | 2 | 4 | NAND gate |
| 21 | 2 | 4 | AND gate |
| 30 | 1 | 8 | NAND gate |
| 74 | 2 | | D flip-flop |
| 76 | 2 | | JK flip-flop |
| 77 | 4 | | Latch |
| 86 | 4 | 2 | EXCLUSIVE OR gate |
| 174 | 6 | | D flip-flop |
| 373 | 8 | | Latch |
| 374 | 8 | | D flip-flop |

NOTE: Example of device numbers are 74LS04, 54L04, 5477, and 74H10. The letters after the series number denote the speed and loading of the device.

* 54 series devices are rated for temperatures from −55 to 125°C. 74 series devices are rated for temperatures from 0 to 70°C.

table, the Boolean algebra equations in Table 15.2.11 are another way to describe the behavior of the circuits. The **JK flip-flop** is the most versatile of these three flip-flops because of its separate J and K inputs. The **T flip-flop** is called a *toggle.* When its T input is a 1, its output toggles, from 0 to 1 or from 1 to 0, at each clock pulse. The **D flip-flop** is called a *data cell.* The output of the D flip-flop assumes the state of its input at each clock pulse and holds this data until the next clock pulse. The JK flip-flop can be made to function as a T flip-flop by applying the T input to both the J and K input terminals. The JK flip-flop can be made to function as a D flip-flop by applying the data signal to the J input and applying the inverted data signal to the K input. Some common IC flip-flops are listed in Table 15.2.10.

Various types of gates are shown in Table 15.2.12. Combinational logic defined by means of these various gates is used to define the input to flip-flops, which serve as memory devices. At each clock pulse, these flip-flops change state in accordance with their respective inputs. These new states are retained in the flip-flop and also applied to the gates. The output of the gates change (with only a small delay due propagation time), and at the next clock pulse the flip-flops will change to the next state as directed by the gates.

The gates shown in Table 15.2.12 have only two inputs. As was seen in Table 15.2.10, gates may have as many as eight inputs. In the case of an AND **gate,** all its inputs must be 1 in order for its output to be a 1. For an OR gate, if any of its inputs become a 1, then its output will become a 1. The NAND and NOR gates function in a similar way.

**Boolean algebra** is the branch of mathematics used to analyze logic circuits. Boolean algebra has two operators: $\cdot$, which indicates an AND operation, and $+$, which indicates an OR operation: The $=$ has the same meaning in Boolean algebra as in ordinary algebra. The symbol for ''$X$ not'' is $X'$ (or sometimes $\overline{X}$). The identity element for the AND operation is 0; the identity element for the OR operation is 1. The rules for Boolean algebra can be derived from set theory applied to a system in which only two numbers exist, i.e., zero and one. These rules are summarized in Huntington's postulates and DeMorgan's theorem and are listed in Table 15.2.13.

To facilitate the analysis of digital circuits and to aid in the application of the rules given in Table 15.2.13, **Karnaugh maps** are used. Typical two-variable and four-variable Karnaugh maps are shown in Fig. 15.2.32 along with the algebraic expressions represented by each map.

Looking at Fig. 15.2.32*b* and realizing each of the ones individually would lead to the Boolean expression:

$$\mathrm{OUT} = \mathrm{W'X'YZ} + \mathrm{WXYZ} + \mathrm{WX'YZ} + \mathrm{WXYZ'} \qquad (15.2.11)$$

Realizing this expression directly would require four four-input AND gates, and one four-input OR gates. The reduced expression

$$\mathrm{OUT} = \mathrm{WXY} + \mathrm{X'YZ} \qquad (15.2.12)$$

requires only two three-input AND gates and one two-input OR gate, a simpler and less expensive logic circuit.

Some of the more common large-scale integrated circuits are listed in Table 15.2.14. The adder can add two binary numbers together and output the result. For a single bit adder which adds a bit from word A, a bit from word B, and a carry bit, C, the Boolean expressions for the two outputs of the adder are

$$\mathrm{SUM} = \mathrm{AB'C'} + \mathrm{A'BC'} + \mathrm{A'B'C} + \mathrm{ABC} \qquad (15.2.13)$$

$$\mathrm{CO} = \mathrm{AB} + \mathrm{BC} + \mathrm{AC} \qquad (15.2.14)$$

Adders are available, not for a single bit, but rather for 4 bits, 8 bits, or 16 bits. There is only one carry bit for the whole device. The devices in Table 15.2.14 will be described in words, but the specifications for each of these devices has a truth table as a part of the product description. An arithmetic logic unit (ALU) or accumulator can perform several simple logical or arithmetic operations, such as add, complement, shift left, and shift right. In addition, the set of instructions which command these operations will also be decoded by the ALU. As one might expect, the Boolean expression for a 16-bit or 32-bit ALU can be formidable. A

**Table 15.2.11 Flip-Flop Sequential Devices**

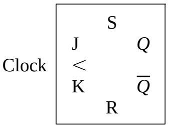
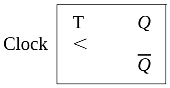
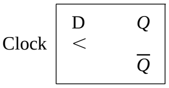
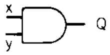
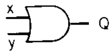
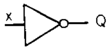
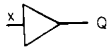
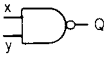
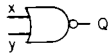
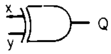
<table>
<tr><th>Name</th><th>Graphic symbol</th><th>Algebraic function</th><th colspan="4">Truth table</th></tr>
<tr><td>JK flip-flop</td><td> </td><td>$Q(t+1) = \mathrm{J}Q'(t) + \mathrm{K}'Q(t)$</td><td>J<br>0<br>1<br>X<br>X</td><td>K<br>X<br>X<br>0<br>1</td><td>$Q(t)$<br>0<br>0<br>1<br>1</td><td>$Q(t+1)$<br>0<br>1<br>1<br>0</td></tr>
<tr><td>T flip-flop</td><td> </td><td>$Q(t+1) = \mathrm{T}Q'(t) + \mathrm{T}'Q(t)$</td><td></td><td>T<br>0<br>0<br>1<br>1</td><td>$Q(t)$<br>0<br>1<br>0<br>1</td><td>$Q(t+1)$<br>0<br>1<br>1<br>0</td></tr>
<tr><td>D flip-flop</td><td> </td><td>$Q(t+1) = D$</td><td></td><td>D<br>0<br>0<br>1<br>1</td><td>$Q(t)$<br>0<br>1<br>0<br>1</td><td>$Q(t+1)$<br>0<br>0<br>1<br>1</td></tr>
</table>

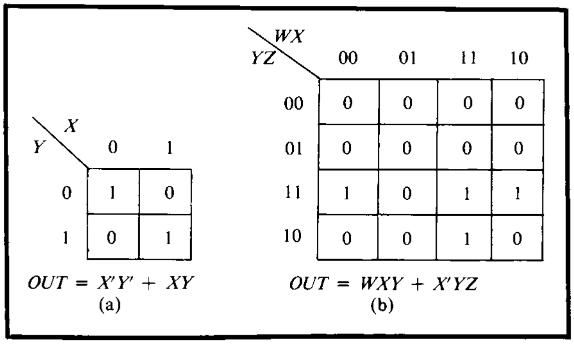
**Table 15.2.12 Combinational Gate Logic**

| Name | Graphic symbol | Algebraic function | Truth table |
|---|---|---|---|
| AND |  | $Q = xy$ | x y Q<br>0 0 0<br>0 1 0<br>1 0 0<br>1 1 1 |
| OR |  | $Q = x + y$ | x y Q<br>0 0 0<br>0 1 1<br>1 0 1<br>1 1 1 |
| Inverter |  | $Q = x'$ | x Q<br>0 1<br>1 0 |
| Buffer |  | $Q = x$ | x Q<br>0 0<br>1 1 |
| NAND |  | $Q = (xy)'$ | x y Q<br>0 0 1<br>0 1 1<br>1 0 1<br>1 1 0 |
| NOR |  | $Q = (x + y)'$ | x y Q<br>0 0 1<br>0 1 0<br>1 0 0<br>1 1 0 |
| EXCLUSIVE-OR |  | $Q = xy' + x'y$<br>$= x + y$ | x y Q<br>0 0 0<br>0 1 1<br>1 0 1<br>1 1 0 |

parity generator/checker is a circuit that can make a cyclic redundancy code which can be used to check the accurate transmission of data. Shift registers perform only the shifting functions of ALUs. Counters are made in many configurations—up-down counters, binary-coded-decimal counters, Johnson counters, etc. A decoder can best be explained by a simple example. A three- to eight-line decoder will be described. The three input lines can have eight binary variations, 000, 001, 010, 011, 100, 101, 110, and 111. For each of these input conditions one, and only one, of the output lines will be set. The input signal is said to have been decoded. The encoder performs the related operation of encoding from eight to three lines. Depending on which one input line is set, an appropriate output bit pattern is set. Encoders and decoders are available in 2 to 4, 3 to 8, and 4 to 16 line configurations. The multiplexer/demultiplexer performs a similar function. The multiplexer has a data input terminal and control input terminal and several data output terminals. It switches a single train of information, ones and zeros, on an input line, and routes this information to one of many output lines depending on the bit pattern placed on a control input. The demultiplexer performs the reverse operation. Multiplexers/demultiplexers are also configured in 2 to 4, 3 to 8, and 4 to 16 line devices.

**Table 15.2.13 Rules for Boolean Algebra**

| | |
|---|---|
| $X + 0 = X$ | $X \cdot 1 = X$ |
| $X + 1 = 1$ | $X \cdot X' = 0$ |
| $X + X' = 1$ | $X \cdot X = X$ |
| $(X')' = X$ | $X \cdot 0 = 0$ |
| $X + Y = Y + X$ | $X \cdot Y = Y \cdot X$ |
| $X + (Y + Z) = (X + Y) + Z$ | $X \cdot (Y Z) = (X \cdot Y)Z$ |
| $X + X \cdot Y = X$ | $X \cdot (X + Y) = X$ |
| DeMorgan's theorem: | |
| $(X + Y)' = X' \cdot Y'$ | $(X \cdot Y)' = X' + Y'$ |



| Y \ X | 0 | 1 |
|---|---|---|
| 0 | 1 | 0 |
| 1 | 0 | 1 |

$OUT = X'Y' + XY$

(a)

| YZ \ WX | 00 | 01 | 11 | 10 |
|---|---|---|---|---|
| 00 | 0 | 0 | 0 | 0 |
| 01 | 0 | 0 | 0 | 0 |
| 11 | 1 | 0 | 1 | 1 |
| 10 | 0 | 0 | 1 | 0 |

$OUT = WXY + X'YZ$

(b)

**Fig. 15.2.32** Karnaugh maps of typical logic functions.

There are a wide variety of display controllers and drivers. These are devices which interface between digital circuits and displays which humans can use. Light-emitting diodes, liquid crystals, and fluorescent displays have different drive requirements. The digital device may perform in binary, but the display requires decimal. In many cases, the display driver is separate from the display itself, but more recently the display driver has been incorporated in the display.

The complexity of integrated circuits is growing continually. The simple gates and flip-flops discussed so far are still used to some extent. Logically, these gates and flip-flops can be integrated into larger single-chip circuits called *large-scale integrated circuits* (LSI). Combinations of these circuits are grouped together on single chips called *very large scale integrated circuits* (VLSI). VLSI chips contain 500,000 to more than 2,000,000 gates. VLSI chips have enabled the explosive growth of personal computers, by allowing ever-increasing functionality at lower cost. These circuits are custom-designed VLSI circuits which are developed for large-volume applications. Bridging the gap between LSI and custom VLSI circuits are a series of linear and digital user-designed circuits.

The first of these user-designed circuits is called programmable logic arrays (PLAs) or programmable array logic (PAL). The PLA grew out of the programmable read-only memory (PROM). A programmable read-only memory is a computer memory which can be programmed one time, and then can be read many times. The PROM consists of a series of gates, initially all ones, each of which can be electrically altered to be a zero. A PROM might be logically organized to be 1 bit wide by 64K bits long, or 4 bits by 16K bits, 8 bits by 8K bits. The example just given is a series of 64K-bit PROMs. PROMs are available up to 4M bits on a single chip. The PLA is also field programmable, but has a more limited programming capability than the PROM. The limited capability makes

**Table 15.2.14 Large-Scale Digital Integrated Circuits**

| | |
|---|---|
| Adder | Accumulator |
| Arithmetic logic unit | Parity generator-checker |
| Shift register | Encoder |
| Multiplexer | Decoder |
| Demultiplexer | Counters |
| Display controller-driver | |

it less costly to program. The PLA is adaptable to replacing Boolean functions in both combinational logic and sequential logic circuits. The PLA can replace 10 to 40 gate and flip-flop chips, resulting in a simpler, more reliable, less costly design.

There are two other approaches to application-specific integrated circuits, **(ASICs)**. These are field-programmable gate arrays **(FPGAs)** and standard cells. The FPGA is sometimes referred to as a ‘‘sea of gates.’’ The chip is designed with a series of identical gates, but without any interconnections between them. The user specifies the interconnections, and thus makes the chip specific to the application. The manufacture of the chip cannot be completed until the interconnections have been specified, however. There was initially some concern that the circuit designer would be losing design control, but this has largely disappeared now that alternative sources of supply are available. The customizing production drawings and specifications can be pulled from one manufacturer, and sent to another. The standard cell device is similar to an FPGA, except that some interconnections are specified to connect gates to form subcircuits. The design by the user consists of selecting the individual cells, AND gates, OR gates, flip-flops, etc. and specifying the interconnections of these standard cells. The standard cells may be as simple as an AND gate or as complex as a 16K-bit memory or a microprocessor. The standard cell also allows the user to specify light-current cells or heavy-current cells. The standard cell gives the user much more flexibility in the design. Standard cells have also been extended to include linear circuits, op amps, difference amplifiers, limiters, etc. Some standard cell chips are suitable for hybrid digital and linear circuits on a single chip.

Two problems arise as more complex circuitry is incorporated in ASICs, and also in microprocessors (which will be discussed in the next section). These devices require more input and output data pins than are available in dual in-line packages (see Fig. 15.2.24), and they generate more heat on the chip. One solution to the pin problem is the pin array package, shown in Fig. 15.2.33. These packages still maintain 0.1-in spacing between pins, but the pin count has been increased to 132 and 208 in the examples shown. The package size has increased from dual in-line packages, and the force necessary to install and remove the package is not appreciably greater than for dual in-line packages. There are additional microcircuit packages at various stages of development and standardization that have up to 500 pins and 0.05-in pin spacing.

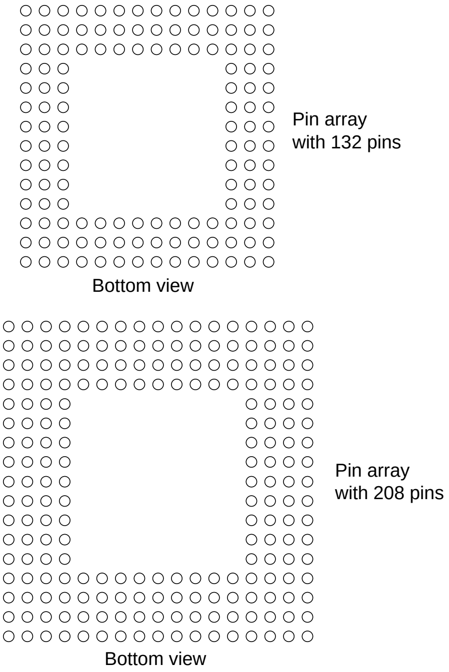


**Fig. 15.2.33** Typical pin grid array packages. (All pins are on a 0.1 in grid.)

Higher-speed and higher-density digital electronics lead to higher heat dissipation in devices. One solution is to provide heat sinks and fans to remove heat. A more recent development is the **heat pipe**. The heat pipe consists of boiling fluid/vapor refrigerant in a closed chamber. The semiconductor boils the fluid to change it to the vapor state. A pipe conducts the vapor to a vapor-to-air heat exchanger, where the vapor is condensed. The heat pipe also provides a return path for the fluid to return to the semiconductor. An attractive feature of the heat pipe is that there is no requirement for a mechanical compressor.

A further problem for complex electronic circuits is proof of design and proof of manufacture testing. To adequately test a device, it is necessary to have access to additional test points in the circuit, beyond those needed to interface in actual operation. With a limited number of output pins and highly complex internal logic, the design of the circuit must include a fairly long test vector that will excite the various circuit functions. In addition, a fairly long results vector will be generated by the circuit. One approach to test design is called **boundary scan** design, described in specification IEEE 1149.1 of the Institute of Electrical and Electronics Engineers. This specification outlines a four- or five-wire test circuit, and the internal circuitry, which allows a test vector to be entered serially onto the chip, and allows a results vector to be serially unloaded from the chip. Internal circuitry is required to accept each bit of the input test vector and to generate each bit of the results vector. The serial transfer is a tradeoff between the time required to enter and retrieve the test vectors and the cost of additional input/output pins for the device. Serial transfer would be unacceptable for normal operations, but is all right for test purposes.

### Computer Integrated Circuits

One of the devices which has become feasible as a result of VLSI is the **microprocessor**. A complete computer can be built in a single IC device. In most cases, however, several devices are employed to build a complete computer system. In most computers, the cost of the microprocessor is negligible compared with the total system cost. Not long ago, the **central processing unit (CPU)** was the most expensive part of a computer. The microprocessor provides the total CPU function at a fraction of the earlier cost.

The power of a microprocessor is a function of its clock speed and the size and number of its registers. Clock rates vary from 1 to 200 MHz. Common register sizes are 8, 16, 24, 32, and 64 bits. Most personal computers currently use 32-bit registers. Commonly microprocessors have 12 to 16 registers. Other factors affect processor power and speed. Most microprocessors have a data bus, an address bus, and a set of control and power supply terminals. The number of each of these buses may vary. A small inexpensive microprocessor might have 8 data lines, 16 address lines, and 8 control/power supply lines. A large sophisticated microprocessor might have 64 data lines, 24 address lines, and 20 control/power supply lines. Some microprocessors have 32-bit internal registers and only 16 data bit terminals. The 16 data terminals are time-multiplexed to allow the complete 32-bit word to be entered onto the microprocessor chip in two read cycles. Once in the microprocessor, the 32-bit registers communicate with each other over a data bus which is a full 32 bits wide. This scheme reduces the number of terminals on the microprocessor, and reduces its cost, with a slight timing penalty.

Clock speed is limited by clock skew and parasitic capacitance. There is a finite time required for electric pulses to move along wires and for gates to change state. Typically electric pulses move along wires at about half the speed of light. Gates change state in a few nanoseconds. Parasitic capacitance is the stray capacitance that exists between any circuit and ground. When the gate changes state, this capacitance must be charged. The charging current increases linearly with switching rate and voltage. Because of the small circuit components and short wire lengths, the parasitic capacitance is much smaller for circuits on a chip compared with circuits on printed boards. Modern microprocessors use an on-chip clock rate that is 3 times as fast as the off-chip clock.

The **microcontroller** is a device similar to the microprocessor, in that it is also a CPU. Microcontrollers are configured for controlling applications. In general, they have greater input and output capability. It is very easy to control a single output bit for turning on an electric relay. With a microprocessor, 8 bits are switched together, but with a microcontroller individual bits can be switched. Some microcontrollers have 256 internal registers, rather than the 15 to 20 of a microprocessor. Microcontrollers are often stand-alone single-chip devices, and are a less expensive system than a microcomputer. Typical applications for microcontrollers are microwave oven controllers, washer and dryer controls, and automobile engine controls.

Memory is an important part of a computer system. Memory can be divided into two broad classes: volatile and nonvolatile. Volatile memory forgets what it contains when the power is removed from it. Nonvolatile memory retains its contents when power is removed. Random-access memory **(RAM)** is volatile memory that is sometimes called *main memory.* This is the memory that the CPU uses for most of its operations. RAM is a semiconductor memory. RAM may be dynamic memory or static. In a static RAM the memory elements are flip-flops, and retain their memory for as long as power is applied. Dynamic RAMs are also semiconductor memories, but hold the information as charges on capacitors. This charge will leak off even though the power is still applied to the memory. To retain the memory in a dynamic RAM, it is necessary to continually refresh the memory. This is typically done every 10 ms. Dynamic RAMs are much cheaper and have less loss than static RAMs. Large banks of memory are made with dynamic RAMs. Small memories, or memories with special requirements, are made with static RAMs. Typical dynamic RAMs are 256K, 1M, and 4M bytes. Typical static RAM may be as small as 1K bytes and can be as large as 1M bytes.

**Nonvolatile memory** can take several forms: ROMs, disk storage, compact disks, and tapes. A read-only memory (ROM) is a set of flip-flops which are programmed to take a particular state. This programming may be installed at the time of manufacture. Some devices are programmable by the user **(PROMs)**. A PROM is typically all ones as shipped. The individual memory cells may be programmed to a zero or left a one. Programming memory cell is done by applying a high voltage to a programming pin when that cell's address is set. Normally the ROM or PROM is written once and read many times. An **EPROM** is an erasable, programmable read-only memory. The EPROM is programmed in the same way as a PROM. To erase the memory, the EPROM is placed under a high-intensity ultraviolet light. When the EPROM is erased, all of the memory is lost, so the entire program must be reentered.

Disks and tapes are magnetic storage devices. When power is removed from these devices, the memory is retained due magnetic retentivity. Magnetic memory can only be read (or written) by moving the magnetic medium under a read/write head. **Compact disks** are a form of read-only memory. In the compact disk, the information is stored optically rather than magnetically.

The magnetic tape is a removable nonvolatile memory device. Hard disks are usually not removable. Floppy disks are removable, but for large quantities of data, the tape medium is cheaper and more convenient. Tape is either in a cartridge or on a reel. Newer tape cartridges have large volumes, 50M bytes to 1000M bytes. The trend is that cartridge tape is replacing reel tape as a storage means. Magnetic tape can store computer data for over a year, and with a periodic refreshing can store data indefinitely.

**Table 15.2.15 Digital Computer Integrated-Circuit Devices**

Tristate buffer
Parallel interface adapter
Universal asynchronous transmitter-receiver
Analog-to-digital converter
Programmable timer
Programmable interrupt controller
Tristate transceiver
Programmable peripheral interface
Floppy/hard disk controller
Digital-to-analog converter
Direct memory access controller

In addition to the CPU and storage devices, other integrated circuits have been designed for computer systems. These are listed in Table 15.2.15. The **tristate buffer** is a switching amplifier which can be a zero, a one, or high impedance. When a computer bus line can be driven by several devices, all of the devices are high impedance except the one which is controlling the bus line at that time. Typically eight tristate buffers are contained in one IC package. The **tristate transceiver** is similar to the tristate buffer except that it allows the bus signal to be received as well as written. The **parallel interface adapter** is a device that permits a parallel output device, such as a printer, to be connected to a computer bus. There are several variations of the parallel interface adapter. Some control two, three, four, or more parallel devices. Some have been designed to work with Intel microprocessors, others to work with Motorola microprocessors. The **programmable peripheral interface** is a parallel interface adapter designed for use with Intel computers. The **universal asynchronous receiver-transmitter (UART)** is a device which will allow a serial output device to be connected to a computer bus. The UART has a parallel connection to the computer bus, but provides a serial output to the peripheral device. The UART is programmable, so that it can be set for 7-bit or 8-bit transmission. It can be set for even or odd parity checking, and the transmitting/receiving speed can be set. The **floppy/hard disk controller** is a programmable device which can handle the interfacing requirements for floppy and/or hard disks. Analog-to-digital and digital-to-analog converters allow the digital computer to interface with analog signals. The **programmable timer** is a timing circuit which can be programmed by the computer either to generate an interrupt periodically, or to generate an interrupt after a programmed time. An interrupt is a signal on one of the control lines of the computer bus. The **direct memory access controller (DMA)** is a CPU type of device which can control the computer bus. The direct memory access controller generates a DMA request signal on a computer control line. The main CPU will complete the portion of the instruction that it is executing, and generate a DMA grant signal. The DMA controller then transfers data into or out of main memory or disk memory. Since the CPU is not involved in the memory transfer, it can proceed with the instruction it is executing, as long as that instruction does not require the computer bus that the DMA controller is using. DMA controllers can off-load the CPU, allowing the overall system to have more power. The **programmable interrupt controller** is a general-purpose semiconductor which can be used in various types of computer printed boards to service interrupts.

### Computer Applications

The computer is universally used, and a complete discussion of computer usage is beyond the scope of this section. Computer techniques are used in electronic design so extensively that some description of these electronic applications of computers are necessary in order to understand modern electronic design.

Computers can be used as control devices. The computer might be a controlling device to simply turn a pump on and off. On the other hand, a variable displacement pump might incorporate a microcontroller in its feedback control loop in place of pilot hydraulic circuits. Entire processes may be controlled by computers. For example, modern paper machines use computers throughout for control purposes. Computer terminals at various locations show the operation conditions throughout the machine. Entire chemical-producing plants are under computer control.

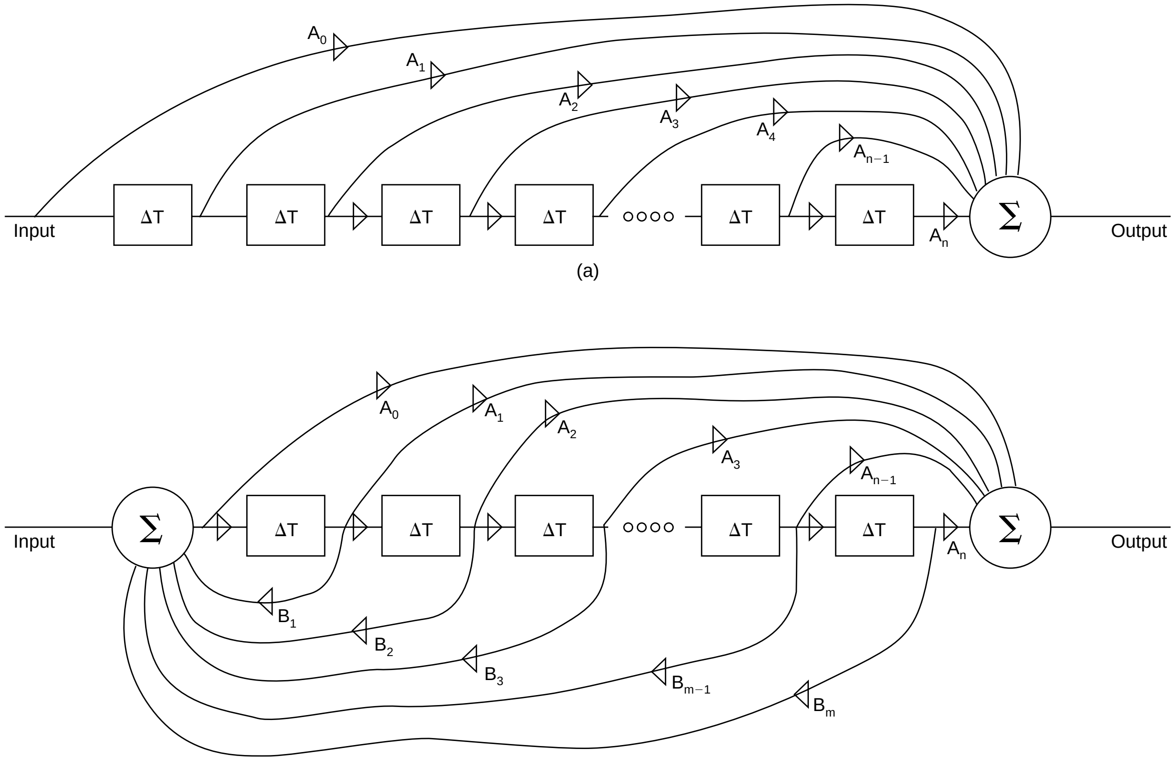
Some automotive applications include control of air, fuel mixture, and spark timing in an automobile engine. This is typical of an application in which there are several input variables that must be measured, and several controlled outputs. The input variables that must be measured are air temperature, manifold temperature, crankcase temperature, engine speed, fuel flow, etc. The outputs which are controlled by the computer are ignition timing and fuel/air mixture. Automobile brakes, transmissions, and suspensions are automotive subsystems that incorporate microcontrollers for improved automobile performance. Microcomputers may also be used to reduce the complexity of automobile wiring. In such a system, battery power is distributed to all parts of the car along a single wire. Intelligence for the control of lights and accessories flows along a single control wire. Relays are provided at each lamp, switch, etc. to interface between the control and battery wire. Messages along the control wire are time-multiplexed so that all devices share the same control wire.

Testing, data acquisition, and analysis is another use of computers. Modern testing systems make extensive use of computers. Either digital or analog signals can be incorporated into a test system. Analog-to-digital converters convert analog signals into digital signals which the computer can use. Within the computer, a model of the process being tested can be constructed, and monitored by the test data being accumulated. Within the computer, signals can be generated which are not being actually measured. For example, the velocity of a mass may be measured, but the acceleration or the position of the mass may be calculated within the computer. Highly reliable systems can be developed using electronic control and computers, if redundancy is incorporated into the measuring and computer systems. In the aerospace industry, these systems are called **fly-by-wire** control systems. The space shuttle and supersonic fighters are examples of craft using fly-by-wire. In such systems, failure of a computer, a controller, or a sensor must not cause a failure of the craft.

Data acquisition systems give the user much greater insight into the data being taken. Limitations and anomalies of the measured data become much more apparent than with analog data. The need for signal conditioning becomes imperative in a digital data acquisition system. Signal processing is an integral part of any digital data system. Analog signals can be filtered as a part of signal conditioning, but after the signal has been converted to digital data, digital filtering may also be used. Digital filters can be broken into two classes: **finite impulse response (FIR)** and **infinite impulse response (IIR)** filters. As can be seen in Fig 15.2.34, the FIR filter does not have any feedback from a later part of the filter to a previous part. The IIR filter incorporates feedback from a later part of the filter to an earlier part. The FIR filter normally requires a greater length to accomplish the filtering objective than does the IIR filter. Because the IIR filter incorporates feedback, it is possible for it to be unstable. The FIR filter cannot be unstable. Both FIR and IIR filters employ a clock to generate a fixed delay from point to point in the filter. The clock delays are shown as $\Delta T$ in the figure. Each delay is a clock period. FIR filters are often 45 to 75 delays long. IIR filters are usually 8 to 10 delays long. The effective delay for an IIR filter is longer than the actual number of delays, because of the feedback in these filters. Although the infinite response suggests that the filter never completes its response, in a practical sense the IIR filter response is finite. The design approach for FIR filters and IIR filters is quite different. For an FIR filter, the filter coefficients $A_0$ through $A_n$ are designed to optimally fit a desired filter response curve. The response of this optimal filter often has excessive sidebands, that is, high output in the nonpass frequency range. The sidebands can be reduced by applying a window function, which modifies the filter coefficients. The effect of the window function is to broaden the transition region between the passband and the stopband, and reduce the magnitude of the sidebands. The response equation, or transfer function, for the FIR filter with even symmetry is

$$H(\omega) = \sum_{i=0}^{i=n} A_i \cos(\omega i) \tag{15.2.15}$$

In this equation, the frequency $\omega$ is a continuous variable in radians per second. Although the filter is a discrete device, its frequency response can be viewed as continuous. The digital signal is discrete, and when a signal is converted from digital to analog, this conversion adds its own modification of the signal.



(a)

(b)

**Fig. 15.2.34** (*a*) Finite impulse response (FIR) and (*b*) infinite impulse response (IIR) digital filters.

The design approach for an IIR filter is quite different. For an IIR filter, the first step is to design a low-pass analog filter for a particular filter response, such as a Butterworth, Chebychev, or Cauer response. The analog filter can then be converted to a low-pass digital filter using the bilinear transform. Finally, the low-pass digital filter can be converted to a high-pass, band-pass, or band-stop filter. The resulting filter has a transfer function given by

$$H(\omega) = \frac{\sum_{i=0}^{i=n} A_i \cos(\omega i)}{1 - \sum_{i=1}^{i=m} B_i \cos(\omega i)} \tag{15.2.16}$$

A more complete discussion of digital filter technology can be found in the references at the beginning of this section. Further help in digital filter design can be obtained by using a computer program, such as MATLAB.

Digital filter calculations consist of a series of mathematical operations which follow a consistent pattern. Each calculation is performed by retrieving a number, multiplying it by a coefficient, adding it to another number, and storing the result. This is the operation at each of the summation points in the FIR and the IIR. A microprocessor called a **digital signal processor (DSP)** has been developed for this purpose. DSPs complete a retrieve, multiply, add, and store in a single clock pulse (30 ns), several times faster than a general-purpose microprocessor. DSP microprocessors are widely used in test equipment, telephone equipment, television, and military equipment. Because of the wide usage, DSP microprocessors are quite inexpensive. DSPs were developed in order to increase the bandwidth of digital signal processing. It should be further noted that digital filters can employ parallel processing, in which several DSP chips can operate in parallel to further increase bandwidth.

Digital signal processing is not limited to analog and digital filtering. Digital data may also be improved by using smoothing algorithms, or by removing inconsistent data points, such as outliers. Insight into data content can also be obtained by statistical analysis. Digital signal processing is also used to improve the quality of voice signals, and to enhance video signals.

### Digital Communications

The bandwidth required to transmit information depends on the digital pulse rate. A fundamental relationship exists for the bandwidth required for the transmission of digital or analog information. For analog signals, the bandwidth depends on the highest frequency component in the signal. For digital circuits, the bandwidth depends on the maximum pulse rate. The relationship between the two is known as the Nyquist criterion. The minimum pulse rate pr necessary to transmit an analog signal digitally must be twice the highest frequency $f$:

$$\text{pr} = 2f \tag{15.2.17}$$

This is a bilateral relationship. The frequency bandwidth BW of a transmission system must be equal to at least half the pulse rate:

$$\text{BW} = \text{pr}/2 \tag{15.2.18}$$

These conditions are minimum requirements. A transmission system that has greater bandwidth can support slower pulse rates, and similarly, a high-pulse-rate system can be used to pass a low-frequency signal. A higher pulse rate than the Nyquist criterion will approximate an analog signal waveform more accurately, but is not necessary to pass the information. Voice-grade lines have a bandwidth of 4,000 Hz, and will pass 8,000 bits per second (bps). Twisted-pair cable, properly terminated, can pass about 1 MHz or 2 Mbps. Coaxial cable can pass 100 to 200 MHz. To obtain greater bandwidths, light is being used to transmit information, rather than electricity. Inexpensive fiber-optic devices can be used for distances up to several hundred feet. For longer distances, phase-locked lasers and single-mode fiber-optic cable is being employed. Single-mode fiber is quite small and somewhat hard to terminate. Tooling to facilitate connecting single-mode cable is becoming more readily available.

Electric instrumentation has several communication standards which facilitate the connection of measuring systems. A low-speed instrument bus, IGIB, has been developed and described in a standard, IEEE 488. For higher communication rates, a CAMAC crate has been standardized. These standards give physical characteristics, such as connectors and plugs, mounting dimensions, printed board sizes, etc. These standards also define communications protocol, bus timing, and connector pin assignment.

In most computers, the interconnection of computer printed boards is accomplished using a ‘‘mother board.’’ The mother board may contain the CPU, semiconductor memory, and several input/output devices. While these devices are somewhat arbitrary, it is essential that the mother board contain a computer bus structure. The computer bus is defined by a standard which defines the type connector, the connector circuit configuration, and the computer communication protocol. There are several agencies which define computer bus standards in the United States and around the world. Some of the more common IEEE bus standards are listed in Table 15.2.16.

### Power Electronics

Power electronics can be divided into three major groups: motor drives, power supplies, and power amplifiers. Motor drives can be divided into dc motor drives and ac motor drives. Power supplies include power supplies for electronic circuits, battery back-up systems, electric power applications, and induction/dielectric heating supplies. Power amplifiers cover other power conditioning topics.

The power for dc motor armatures can be derived from thyristor circuits like those shown in Fig. 15.2.9. Single-phase bridge circuits are used for 5-hp drives and smaller. Three-phase bridge circuits are used for drives larger than 5 hp. A single set of six thyristors can supply power for about 300 hp. Above 300 hp, multiple sets of thyristors must be used in parallel. Mill drives have been built with more than 10,000 hp provided by thyristors.

The control of dc motors whether powered by thyristors or by dc generators is accomplished electronically. Control of individual drives can be accomplished by tachometer feedback or by armature voltage feedback. The speed-regulation accuracy for armature feedback is 5 percent; for tachometer feedback speed-regulation accuracy is from 0.1 to 1.0 percent. When two drives must be coordinated with each other, as in a continuous-web processing machine, they can be regulated to control torque, speed, position, draw, or a combination of these parameters. Torque controls can be achieved using dc motor armature current for a feedback signal. Speed-control signals are derived as for single motors. Position or draw control can be accomplished by using selsyn ties or dancer rolls. A **dancer roll** is a weight- or spring-loaded roll that rides on the web. It is free to move up and down, and as it does, a signal is taken from its position to serve as a feedback for the drive regulator before the dancer or after it.

Coordination of the motions of two or more drives requires tracking of the drives in both steady-state and transient conditions. Linearity of the control and feedback signals determine steady-state tracking. Provision must be made for both low-speed and high-speed matching signals. Transient matching requires that signals not only be the right magnitude but also arrive at the right time. An example will serve to illustrate this point. Suppose it is desired to have two drives with tachometer feedback

**Table 15.2.16 IEEE Computer Bus Standards**

| Identifier | Common name | Description |
|---|---|---|
| IEEE 488 | GPIB | General-purpose instrument bus |
| IEEE 796 | Multibus | General-purpose computer bus |
| IEEE 961 | STD bus | Standard computer bus |
| IEEE 1014 | VMEBUS | European computer bus |
| IEEE Proposal | VXIBUS | Instrumentation adaptation of VMEBUS |
| IEEE Proposal | MXIBUS | Extension of VXIBUS |

which have a continuous web between them. One way to accomplish this would be to designate one drive as a master and the other as a slave. The tachometer on the master drive would serve as its own feedback signal and as the reference or command signal for the slave drive. The slave drive would have its own feedback from its own tachometer and so its regulator would try to minimize the difference between the two tachometer signals. On a transient basis the master drive will always start before the slave. An alternate and more common arrangement is to provide a common reference for both drives and let each drive receive its command signals at the same instant.

Digital computers are being used on-line in mills and continuous processing industries. DC motors can be controlled by either analog or digital regulators. With the greatly reduced cost of integrated circuits, digital regulators are being increasingly used.

For digital speed control, feedback is taken from a digital tachometer, which generates a pulse frequency proportional to motor speed. An adjustable frequency reference is compared with the feedback, and the difference is applied to an up/down counter. The output of the counter is converted to a dc control signal for the motor controller. In this system the dc drive functions as a form of phase-locked loop, and in fact, a phase-locked loop can be substituted for the up/down counter in digital speed control. For digital position control, a shaft encoder is used for feedback. In a shaft encoder, a single turn of the motor shaft is encoded in a binary code. For example, an eight-track shaft encoder can define $2^8$, or 256, parts of a revolution. The output of the shaft encoder is compared with a digitally derived reference code. The difference between the feedback and the reference is converted into a dc signal which controls the motor, and holds the desired position. Sometimes the position encoder is mounted on the driven machine. The accuracy of sensing the machine position is improved. Accurate milling machines have feedback from machine position, rather than from the drive motor. Computers can be used to derive a speed reference or a position reference for several motors, and thus, an entire process line can be controlled. Modern high-speed paper making machines are one example of coordinated computer control of several motors. Graphic terminals, which display the entire paper making machine, are located at various positions allowing several operators to coordinate the operation of the machine.

DC motors can also be supplied from a fixed dc voltage such as a battery or a fixed dc power supply. Inherently, fixed voltage on the field and on the armature of a dc motor implies constant-speed operation. The armature voltage can be controlled by a proportional device such as a transistor. Proportional devices are limited to low-power applications. At low speeds, the dc motor requires low voltage and full current to produce full torque. The losses in the control device are proportional to the product of voltage and current. The full battery voltage is applied to the control device and the motor in series. Thus, the control device has a high voltage drop across it at low motor armature voltages and low motor speeds. To reduce controller losses, a **chopper** may be used. The chopper is thyristor, power MOSFET, or IGBT circuit which can rapidly switch on and off. When the chopper is on, the loss in the control device is low because the voltage drop is small. When the chopper is off, the loss in the control device is small because the current through the device is very small. Large amounts of power can be controlled with low losses by means of a switching controller. For large dc motors, the switching rate of the chopper is made high enough that the inherent inductance of the motor armature maintains a nearly constant motor current.

The speed range of a variable-speed dc motor is limited by its armature resistance, which produces *IR* drop. For a very small motor, the *IR* drop can be as much as 20 percent of rated armature voltage. The resistance-to-inductance ratio of small motors is much greater than for large motors. To extend the speed range of small motors, a low-frequency chopper can be used which will cause the armature current to be discontinuous. Discontinuous conduction reduces the effective *IR* drop for the motor allowing its speed range to be extended.

DC motors have been widely used for variable-speed applications because of their excellent characteristics. AC motors have been used primarily for constant-speed applications. The control schemes described above are equally applicable to ac motors (except of course for armature voltage and armature current feedback). If power circuitry is properly handled, the control of an ac motor is just as flexible and versatile as that of a dc motor.

AC motors can be supplied either from **phase-controlled circuits** or from **inverter circuits**. Phase control uses a simpler electronic circuit than the inverter, but it results in high loss in the ac motor. The phase control switches at line frequency, and so the frequency applied to the motor is constant. This means that the synchronous speed of the induction motor is constant. The difference between the operating speed of the motor and synchronous speed produces losses in the rotor of the motor proportional to the torque demanded of the motor. For this reason, phase-controlled ac motor drives are limited to applications with slight speed change requirements or to loads that require much lower torque at low speed, such as pumps or fans. Inverters are used for ac motor drives which require constant torque operation over a wide speed range. Several different schemes have been used for ac motor inverters. Some of these are **pulse width modulation (PWM), six-step inverters,** and **current link inverters**. Most modern drives are PWM inverters. In a PWM inverter, the ac line voltage is converted into a fixed dc voltage, and then this dc voltage is inverted into a variable frequency and a variable voltage. Figure 15.2.35 shows a block diagram of PWM inverter. Since the motor is an ac motor, both positive and negative voltages must be applied to each motor phase. The motor shown in Fig. 15.2.35 has three phases. Consider the operating conditions at only one of the phases of the motor. To apply a positive voltage to phase A-B of the motor, switches SW1 and SW4 are turned on. To apply a negative voltage to phase A-B, SW2 and SW3 are turned on. To apply zero volts to phase A-B, either SW2 and SW4 or SW1 and SW3 are turned on. A similar operation takes place for phase B-C and phase C-A of the motor. The dc voltage in the PWM inverter is constant. To generate an approximate sine wave of voltage, the inverter must produce a low voltage during part of the cycle and high voltage during another part of the cycle, and it must do this on both the positive half of the sine wave as well as the negative half. On the positive half-cycle, switching occurs alternately between switches SW1 and SW4 and switches SW1 and SW3. To control the speed of the ac motor and keep its losses low, one must vary both the frequency of the motor voltage and its magnitude. The motor requires an approximately constant volts per hertz rate for full torque and low losses. Although this control scheme seems very complicated, PWM inverter drives have been developed which are far more dependable than dc drives. The commutator and brushes required for a dc motor limit its reliability. The motor frequency for an ac motor inverter drive varies from nearly zero to a maximum of 120 Hz typically. To reverse the rotation of the ac motor, the phase sequence applied to the motor is reversed. The actual switching frequency of the inverter is approximately 10,000 Hz, allowing the inverter switch on and off several times during a cycle applied to the motor. The pulse width is varied or modulated, to change the output voltage, hence the name pulse-width-modulated inverter. The inductance of the motor keeps the current variations in the motor from being too great.

Switching power supplies use technology similar to ac motor inverters. In Fig. 15.2.35, SW1 and SW2 are called an *inverter leg.* The inverter leg is fundamental to switching power supplies. The dc chopper described earlier could be made with a single inverter leg. Regulated dc power supplies are also made using an inverter leg. A higher intermediate voltage is produced in an ac-to-dc rectifier. This voltage is then chopped to make a lower output voltage. Feedback is taken from the load point of the power supply to control the pulse width of the inverter leg, or chopper. Precise computer power supplies are often switching power supplies of this type. They maintain precise dc output voltage under changing load conditions and changing supply voltage. Because the power supplies switch, the loss in these power supplies is much lower than for proportionally controlled power supplies.

The switching behavior of the inverter leg is actually more complex than simply turning on one switch and turning off another. Each switching action involves a resonant transient. At each switching point an

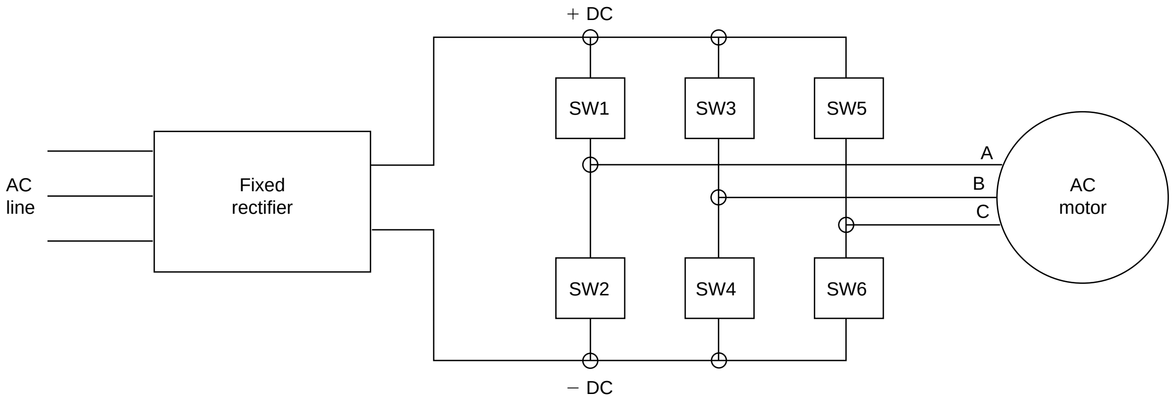


**Fig. 15.2.35** Pulse width modulation inverter.

*R-L-C* circuit rings from one voltage to another. At very high switching rates, a second transient starts before the first transient is over. This leads to a power supply with a parade of transients. Such power supplies are called *resonant converters.* These power supplies may be used for dc-to-dc, dc-to-ac, ac-to-dc, and ac-to-ac conversions. By using the ring-up inherent in resonant circuits, voltage levels can be increased as well as decreased. Induction heating power supplies are typical of these kinds of circuits. Induction heating is produced by the magnetic losses generated in nonmagnetic and magnetic metals. If the frequency and voltage are increased sufficiently, dielectric heating may also be produced in high-frequency power supplies. High-frequency, high-voltage power supplies are also used to produce a corona discharge to treat the surface of plastic materials. Plastics which are normally hydrophobic can be made hydrophilic by corona discharge treatment.

### Communications

The Federal Communications Commission (FCC) regulates the use of radio-frequency transmission in the United States. This regulation is necessary to prevent interfering transmissions of radio signals. Some of the frequency allocations are given in Table 15.2.17. The frequency bands are also classified as shown in Table 15.2.18. Very low frequencies are used for long-distance communications across the surface of the earth. Higher frequencies are limited to line-of-sight transmission. Because of bandwidth considerations, high frequencies are used for high-density communication links. Orbiting **satellites** allow the use of high-frequency transmission for long-distance high-density communications.

A **radio transmitter** is shown in Fig. 15.2.36. It consists of four basic parts: an rf oscillator tuned to the carrier frequency, an information-input device (microphone), a modulator to impress the input signal on the carrier, and an antenna to radiate the modulated carrier wave.

A radio wave can be modulated in several ways. It can be amplitude-, frequency-, or phase-modulated. These are examples of analog signal modulation. A radio wave may also be digitally modulated. Examples of digital modulation include on-off, binary phase-shift keying (BPSK), frequency-shift keying (FSK), quadrature phase-shift keying (QPSK), and quadrature amplitude modulation. Regardless of which method of modulation is used, the frequency content in the signal requires a bandwidth of frequencies to support the transmission. If a 10-kHz signal is to be broadcast, the transmitted radio wave will consist of a center frequency, called the *carrier frequency*, and an upper and lower sideband, for a frequency bandwidth of 2 times 10 kHz, or 20 kHz. It is possible to suppress the upper or lower sideband leading to single-sideband transmission, but this is a special case. Regardless of the modulation scheme, the bandwidth required for signal transmission is the same for a given signal bandwidth. Higher frequencies or higher digital pulse rates require greater bandwidth for transmission.

A **radio receiver** is shown in Fig. 15.2.37. This is called a **superhetero-**

**Table 15.2.17 Partial Table of Frequency Allocations**

(For a complete listing of frequency allocations, see ''Reference Data for Radio Engineers,'' published by Howard Sams & Co.)

| Frequency, MHz | Utilization |
|---|---|
| 0.535–1.605 | Commercial broadcast band |
| 27.255 | Citizen's personal radio |
| 54–72 | Television channels 2–4 |
| 76–88 | Television channels 5–6 |
| 88–108 | Frequency-modulation broadcasting |
| 174–216 | Television channels 7–13 |
| 460–470 | Citizens' personal radio |
| 470–890 | Television channels 14–83 |

**Table 15.2.18 Frequency Bands**

| Designation | Frequency | Wavelength |
|---|---|---|
| VLF, very low frequency | 3–30 kHz | 100–10 km |
| LF, low frequency | 30–300 kHz | 10–1 km |
| MF, medium frequency | 300–3,000 kHz | 1,000–100 m |
| HF, high frequency | 3–30 MHz | 100–10 m |
| VHF, very high frequency | 30–300 MHz | 10–1 m |
| UHF, ultra-high frequency | 300–3,000 MHz | 100–10 cm |
| SHF, super-high frequency | 3,000–30,000 MHz | 10–1 cm |
| EHF, extremely high frequency | 30,000–300,000 MHz | 10–1 mm |

NOTE: Wavelength in meters = $300/f$, where $f$ is in megahertz.

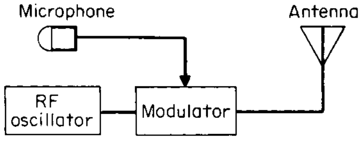
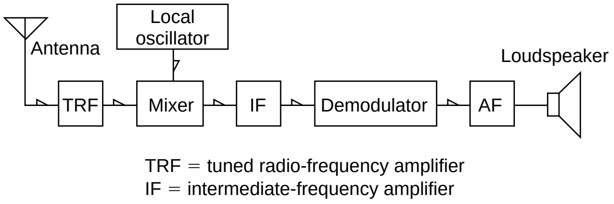


**Fig. 15.2.36** Radio transmitter.



TRF = tuned radio-frequency amplifier
IF = intermediate-frequency amplifier
AF = audio-frequency amplifier

**Fig. 15.2.37** Superheterodyne radio receiver.

**dyne** receiver because it utilizes a frequency-mixing scheme. The tuned radio-frequency amplifier is tuned to receive the desired radio signal. The local oscillator is adjusted by the same tuning control to a lower frequency. The mixer produces an output frequency which is the difference between the incoming radio-signal frequency and the local-oscillator frequency. Since this difference frequency is constant for all tuning positions, the intermediate-frequency amplifier always operates with a constant frequency. This allows optimum design of the intermediate-frequency (IF) amplifiers since they are constant-frequency amplifiers. The IF frequency signal is modulated in just the same way as the radio signal. The demodulator separates this audio signal, which is then amplified so that the loudspeaker can be driven.

The term **radar** is **derived** from the first letters of the words ''*ra*dio *d*etection *a*nd *r*anging.'' It is essentially an echo system in which the location of an object is determined by sending out short pulses of radio waves and observing and measuring the time required for their reflections or echoes to return to the sending point. The time interval is a measure of the distance of the object from the transmitter. The velocity of radio waves is the same as the velocity of light, or 984 ft/$\mu$s, so that each microsecond interval corresponds to a distance of 492 ft. The direction of an object can be determined by the position of the directional transmitting and receiving antenna. Radio waves penetrate darkness, fog, and clouds, and hence are able to detect objects that otherwise would remain concealed. Radar can be used for the automatic ''tracking'' of objects such as airplanes.

A block diagram of a radar system is shown in Fig. 15.2.38. The transmitting system consists of an rf oscillator which is controlled by a modulator, or pulser, so that it sends to the antenna intermittent trains of rf waves of relatively high power but of very short duration, corresponding to the pulses received by the modulator. The energy of the oscillator is transmitted through the duplexer and to the antenna through either coaxial cable or waveguides. The **receiver** is an ordinary heterodyne-type radio receiver which has high sensitivity in the band width corresponding to the frequency of the oscillator. For low frequencies the local oscillator is an ordinary oscillator for frequencies of 2,000 MHz; and higher a reflex **klystron** (hf cavity oscillator) is used. A common intermediate frequency is 30 MHz but 15 and 60 MHz are also frequently used.

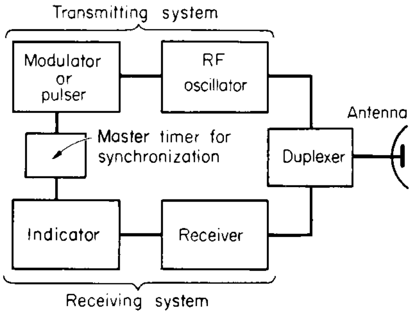


**Fig. 15.2.38** Block diagram of radar system.

In most radar systems the same antenna is used for receiving as for transmitting. This requires the use of a **duplexer** which cuts off the receiver during the intervals when the oscillator is sending out pulses and disconnects the transmitter during the periods between these pulses when the echo is being received.

The antenna is highly directional. By noting its angular position, the direction of the object may be determined. In the PPI (plan position indicator), the angle of the sweep of the cathode-ray beam on the screen of the oscilloscope is made to correspond to the azimuth angle of the antenna.

The receiver output is delivered to the indicator which consists of a cathode-ray tube or oscilloscope. The pulses which are received, corresponding to echoes from the target, must be synchronized with the sending pulses in order that the distance to the target may be determined. This is accomplished by synchronization of the sweep circuit of the oscilloscope with the pulses by the master timer.

**Displays** Conversion of the received radar signals to usable display is accomplished by a cathode-ray oscilloscope. The simplest type, called the **A presentation,** is shown in Fig. 15.2.39*a*. When the pulser operates, a sawtoothed wave produces a linear sweep voltage (Fig. 15.2.39*b*) across the sweep plates of the cathode-ray tube; at the same time a transmitter pulse is impressed on the deflection plates and the return echoes appear as AM pulses, or ''pips,'' on the screen, as shown in Fig. 15.2.39*a*. The distance on the screen between the transmitter pulse and the pip caused by the echo is proportional to the distance to the target, and the screen can be calibrated in distance such as miles.

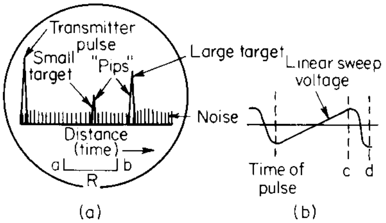


**Fig. 15.2.39** Type A presentation.

[The return of the spot to its initial starting position, produced by the sweep interval *cd* (Fig. 15.2.39*b*), is so rapid that it is not detectable by the eye.] The direction of the target may be determined by the angular position of the antenna, which can be transmitted to the operator by means of a selsyn. Different objects, such as airplanes, ships, islands, and land approaches, have characteristic pips, and operators become skilled in their interpretation. A bird in flight can be recognized on the screen. Also a portion of the scale such as *ab* can be segregated and amplified for close study of the characteristics of the pips.

**Plan Position Indicator (PPI)** In the PPI (Fig. 15.2.40) the direction of a radial sweep of the electron beam is synchronized with the azimuth sweep of the antenna. The sweep of the beam is rotated continuously in synchronism with the antenna, and the received signals intensity-modulate the electron beam as it sweeps from the center of the oscilloscope screen radially outward. In this way the direction and range position of

**Fig. 15.2.40** Plan position indicator (PPI) of southeastern Massachusetts.

an object can be determined from the pattern on the screen of the oscilloscope, as shown in Fig. 15.2.40.

There are two methods by which the angular direction of the cathode spot is made to correspond with the angular position of the antenna. In one method, used on board ship, two magnetic deflecting coils are rotated around the neck of the tube in synchronism with the antenna, by means of a selsyn. In the other method, used on aircraft, two fixed magnetic deflecting coils at right angles to each other and placed at the neck of the tube are supplied with current from a small two-phase synchronous generator whose rotor is driven by the antenna. Thus a rotating field, similar to that produced by the stator of an induction motor, is produced by the magnetic deflecting coils. These two rotating fields, although produced by different means, are equivalent and cause the cathode beam to sweep radially in synchronism with the antenna. Circular coordinates spaced radially corresponding to distance are obtained by impressing on the control electrode short positive pulses synchronized with the transmitted pulse but delayed by time values corresponding to the desired distances. These coordinates appear as circles on the screen. Since the time of rotation of the antenna is relatively slow, it is necessary that a persistent screen be used in order that the operator may view the entire pattern. In Fig. 15.2.32 is shown a line drawing of a PPI presentation of Cape Cod, Mass., on a radar screen, taken from an airplane.

The applications of radar to war purposes are well known, such as detecting enemy ships and planes, aiming guns at them, and locating cities, rivers, mountains, and other landmarks in bombing operations. In peacetime, radar is used to navigate ships in darkness and poor visibility by locating navigational aids such as buoys and lighthouses, as well as protruding ledges, islands, and other landmarks. It can be similarly used in air navigation, as well as to operate altimeters for determining the height of the plane above ground. It is also used for aerial mapping.

**Sonar** is closely related to radar. The difference is that sound is used as the transmitting signal. Since the velocity of sound in water is so much slower than radio waves in free space, the timing for sonar signals is much slower than for radar signals. A 1-s delay of a sonar return echo implies that the target is 2,500 ft away. A 1-s delay of a radar return echo would imply that the target is 193,000 miles away. Although A displays and PPI displays are used with sonar signals, much reliance is placed on hearing. Transmitting a sonar pulse is an excellent way of disclosing your presence to an enemy vessel. Today more reliance is placed on passive detection of enemy vessels, by **signature analysis**. Signature analysis is signal analysis using fast Fourier transforms and filters.

**Television** is accomplished by systematically scanning a scene or the image of a scene to be reproduced and transmitting at each instant a current or a voltage which is proportional to the light intensity of the elementary area of the scene which at the instant is being scanned. The varying voltage or current is amplified, modulated on a carrier wave, and then transmitted as a radio wave. At the receiver the radio wave enters the antenna, is amplified, and demodulated to give a voltage or a current wave similar to the original wave. This voltage or current wave is then used to control the intensity of a cathode-ray beam which is focused on a fluorescent screen in a cathode-ray reproducing tube. The cathode-ray beam is caused to move over the screen in the same pattern as the scanning beam at the transmitter and in synchronism with it. Thus each small area of the receiver screen is illuminated instantaneously with light intensity corresponding to that of a similarly placed area in the original scene. This process is conducted so rapidly that owing to persistence of vision of the eye, the reproduction of each instantaneous scene appears to be a complete picture and the effect with successive scenes is similar to that produced by the projection of successive frames of a motion picture.

**Scanning and Blanking** In the United States the ratio of width to height of a standard television picture is 4 : 3, and the picture is composed of 525 lines repeated 30 times a second, this last factor being one-half 60, the prevalent electric power frequency in the United States. The scanning sequence along the individual lines is from left to right and the sequence of the lines is from top to bottom. Also, interlacing is employed, the general method of which is shown in Fig. 15.2.41. The cathode-ray spot starts at 1 in the upper left-hand corner and is swept rapidly from left to right either by a sawtooth emf wave applied to the sweep plates or by the sawtooth current wave applied to the sweep coils of the tube. When the spot arrives at the right-hand side of the picture, the sawtooth wave of either emf or current in the sweep circuit acts to return the cathode-ray spot rapidly to point 3 at the left-hand side of the picture. However, during this period the cathode-ray is blanked, or entirely eliminated, by the application of a negative potential to the control grid of the tube. At the end of the return period, the blanking effect ceases and the spot appears at point 3, from which it again is swept across the picture and this process is repeated for 262.5 lines until the spot reaches a midpoint *C* at the bottom of the picture. It is then carried vertically and rapidly to *B*, the midpoint of the top of the picture, the beam also being blanked during this period. This process of scanning is then repeated, a second set of lines corresponding to the even numbers 2, 4, 6 being established between the lines designated by the odd numbers. These lines are shown dashed in Fig. 15.2.41. This method or pattern of scanning is called **interlacing**. The two sets of lines taken together produce a frame of 525 lines, which are repeated 30 times each second. However, owing to interlacing, the flicker frequency is 60 Hz which is not noticeable, 50 Hz having been determined as the threshold of flicker noticeable to the average eye. In Fig. 15.2.41, for the sake of clarity, the distances between horizontal lines are greatly exaggerated and no attempt is made to maintain proportions.

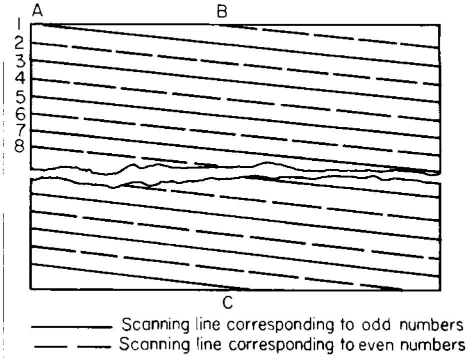


**Fig. 15.2.41** Pattern of interlaced scanning.

**Frequency Band** In order to obtain the necessary resolution of pictures, television frequencies must be high. In the United States, VHF frequencies from 54 to 88 MHz (omitting 72 to 76 MHz) and 174 to 216 MHz are assigned for television broadcasting. A UHF band of frequencies for commercial television use is also allocated and consists of the frequencies of from 470 to 890 MHz (see also Tables 15.2.17 and 15.2.18).

In order to obtain the 525 lines repeated 30 times per second, a bandwidth of 6 MHz is necessary. The video, or picture, signal with the superimposed scanning and blanking pulses is amplitude-modulated, amplified, and transmitted. The carrier frequency associated with the sound transmitter is 4.5 MHz higher than the video carrier frequency and is frequency-modulated with a maximum frequency deviation of 25 kHz.

In scanning motion-picture films a complication arises because standard film rate is 24 frames per second, while the television rate is 30 frames per second. This difficulty is overcome by scanning the first of two successive film frames twice and the second frame three times at the 60-Hz rate, making the total time for the two frames $\frac{1}{12}$ ($\frac{2}{60} + \frac{3}{60}$) or $\frac{1}{24}$ s average per frame.

**Kinescope** The kinescope (Fig. 15.2.42) is the terminal tube in which the televised picture is reproduced. It is relatively simple, being not unlike the cathode-ray oscilloscope tube. It has an electric gun operating at 8,000 to 20,000 V which produces an electron beam focused on a fluorescent surface within the front wall of the tube. The picture is viewed at the front wall. The horizontal and vertical deflections of the beam are normally controlled by deflection coils, as shown in Fig. 15.2.42.

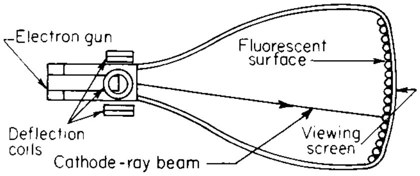


**Fig. 15.2.42** Kinescope for television receiver.

**Television Receivers** A block diagram for a television receiver is given in Fig. 15.2.43. It is in reality a superheterodyne receiver with tuned rf amplification, the separating of the sound and video or picture channels taking place at the intermediate frequency in the mixer. The sound channel is then conventional, a discriminator being used to demodulate the FM wave (Fig. 15.2.21). The object of the dc restorer is to make the picture reproduction always positive, and it consists of applying a dc voltage at least equal in magnitude to the maximum values of the negative loops of the ac waves. The synchronizing pulses for both the vertical and the horizontal deflections are delivered by the dc restorer to an amplifier and the two pulses are then divided into the V and H components. The integrating and differentiating circuits are necessary to separate horizontal and vertical synchronizing signals.

As stated earlier, at any instant the magnitude of the current from the pickup tube varies in accordance with the light intensity of the part of the scene being scanned at that instant. This current is amplified and, together with the sound and synchronizing current, is broadcast and received by the circuit shown in Fig. 15.2.43. The video current is detected by rectification, is amplified, and is then made to control the intensity of the kinescope electron beam. Tubes produce a scanning pattern, identical with that in the pickup tube, and these tubes are triggered by the synchronizing pulses which are transmitted in the broadcast wave. Hence, the original televised scene is reproduced on the fluorescent screen of the kinescope.

**Color-television** transmission is similar to black-and-white television, and the two signals must be compatible with each other. The kinescope for color TV has three electron guns, one for each primary color. The fluorescent screen has a matrix of three different colors of phosphor and a mask with many small holes in it. The intensity signals for each color are phase-shifted from each other so that the proper phosphors are excited by each electron stream at each mask point over the entire screen. A black-and-white signal does not have the same synchronizing signal as a color signal. The color receiver has circuits which recognize this state and switch it to black and white reception.

### Telephone Communications

Telephone communications is an important aspect of electronics because it provides a source of low-cost electronic devices which can be adapted for electronic circuit design. One of the big problems in telephone system design is switching. Each long-distance phone call requires that several circuits be joined together, and thousands of phone calls take place simultaneously. Older telephone exchange buildings had rack upon rack of telephone relays. These are being replaced by semiconductor switching. Older trunk lines were coaxial cable or microwave radio links. These are being replaced by fiber-optic cables. Fiber-optic cables have a tremendous bandwidth. A telephone voice circuit has a bandwidth of 4 kHz. Thousands of these circuits can be routed through one fiber-optic cable. Separating these voice circuits into communication channels by frequency separation and filtering is not feasible. Communication on fiber-optic cables is done digitally, and in packets. Each packet is a few hundred bytes long, and includes a header with an address and other control information, the message, and a trailer with error-correcting codes. The address is a session address to identify where the packet is from and where it is going. Users time-share the fiber-optic cable, and all of this signal processing must be done at a high enough rate to appear to be instantaneous to the subscriber.

Any form of signal modulation can be considered to be data encryption. The information is coded or encrypted onto the transmitting medium. At the transmitting end, a clear signal with no noise is sent, but at the receiving end of the medium, the signal contains the signal plus unwanted noise. Since the coding method is known, and since the noise is known to be random, separation of signal and noise is possible. This process of separating signal from noise will be repeated several times for long-distance communications. Each time, the noise is discarded and only the signal is sent on. Such a scheme of data encryption, or modulation, is also warranted in data telemetry, in order to allow noise to be removed from the desired signal.

Long-distance communications takes several different forms. Historically, cables with hundreds of twisted-pair circuits were used for long-distance communication. These are used for local subscriber service today. The next step was a cable made up of many wideband microwave coaxial cables. The coaxial cables were replaced by microwave radio links. Then, fiber-optic cables replaced microwave links. Wireless communication, using laser-generated signals, is the latest form of high volume data transmission. In a telephone system, all of these systems must coexist and work together.

There is great interest in cellular communications. This is a microwave broadcast system. The cellular communication system is evolving today, and promises to allow mobility of telephone communications.

### Global Positioning Information

Navigational aids take several different forms. **Shoran** (short-range navigation) and **loran** (long-range navigation) are methods by which ships or planes can locate their position. A loran station consists of a master

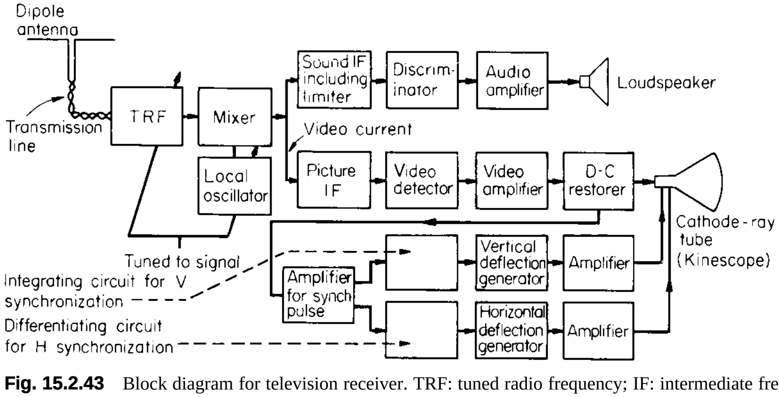


**Fig. 15.2.43** Block diagram for television receiver. TRF: tuned radio frequency; IF: intermediate frequency.

transmitter and slave transmitter located about 200 mi apart. A pulse is broadcast from the master transmitter and, when received by the slave transmitter, causes it to also broadcast a pulse. The loran receiver, located on a ship or airplane, receives both the master and the slave pulses. The receiver allows the user to measure the delay between receiving the master and slave pulses. The delay defines a line across the surface of the earth. By picking three loran stations, determining the delay of each of the transmitter pairs, and using loran charts, three lines can be defined, allowing the user to determine the triangle which defines the receiver's position. **Very high frequency omnirange (VOR)** is used for short-range aircraft navigation, often in conjunction with **direction measuring equipment (DME)**. VOR stations are located approximately 100 mi apart. The receiver in the aircraft receives a signal from the VOR transmitter with two pieces of information, which allows the pilot to determine the bearing from the VOR station. The first piece of information is a 30-Hz amplitude-modulated signal which is broadcast from a rotating directional antenna. The antenna rotates 30 times per second, and broadcasts in the 108- to 112-MHz range. The second piece of information is a frequency-modulated signal which varies between 9,480 and 10,440 Hz. This FM signal changes frequency at 30 Hz, and forms a reference for the VOR system. A receiver on the aircraft compares the 30-Hz amplitude-modulated signal and the 30-Hz frequency-modulated reference, and translates the difference in phase between the FM signal and the AM signal to give the airplane its bearing. The VOR also broadcasts station identification information in the 112- to 118-MHz range. Most VOR stations can also broadcast a **distance measuring equipment (DME)**. The aircraft has a DME transmitter which broadcasts a pulse which activates a ground mounted transponder. The aircraft sends an FM signal in the 1,025- to 1,150-MHz range. The DME ground station responds with a delayed signal in the 962- to 1,024-MHz or 1,151- to 1,213-MHz range. Distance is determined by the time delay required for the propagation of the signals. The depressed, straight line distance from the aircraft is measured by the DME equipment. To relieve the pilot of the job of correcting for altitude in the DME signal and to allow the pilot to fly any heading, a computer system called RNAV was introduced. RNAV uses the VOR and DME information, plus wind velocity and airspeed, to calculate the required aircraft heading and the estimated time of arrival at the destination.

Most major airports have an **instrument low approach system (ILS)**. This produces a set of signals in the 108- to 112-MHz region. There a right-hand antenna lobe, relative to the aircraft, which is modulated at 150 Hz, and a left-hand lobe modulated at 90 Hz. In addition, in the 329- to 335-MHz range there is a vertical set of antenna lobes, with the upper lobe modulated at 90 Hz and lower lobe at 150 Hz. The display on the aircraft is an azimuth needle and a glide path needle. The pilot simply flies the aircraft to center the needles to determine a correct landing approach. There are also ILS marker beacons to tell the pilot how close the aircraft is to the airport. Other aircraft navigation systems are based on ground-operated radar systems. Still others are based on aircraft-mounted Doppler radar. Doppler radar is a velocity measuring system.

**Satellite positioning systems** are the newest development for long-range and short-range navigation. The **global positioning system (GPS)** is a system involving 21 to 24 satellites which broadcast accurate time marks. By knowing which satellite has broadcast the time mark, and measuring its delay to the aircraft, one can determine a spherical surface in space. By determining the delay from four satellites, four spherical surfaces in space can be determined. Worldwide navigation accurate within 50 m in longitude and latitude and within 100 m vertically is being realized commercially. The military capabilities are better than the commercial, in the submeter range. The commercial timing signals are deliberately disturbed with a random timing variation to degrade them. The capability of the military system was demonstrated by the accuracy of ''smart'' bombs during the Iraq-Kuwait war.

GPS is being used for commercial truck fleets to provide better fleet utilization. GPS is also being used by the Tennessee Valley Authority to monitor power system performance, by determining the phase angle of the 60-Hz voltage wave throughout its system. GPS is also being used by search and rescue teams. GPS receivers for search and rescue cost $300 to $600, and are dropping in price at this time.