SECTION 42

ELECTRICAL ENGINEERING

BY

WALTER I. SLICHTER

PROFESSOR OF ELECTRICAL ENGINEERING, COLUMBIA UNIVERSITY

<table>
<thead>
<tr>
<th>ART</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Definitions, Units, and Standards</td>
<td>02</td>
</tr>
<tr>
<td>2. Principles</td>
<td>04</td>
</tr>
<tr>
<td>3. Conductors</td>
<td>05</td>
</tr>
<tr>
<td>4. Measuring Instruments</td>
<td>06</td>
</tr>
<tr>
<td>5. Direct-current Generators</td>
<td>08</td>
</tr>
<tr>
<td>6. Direct-current Motors and Motor-generator Sets</td>
<td>10</td>
</tr>
<tr>
<td>7. Alternating-current Circuits</td>
<td>13</td>
</tr>
<tr>
<td>8. Alternating-current Generators</td>
<td>15</td>
</tr>
<tr>
<td>9. Synchronous Motors</td>
<td>17</td>
</tr>
<tr>
<td>10. Induction Motors</td>
<td>19</td>
</tr>
<tr>
<td>11. Synchronous Converters and Rectifiers</td>
<td>22</td>
</tr>
<tr>
<td>12. Electric Power Plants</td>
<td>24</td>
</tr>
<tr>
<td>13. Electric Transmission</td>
<td>26</td>
</tr>
<tr>
<td>14. Electric Distribution</td>
<td>29</td>
</tr>
<tr>
<td>15. Electric Lighting</td>
<td>32</td>
</tr>
<tr>
<td>16. Applications of Electric Transmission to Mine Service. (See Sec 16)</td>
<td>34</td>
</tr>
<tr>
<td>17. Electrochemistry</td>
<td>34</td>
</tr>
<tr>
<td>18. Batteries, Storage and Primary</td>
<td>35</td>
</tr>
<tr>
<td>19. Costs</td>
<td>37</td>
</tr>
</tbody>
</table>

Bibliography | 38 |
ELECTRICAL ENGINEERING

1. DEFINITIONS, UNITS, AND STANDARDS

Potential (E or V), or difference in potential between two points, is theoretically the work required to move a unit quantity of electricity from one point to the other. It is analogous to difference in pressure, or head, of a current of water. The practical unit is the (International) volt, or electrical pressure which, when steadily applied to a conductor, the resistance of which is 1 ohm, will produce a current of 1 ampere. Difference of potential is measured in practice by a voltmeter (Art 4). For comparison and calibration the Weston Normal Cell is used, the electromotive force (e.m.f.) of which is 1.0183 volt at 20°C. These cells are calibrated by Bureau of Standards, Washington. A millivolt is 0.001 volt.

Current (I) expresses the quantity of electricity flowing past a given point in 1 sec; it is analogous to gal per sec of a current of water, or to the miner's inch. The practical unit is the (International) ampere, or the unvarying electric current which, when passed through a solution of AgNO₃ in water, in accordance with standardised specifications, deposits silver at the rate of 0.001118 gm per sec. Current is measured by an ammeter (Art 4). A milliampere is 0.001 ampere. Direct current (d c) is officially one which always has the same direction, though it may pulsate in value; but the term is popularly applied to a unidirectional current of constant value, officially called a continuous current (c c). Alternating current (a c) is one which changes its direction and amount in regularly recurring periods.

Resistance (R) in an electric circuit is similar to friction in mechanics. It is the property by which a circuit limits the amount of current caused by a steady voltage. The (International) ohm is the practical unit of resistance, and is the resistance offered to an unvarying electric current by a column of mercury, at temp of melting ice, which is 14.4521 gm in mass, of constant cross-sec and a length of 106.3 cm. Resistance is usually determined by computing the ratio between volts and amperes in a circuit according to Ohm's law (Art 2).

Power unit is the watt or kilowatt (kw). A watt equals 10 million units of power in the centimeter-gram-second system, and in practice equals the product of 1 volt by 1 ampere, or is the rate of expenditure of energy by 1 ampere in a circuit of 1 ohm. A kilowatt is 1 000 watts; a horsepower (US) = 746 watts.

Energy. The theoretical unit is the joule, which is 10 million ergs; in practice, equal to 1 watt times 1 sec. Commercial unit is the kilowatt-hour (kw-hr), equal to 3 600 000 joules. A circuit taking 10 amperes at 100 volts receives 1 kw of power, or 1 kw-hr of energy per hr; hence 1 kw-hr = 2 655 000 ft lb.

Coulomb is the unit of quantity of electricity (corresponding to a gallon of water), or the quantity transferred in 1 sec by a current of 1 ampere.

Capacity is the ability of an electric circuit to store energy in the space between conductors, measured in coulomb or quantity of electricity. A condenser is a device to provide capacity. Farad (C) is the unit of capacity; or the capacity of a condenser which will be charged to a potential of 1 volt by 1 coulomb of electricity. A microfarad is one-millionth of a farad.

Maxwell (s) is the unit quantity of magnetic flux, and is equal to 1 line of force.

Gauss (B) is the unit of magnetic flux density, and is equal to 1 line or 1 maxwell per sq cm.

Gilbert (F) is the unit of magneto-motive force (m m f.), and is that m m f. which will produce 1 line or 1 maxwell in a path in air having a cross-sec of 1 sq cm and a length of 1 cm. One gilbert = 1.257 ampere-turns.

Oersted is the unit of magnetizing force or magneto-motive force per unit length of path, expressed in gilberts per centimeter, or 0.4πNI + 1.

Reluctance. The practical unit is defined as the reluctance of a magnetic circuit in which a magneto-motive force of one ampere-turn produces a flux of one weber.

Weber is the practical unit of quantity of flux and is equal to 10⁵ maxwells.

Henry (L), the unit of inductance, is the inductance of a circuit in which a variation in current of 1 ampere in 1 sec will induce an e m f. of 1 volt.

Hysteresis. When iron or steel is magnetized by an electric current, the value of magnetic flux does not vary directly with the current. An increasing current does not produce the same flux for a given current as a decreasing current. This lagging of the
flux behind the magnetising force is called hysteresis, and may be considered as the effect of friction between the molecules of iron which, in aligning themselves with the flux like little magnets, rub against each other. Hysteresis causes loss of energy and heating of the iron, when the direction or magnitude of flux is changed. If the magnetising force varies through complete cycles, positive and negative, the power lost in hysteresis is:

$$\text{Watts} = k_1/V(B_m + 1000)^{1.4} \times 10^{-6}$$

where $k_1$ = 6 to 18, depending upon quality of iron; $f$ = frequency in cycles per sec; $V$ = volume, cu in.; $B_m$ = maximum magnetic density in lines per sq in.:

Eddy currents are local currents induced in any conducting material located within the influence of any varying magnetic field. The term is especially applied to currents set up in the iron core of a machine, or in a conductor carrying an a-c. These currents cause heating and loss of power and energy.

Effective resistance of a circuit carrying an a-c is found by dividing the total loss in watts due to the combination of true resistance, eddy currents and hysteresis, by the square of the effective value of the current.

Series. Two circuits are in series when the same current passes through both successively.

Shunt. A circuit is in shunt, in multiple or in parallel, with another when they form a divided circuit, so that a part of the total current passes through each, while the potential across them is common.

Constant potential circuit is one across which the potential is kept as nearly as possible constant, irrespective of the current flowing. It implies a supply from a circuit of low resistance. Most house lighting (incandescent), motor supply, and transmission systems are of constant potential type.

Constant current. Certain systems of lighting by arc lamps require constant value of current in all the lamps, which are therefore connected in series and the voltage across the whole circuit is varied to suit the number of lamps in operation. A special type of generator or transformer is required. In Europe the Thury system of long-distance transmission employs a constant d-c, the voltage generated being varied with the load.

Conductance ($G$) of a circuit is that quantity which, if multiplied by the voltage, will give total current if voltage is unvarying, and which will give the component of current in phase with voltage ($I \cos \phi$) if voltage is alternating. For d-c, conductance is the reciprocal of resistance. For a-c conductance, see Art 7. Conductance is used in analysing multiple circuits. 1 volt applied to a circuit of 1 mho conductance will cause 1 ampere to flow.

Rating of an electrical machine is the load in kw which it will give for a specified period of time without injury to itself. There are several limitations to the output, but the one most frequently met and inferred is injury to insulation by the heat developed. The limit is the temp of the hottest part of the machine, and the allowable temp depends upon character of the insulating materials. These are divided into 3 classes: (a) cotton, silk, and other fibrous materials, not so treated as to increase their heat-resisting qualities; (b) similar materials, but treated and impregnated, including enameled wire; (c) mica, asbestos, and other materials capable of resisting high temp. Temp of machines is usually determined by thermometer or by resistance measurements. Since neither method gives the temp of the hottest spot, it has been agreed to assume the temp of the hottest part as 15° C higher than indicated by a thermometer on the surface, and 10° C hotter than indicated by resistance measurement. Temp of surrounding air (ambient temp) influences directly the temp of the machine. Provision must be made that, when the air is at its highest possible temp (assumed at 40° C), the machine will not become excessively hot. This is done by specifying that the rise in temp above surrounding air shall be such that, if operating in a room of 40° C, its hottest spot shall not exceed certain established values. Continuous rating is the load in kw which a machine will carry continuously without exceeding the above temp rise. Intermitte rating, or short time rating, is the load in kw a machine will carry for a short specified period (up to 2 hr) without exceeding these limitations. Unless otherwise specified, continuous rating is understood (Art 6).

Table 1. Temperature Conventions (Standard Rules of Am Inst Elec Engs)

<table>
<thead>
<tr>
<th>Class of insulation</th>
<th>Highest permissible temp</th>
<th>Limiting temp by thermometer</th>
<th>Limiting temp rise</th>
<th>Limiting temp by resistance</th>
<th>Limiting rise by resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>95° C</td>
<td>80° C</td>
<td>40° C</td>
<td>85° C</td>
<td>45° C</td>
</tr>
<tr>
<td>b</td>
<td>105</td>
<td>90</td>
<td>50</td>
<td>95</td>
<td>55</td>
</tr>
<tr>
<td>c</td>
<td>125</td>
<td>110</td>
<td>70</td>
<td>115</td>
<td>75</td>
</tr>
</tbody>
</table>
2. PRINCIPLES

Electric circuit. Ohm's Law: \( E = IR \), where \( I = \) current, amperes; \( E = \text{e.m.f. or difference of potential, volts}; \) \( R = \) resistance, ohms. Used for solution of all simple d-c circuits and for a-c circuits having no resistance. For an a-c circuit having reactance, \( E = ZI \), where \( I \) and \( E \) are effective values and \( Z \) is impedance in ohms (Art. 7).

Kirchhoff's laws are for solving any combination of series, multiple, or series-multiple circuits. First Law, for series d-c circuits: \( E_0 = E_1 + E_2 + E_3 \), where \( E_0 \) is generated e.m.f., \( E_1 = \) counter e.m.f. (motor), and \( E_2 = IR_2 \), etc., are the drops in voltage in different resistances (Fig 1). Special case: \( R_0 = R_1 + R_2 + R_3 \). Second Law (for multiple d-c circuits): the algebraic sum of all currents meeting at a point = 0 (Fig 2). \( I_0 = I_1 + I_2 + I_3 \), where \( I_1 \) may be found by \( I_1 = E + R_1 \), whence

\[
I_0 = \frac{E}{R_1} + \frac{E}{R_2} + \frac{E}{R_3}; \quad \text{or, in general,} \quad \frac{1}{R_0} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}
\]

Magnetic circuit is calculated similarly to electric circuit: \( \phi = \frac{m \text{ m f}}{\text{ reluctance}} \) where \( \phi = \) flux in maxwells, \( m \text{ m f} \) is in giberts and reluctance = \( I + \mu A \), where \( I = \) length of path, cm; \( A = \) cross-sec of path, sq cm; \( \mu = \) permeability of the material, varying from 1 for air to 3,000 in some steels.

Permeability. Since \( \mu \) varies greatly with different materials, and with different densities in same material, it is more practical to calculate a magnetic circuit by means of magnetisation curves, which show relation between \( m \text{ m f per unit length of path and flux density in maxwells or lines per sq cm}. \) Such a curve must be made for each different material used. In U.S. it is customary to plot the magnetisation curve between the ampere turns per in length of path and maxwells or lines per sq in (Fig 3). To determine the current to produce a given flux, divide number of lines of flux by cross-section of circuit in sq in, and find required magnetic density in lines per sq in. Referring to magnetisation curve (Fig 3) of the particular material to be used, the number of ampere turns per in of path is obtained for this particular density. Multiplying this number by length of path (in) gives total ampere turns required, which may be divided into any number of amperes or any number of turns, the product of which will give the required number. For a path in air, or in any non-magnetic material, the ampere turns per in = 0.318 times the density in lines per sq in.

Force on a conductor. Experiment shows that if a conductor carrying a current \( I \) and having a length \( l \) is placed in the magnetic field of density \( B \) gausses, at right angles to the direction of lines of force, a mechanical force will be exerted on the conductor, at right angles to the conductor and to the flux, the value of which will be \( f = BI \), where \( f = \) dynes, if the other quantities are expressed in c.g.s. units. Practical form of this equation is \( F = 0.0089 BI \times 10^{-7} \), where \( F = \text{lb}, \) \( B = \text{lines per sq in,} \ l = \text{in}, \ I = \text{amperes.} \) This relation is basis for calculation of torque of any motor. In this case \( I \) must be the length of conductor in the active field only. The pull of any magnet is given by equation:

\[
P = B^2A + 72 \times 134 \ 000
\]

where \( P = \text{lb}, \ B = \text{lines per sq in}, \ A = \text{cross-sec of core, sq in}. \) This is the case when two magnetic elements are in contact; when separated, the average gap density must be used.
CONDUCTORS

Generation of an electromotive force (e m f). When a conductor is moved in a magnetic field so that it cuts lines of the field, an e m f is generated, numerically proportional to the rate of cutting the flux. When conductor cuts 10^6 lines per sec, one volt is generated. If Z conductors are connected in series, as is usual in practice, \( E = Z\phi + 10^6 T \), where \( E \) = average volts generated and \( \phi \) = flux cut in \( T \) sec. In the armature of any machine the relations are:

Average \( E \) of a d-o machine = \( 4PNS\phi \) + \( 120 \times 10^6 \)

Effective \( E \) in an e-o machine = \( 4.44PNS\phi \) + \( 120 \times 10^6 \)

where \( P \) = number of poles, \( N \) = rev per min, \( S \) = turns in series between terminals, \( \phi \) = flux per pole, maxwells.

3. CONDUCTORS

Copper is generally used, iron and aluminum being next in importance. Though all metals are conductors, only these 3 are of commercial value, since their cost is reasonable and loss of energy is low. Silver is the best conductor, but is too expensive for practical use. Copper is nearly as good as silver, and is best economically. Aluminum is next; in the form of solid wire it is as cheap as copper, but lacks uniformity in mechanical strength. It is better when in form of stranded cables, but is then more expensive than copper of equal conductivity. Iron and steel approach copper in economic value, and for small-diam conductors are preferable due to their mechanical strength. An insulator is a material used to prevent flow of current, but the division between insulators and conductors is not sharp; all insulators conduct some current. Common insulators are air, glass, porcelain, rubber, cotton, paper, and dry wood.

Resistance of any conductor is given by: \( R = \rho L + A \), where \( R \) = resistance, ohms; \( L \) = length of conductor, ft; \( A \) = cross-sec of conductor, circular mils; \( \rho \) = specific resistance, or resistance of a conductor of unit cross-sec and length. Though the cm and sq cm are the more scientific units, it is convenient to use the circular mil for unit of cross-sec and the foot for unit of length, as adopted for commercial wires. A circular mil is the area of a circle having a diam of one mil (0.001 in). A circle 1 in diam has an area of 1,000,000 circ mils, and 1 sq in = 1,270,000 circ mils. Hence, in above equation, if length be 1 ft and \( A \) = cross-sec in circ mils, then \( \rho \) has values given in Table 3.

Specific resistance \( \rho \) varies directly with the temp. Table 3 gives a constant for determining the percentage of increased resistance per deg C in excess of 20° C. General law of increase in resistance of copper with rise in temp is \( R_t = R_0 (1 + 0.0042 t) \), where \( R_t \) = resistance at any temp., \( t^\circ C \); \( R_0 \) = resistance at 0° C; \( t \) = temp above 0° C.

Wire gages. Standard classification of wires in the U S is the Brown and Sharpe or American wire gage (Table 4).

B & S gage sizes have definite relations, readily remembered: A wire 8 sizes larger than another has nearly half the resistance, twice the area, and twice the wt per unit length. Thus, No 7 has

<table>
<thead>
<tr>
<th>Material</th>
<th>Cross-sec for equal resistance</th>
<th>Wt for equal resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Aluminum</td>
<td>1.6</td>
<td>0.48</td>
</tr>
<tr>
<td>Iron, steel</td>
<td>6</td>
<td>7.1</td>
</tr>
</tbody>
</table>

Table 2. Relative Characteristics of Conductors of Equal Resistance and Length

<table>
<thead>
<tr>
<th>Material</th>
<th>Ohms resistance per mil-foot at 20° C, ( \rho )</th>
<th>Temp coeff, per cent increase per deg C, from 20° C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silver, annealed</td>
<td>9.5</td>
<td>0.377</td>
</tr>
<tr>
<td>Copper, annealed</td>
<td>10.3</td>
<td>0.368</td>
</tr>
<tr>
<td>&quot; , hard drawn</td>
<td>10.5</td>
<td></td>
</tr>
<tr>
<td>&quot; , cast</td>
<td>12.0 to 97.0</td>
<td></td>
</tr>
<tr>
<td>Gold, annealed</td>
<td>13.5</td>
<td>0.365</td>
</tr>
<tr>
<td>Aluminum, commercial</td>
<td>16.8</td>
<td>0.388</td>
</tr>
<tr>
<td>Zinc</td>
<td>38.0</td>
<td>0.379</td>
</tr>
<tr>
<td>Platinum</td>
<td>57.0</td>
<td>0.24</td>
</tr>
<tr>
<td>Iron, pure</td>
<td>61.5</td>
<td>0.56</td>
</tr>
<tr>
<td>&quot; , cast</td>
<td>34.0 to 68.0</td>
<td>0.388</td>
</tr>
<tr>
<td>Steel, soft</td>
<td>104.0</td>
<td></td>
</tr>
<tr>
<td>&quot; , rails</td>
<td>121.0</td>
<td></td>
</tr>
<tr>
<td>&quot; , special</td>
<td>84.0</td>
<td>0.56</td>
</tr>
<tr>
<td>Nickel</td>
<td>86.0</td>
<td>0.365</td>
</tr>
<tr>
<td>Tin, pure</td>
<td>130.5</td>
<td>0.387</td>
</tr>
<tr>
<td>Lead</td>
<td>570.0</td>
<td>0.072</td>
</tr>
</tbody>
</table>

* Steel being an alloy has varying spec resist. Steel used for track rails has approximately the value given in table, while for the "third" or conductor rail a special composition is used with lower spec resist.

Table 3. Resistances of Conductors

in above equation, if length be 1 ft and \( A \) = cross-sec in circ mils, then \( \rho \) has values given in Table 3.

Specific resistance \( \rho \) varies directly with the temp. Table 3 gives a constant for determining the percentage of increased resistance per deg C in excess of 20° C. General law of increase in resistance of copper with rise in temp is \( R_t = R_0 (1 + 0.0042 t) \), where \( R_t \) = resistance at any temp., \( t^\circ C \); \( R_0 \) = resistance at 0° C; \( t \) = temp above 0° C.

Wire gages. Standard classification of wires in the U S is the Brown and Sharpe or American wire gage (Table 4).
Table 4. Brown & Sharpe Wire Table

<table>
<thead>
<tr>
<th>B &amp; S or A W G size</th>
<th>Bare diam, in</th>
<th>Double cotton covered, diam, in</th>
<th>Areas, cire mile</th>
<th>Wt, lb * per 1000 ft</th>
<th>Resistance</th>
<th>Current capacity, rubber insulation, amperes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.152</td>
<td></td>
<td>1000000</td>
<td>3.050</td>
<td>0.01051</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.058</td>
<td></td>
<td>800000</td>
<td>2.440</td>
<td>0.01313</td>
<td></td>
</tr>
<tr>
<td>0.991</td>
<td></td>
<td></td>
<td>600000</td>
<td>1.830</td>
<td>0.01751</td>
<td></td>
</tr>
<tr>
<td>0.819</td>
<td></td>
<td></td>
<td>500000</td>
<td>1.525</td>
<td>0.02101</td>
<td></td>
</tr>
<tr>
<td>0.728</td>
<td></td>
<td></td>
<td>400000</td>
<td>1.220</td>
<td>0.02627</td>
<td></td>
</tr>
<tr>
<td>0.590</td>
<td></td>
<td></td>
<td>250000</td>
<td>0.762</td>
<td>0.04203</td>
<td></td>
</tr>
<tr>
<td>0.460</td>
<td></td>
<td></td>
<td>216000</td>
<td>0.640</td>
<td>0.04906</td>
<td></td>
</tr>
<tr>
<td>0.409</td>
<td></td>
<td></td>
<td>167805</td>
<td>0.507</td>
<td>0.06186</td>
<td></td>
</tr>
<tr>
<td>0.364</td>
<td></td>
<td></td>
<td>133079</td>
<td>0.420</td>
<td>0.07801</td>
<td></td>
</tr>
<tr>
<td>0.324</td>
<td></td>
<td></td>
<td>105538</td>
<td>0.318</td>
<td>0.09383</td>
<td></td>
</tr>
<tr>
<td>0.283</td>
<td></td>
<td></td>
<td>83694</td>
<td>0.252</td>
<td>0.12404</td>
<td></td>
</tr>
<tr>
<td>0.254</td>
<td></td>
<td></td>
<td>66373</td>
<td>0.206</td>
<td>0.15640</td>
<td></td>
</tr>
<tr>
<td>0.230</td>
<td></td>
<td></td>
<td>52854</td>
<td>0.159</td>
<td>0.19723</td>
<td></td>
</tr>
<tr>
<td>0.204</td>
<td></td>
<td></td>
<td>41742</td>
<td>0.126</td>
<td>0.24669</td>
<td></td>
</tr>
<tr>
<td>0.181</td>
<td></td>
<td></td>
<td>33102</td>
<td>0.100</td>
<td>0.31361</td>
<td></td>
</tr>
<tr>
<td>0.162</td>
<td></td>
<td></td>
<td>26250</td>
<td>0.073</td>
<td>0.39546</td>
<td></td>
</tr>
<tr>
<td>0.144</td>
<td></td>
<td></td>
<td>20816</td>
<td>0.062</td>
<td>0.49871</td>
<td></td>
</tr>
<tr>
<td>0.128</td>
<td></td>
<td></td>
<td>16509</td>
<td>0.049</td>
<td>0.62881</td>
<td></td>
</tr>
<tr>
<td>0.114</td>
<td></td>
<td></td>
<td>13094</td>
<td>0.039</td>
<td>0.79281</td>
<td></td>
</tr>
<tr>
<td>0.101</td>
<td></td>
<td></td>
<td>10381</td>
<td>0.031</td>
<td>1.06156</td>
<td></td>
</tr>
<tr>
<td>0.090</td>
<td></td>
<td></td>
<td>8254</td>
<td>0.024</td>
<td>1.26070</td>
<td></td>
</tr>
<tr>
<td>0.080</td>
<td></td>
<td></td>
<td>6529</td>
<td>0.019</td>
<td>1.58988</td>
<td></td>
</tr>
<tr>
<td>0.072</td>
<td></td>
<td></td>
<td>5176</td>
<td>0.015</td>
<td>2.0047</td>
<td></td>
</tr>
<tr>
<td>0.064</td>
<td></td>
<td></td>
<td>4106</td>
<td>0.012</td>
<td>2.5278</td>
<td></td>
</tr>
<tr>
<td>0.057</td>
<td></td>
<td></td>
<td>3256</td>
<td>0.009</td>
<td>3.1150</td>
<td></td>
</tr>
<tr>
<td>0.050</td>
<td></td>
<td></td>
<td>2582</td>
<td>0.007</td>
<td>4.0190</td>
<td></td>
</tr>
<tr>
<td>0.045</td>
<td></td>
<td></td>
<td>2048</td>
<td>0.006</td>
<td>5.0683</td>
<td></td>
</tr>
<tr>
<td>0.040</td>
<td></td>
<td></td>
<td>1624</td>
<td>0.004</td>
<td>6.3911</td>
<td></td>
</tr>
</tbody>
</table>

Half the resistance of No. 10. A wire 10 sizes larger has 0.1 the resistance and 10 times the area and wts. No. 10 is approx. 0.10 in diam, has area of 10,000 cire mile, resistance of 1 ohm per 1000 ft at 20°C C, and weighs 32 lb per 1000 ft.

Resistance and wt. of standard sizes of wire of other materials are found by using following ratios: Aluminum, multiply resistance given for copper by 1.61 and the wt. by 0.301. Iron telegraph wire, resistance is 5.96 and wt 0.877 that of copper. Steel wire, resistance is 8.82 and wt 0.883 that of copper.

Birmingham wire gage (B W G), also known as Stake, is largely used in Great Britain and somewhat in this country. Metric system is used in France and Germany. Roebling table is used in the U S for steel wires and cables (see Sec 41, Art 9).

Table 5. High-resistance Wires

<table>
<thead>
<tr>
<th>Composition</th>
<th>Resistance relative to copper</th>
<th>Temp coef, % increase per deg C</th>
<th>Max allowable temp, deg C</th>
</tr>
</thead>
<tbody>
<tr>
<td>German silver, 18%</td>
<td>Ni-Cu</td>
<td>19.0</td>
<td>0.0310</td>
</tr>
<tr>
<td>&quot; &quot; 30%</td>
<td>Ni-Cu</td>
<td>28.0</td>
<td>0.0310</td>
</tr>
<tr>
<td>&quot; &quot;</td>
<td>Ni-Cu</td>
<td>27.3</td>
<td>0.0005</td>
</tr>
<tr>
<td>Advance</td>
<td>Cu-Fe-Mn-Ni</td>
<td>28.6</td>
<td>0.0018</td>
</tr>
<tr>
<td>Manganin *</td>
<td>Cu-Fe-Mn-Ni</td>
<td>24.0 to 43.0</td>
<td>0.0011</td>
</tr>
<tr>
<td>Superior</td>
<td>Ni-Steel</td>
<td>51.00</td>
<td>0.0540</td>
</tr>
<tr>
<td>Climax</td>
<td>Ni-Steel</td>
<td>56.0</td>
<td>0.0450</td>
</tr>
</tbody>
</table>

* Manganin is used in electric meters because of its low temp coef.

4. MEASURING INSTRUMENTS

Solenoid. Simplest form of measuring instrument is the plunger type of solenoid. It consists of a coil of thick wire carrying current to be measured, and a soft steel plunger which is pulled into axis of coil by effect of the current acting against weight of plunger,
or against a spring. Operates with both d c and a c, but is not accurate with either. Magnetic vanes is a special form of solenoid instrument. Inside the coil carrying the current is a thin steel vane, pivoted in center of coil, and a fixed vane of triangular cross-section. When current flows in the coil, both vanes are magnetized alike and repel each other; hence, pivoted vane moves away from fixed vane, moving force being proportional to square of the current. Used both for d c and a c, but its accuracy varies with frequency and wave shape. Inclined coil solenoid instrument is very generally used to measure a c. A cylindrical coil of wire carrying current to be measured is set inclined to a spindle or axis carrying a steel vane. When no current flows, the vane is held in plane of coil by a spring. When current flows, the magnetic field is perpendicular to plane of coil and the pivoted vane, in moving to set its longer axis in the line of flux, rotates the spindle to which pointer is attached. Force is proportional to square of the current. Used for d c and a c, but is affected by wave shape and frequency. D’Arsonval principle, used in almost all instruments for d c, employs a coil of fine wire placed in the field of a permanent magnet, suspended so that it can rotate. Current to be measured, or a definite part of it, passes through the movable coil, causing a torque which is resisted by a spring. The force is directly proportional to the current. Only operative with d c, and is affected by stray magnetic fields.

Hot-wire instruments may be used to measure both d c and a c. The current is passed through a wire, which it heats and lengthens. Increase in length is taken up by a spring or weight, the movement of which is proportional to square of current.

Dynamometer consists of 2 coils, fixed and movable, so arranged that their magnetic fields act upon each other. The current, passed through the two in series, develops a torque (as in a series motor) proportional to square of the current. Movement of the coil is resisted by a spring and indicated by a pointer. As no iron is present, this instrument is accurate for d c and a c of all frequencies. The principle is used in the Siemens dynamometer, in some a-c voltmeters and ammeters and in all wattmeters. In wattmeters one coil is in series with the line and the other coil across the load, receiving current through a high resistance proportional to the potential.

Induction-type instruments utilise the fact that, if a coil carrying an a c has within it a piece of copper or aluminum, eddy currents will be induced in the metal, and these will react on the main current, giving a force or torque. The torque is proportional to square of current. Instrument operates only on a c, and is affected by varying frequency.

Ammeter operates on any one of above-mentioned principles. Its electrical circuit must have very low resistance, and usually the measuring coil carries only a small though definite part of the current. In parallel with working circuit, there is usually a metallic "shunt," which has such resistance that the maximum current to be measured causes a drop of about 50 millivolts (Art 1, par 1) in the shunt. Some meters have interchangeable external shunts, while others have shunts placed inside the case and permanently connected in the circuit.

When the instrument is used with an external shunt it is sometimes called a millivoltmeter, its scale being marked in millivolts. An ammeter must never be left connected in the circuit without its shunt. Most ammeters for measuring d c operate on the d'Arsonval principle, as it gives the most accurate results. For a c, the inclined coil is in most general use. Most a-c meters will indicate as correctly on d c as on a c, but not as accurately as an instrument of the d'Arsonval type (Fig 4).

Voltmeter resembles an ammeter and in reality measures current, but its electrical circuit has a high resistance connected in series with it, to limit the current to a reasonable value. Since, in accordance with Ohm's law, with a constant resistance the current is proportional to the potential across the circuit, the scale deflection will indicate volts. The resistance must be non-inductive, and must not vary with temperature. When the resistance coil is separate from voltmeter the coil is called a multiplier.

The dynamometer type voltmeter is to be preferred for a c, and a potential transformer may be used instead of a multiplier if required to measure a voltage higher than the range of the voltmeter proper. Electrostatic voltmeter, a special instrument for measuring very high voltages, utilizes the force exerted between two charged bodies. A moving vane is connected to one side of the circuit, a fixed vane to the other. As the high potential charges these vanes, a force is exerted between them causing the movable vane to rotate. This instrument is used for either a c or d c.

Wattmeter is used on both a-c and d-c circuits for measuring the true or active power in watts; E'I in d-c circuits, E'I cos φ in a-c circuits. In d-c circuits a voltmeter and an ammeter may be used to measure power, the product of the volts and amperes giving true.
power, but in an a-c circuit this is not true. The wattmeter has a potential coil connected in parallel with the load (like a voltmeter), and a current coil connected in series with the load (like an ammeter). If the needle shows negative deflection, the terminals of one coil or other must be reversed. Range of the wattmeter must be selected with reference to the volt and current capacity of its coils. A “multiplier” may be used in the potential coil and a current transformer in the circuit of the current coil.

Watt-hour meter measures energy by recording watt-seconds. Coils are arranged to form a motor, which causes a disk to revolve at a velocity proportional to the power. A counter registers number of revolutions of the disk, and this number represents energy. Watt-hour meters for a-c circuits are constructed differently from those for d-c. (Art 11.)

Power-factor meter determines the phase angle (φ) between voltage and current of an a-c circuit. Since in practice the power factor is the more important, the scale is graduated in cos φ. Instrument is constructed like a wattmeter having 2 coils, one for potential and one for current.

Frequency meter indicates the frequency in electrical cycles per second of the circuit voltage. The two common types are the vibrating reed and the induction. They are connected to the line like voltimeters.

Recording meters are often used in power stations to provide a continuous record of voltage, current or power. A pen, attached to the indicating element, rests on a strip or disk of paper, and draws a line as the paper moves by clock work.

5. DIRECT-CURRENT GENERATORS

Application. Direct-current (which is officially named continuous current) apparatus is used for short transmission distances. For long distances the a-c system (Art 7) is preferable, because the transformer (Art 13) permits transmission at very high voltages. However, since the d-c motor is more convenient and more easily controlled than the a-c motor, the d-c system is used whenever possible. It is often found advisable to generate and transmit by means of a-c, which is then converted to d-c at the place where the motors are located. Thus, most generating stations produce a-c, though many of the motors supplied by these stations use d-c provided by synchronous converters or rectifiers.

Fundamental principle of a dynamo is the production of e m f (Art 2) in one or more conductors by the motion of these conductors in a magnetic field. In most machines the e m f is alternating; first positive, as conductor passes a north pole, then negative, as it passes a south pole. For use as a d-c machine a commutator must be provided to rectify voltage and current. The commutator is the distinguishing feature between d-c and a-c machines. Small machines are usually of the bipolar type, with a more or less enclosed frame of cylindrical shape. Large machines are multipolar; that is, having a large number of inwardly projecting radial pole pieces. Commutating pole or interpole machines have small auxiliary poles placed alternately with respect to the main poles and excited by a few turns in series with the load. Effect of these poles is to improve the commutation of the machine. Machines are divided generally into belt-driven and direct-connected, the former having the higher speed.

Shunt machine, either generator or motor, is one in which the entire field excitation is derived from a circuit of many turns and high resistance, connected in shunt or multiple with the armature circuit (Art 6, Fig 8). The characteristic of a shunt generator is poor regulation; that is, voltage decreases as load increases, and hand regulation of a rheostat in the field is necessary to provide steady voltage.

Compound-wound machine has on each field pole, in addition to its shunt winding, a few turns of thick wire which carry the load current and are known as series winding (Fig 5, 6). This causes excitation to increase as load increases, and tends to keep the terminal voltage constant or even to increase it. If the field windings are proportioned to cause a higher voltage at full load than at no load, the machine is overcompounded. A flat-compounded machine has the same voltage at full load as at no load; an undercompounded machine has a lower voltage at full than at no load. A compound-wound machine may be connected either in short shunt (Fig 5), which is usual practice, or in long shunt (Fig 6), in which the field winding is connected from outside of the series field to outside of the armature.

Constant potential vs constant current. In constant-potential type an endeavor is made to maintain a constant potential across the load. For particular purposes machines sometimes have their field connected in series with the armature, and with a special regulating device for giving constant current irrespective of load. These machines were formerly much used in arc lighting, but are not now built.
Installation. In installing and erecting a d-c machine, certain features must receive careful attention, so that the machine shall operate properly and not deteriorate too rapidly. The most important considerations are: (a) For large machines the base is bolted to the foundation in accordance with the drawings. (b) Bearings are lined up, cleaned, and oiled. (c) Field coils are tested for open circuit and wrong connections. Test is made with a compass for correct polarity. For a self-excited generator there is one particular connection of the field to the armature for each direction of rotation. (d) Armature must be properly centered so that the air gap is correct at all points. Gap is measured by taper wedges. (e) Magnet frame is bolted to base. (f) Commutator is smooth and polished; use sand paper, never emery paper, to polish commutator. (g) Brushes are properly and accurately spaced around the commutator, sandpapered and fitted to its curvature, and their pressure adjusted to the correct value, usually 1.5 to 2 lb per sq in. of contact surface. (h) Field connections are adjusted for correct direction of rotation and substantial connections made. (i) Machine must be protected from moisture during shipment; if it be damp it must be dried out by heat before starting.

Operation. In starting a single generator it may be necessary to charge the field by exciting the shunt field separately for a moment to set up residual magnetism. To cause the machine to pick up, or generate voltage by self-excitation, the rheostat connected in series with the shunt field must be cut out, or short-circuited. If total resistance of shunt-field circuit exceeds a certain critical value the machine will not “pick up,” however much time is allowed.

Parallel operation. For economical operation of a power station there must be a number of machines, whose aggregate capacity equals the maximum demand on the station. As the demand varies the number of machines in operation is adjusted so that those running are operating at a load near their rating, and therefore at good efficiency. To operate SHUNT GENERATORS in parallel (that is, feeding the same bus-bars); it is only necessary to adjust all to the same polarity and voltage, connect them to the bus-bars, and adjust division of load by strengthening the field of the underloaded machine if voltage of the bus-bars is low, or weakening the field of the overloaded machine if voltage is high. To operate COMPOUND GENERATORS in parallel there must be an equalizer connection, making a common connection on all the machines at the point between the armature and the series field (Fig 7). The equalizer divides the load current in proper proportion between the series fields of the different generators, preventing the machines from acting as series generators or differential motors, which would cause short-circuits. For successful operation of compound machines in parallel all those connected to one set of bus-bars must have same amount of compounding, and same voltage at no load. The compounding curves of machines must be investigated before they are operated in parallel. With unlike curves, one machine may be overloaded while another is underloaded, unless the field current of one of them is adjusted.

If a machine is to be connected in parallel with those already in operation it must have proper polarity and voltage, the equalizer circuit must be made, and the switches are closed in the order 1, 2, 3, as in Fig 7. With any other order the effect is the same as having no equalizer. In shutting down one machine, switch No 3 must be opened first; then No 2 and No 1. For MANAGEMENT, see Art 6.

Testing. D-c machines are tested for regulation, commutation, and heating, by subjecting them to a load, but their efficiency is best determined by the separate loss method, for which the machine need not be run under load. Customary commercial tests are:

(a) Resistance measurements are made on armature winding, shunt field, and series field, at known temp, before the machine is run and again after the heat run (d). Resistance of a lap or multiple winding is found by measuring between two diametrically opposite points on commutator. If this resistance be \( R' \), then the actual armature resistance is \( R_a = 4R' + p^2 \), where \( p \) = number of poles on machine. Resistance of a series-wound armature is found by measuring between two commutator segments, separated by a distance equal to periphery of commutator divided by number of poles. Resistance of the brush contact can not be accurately measured by any simple means, as its value is affected by value of the current, speed of commutator and pressure of brushes. An accepted method is to assume a total loss of 2 volts in all brushes.

(b) Core loss and friction (stray power). Machine is run as motor without load, field current being held at proper value and the voltage applied to armature adjusted to give desired speed. Input to armature is measured; subtracting from this the calculated \( IR \) of armature circuit, the net value of input = core loss + friction.
(c) Load runs. Machine is run and the excitation adjusted to give proper voltage at no load. Load is then added and terminal voltage noted. If \( E_0 \) = voltage at no load and \( E \) = voltage at full load, the regulation is \( (E_0 - E) / E \). Brushes must be set in proper position for commutation, which is judged by observing action of brushes at no load, full load, and 150% load.

(d) Heat runs are made by operating at full load until the tempe of the various parts that can be noted during operation become constant. The greater the machine’s capacity, the longer is the testing time required. Heat runs are sometimes made at 1.25 or 1.50 times rated load for 2 hr. Heat runs may be made either by the DEAD-LOAD method, in which a resistance load such as a water rheostat is connected to the terminals and full rated load power is required to drive the machine; or by the Hopkinson of PUMPING-BACK method, in which 2 machines of similar characteristics are run in multiple, one acting as a generator to supply electrical power to the other as motor, which in turn drives the first by a belt or equivalent mechanical connection. For this test a load supply is required, which may consist of a source of either electrical or mechanical power. The power required is from 10 to 20% of the rating of one machine. During a heat run, thermometer readings are taken at stated periods, showing temp of frame, field-coils, bearings, and surrounding air. After the run thermometers are placed on various parts of the machine, the bulbs being protected from radiation by small cotton pads, and the temp are noted of armature core surface, ventilating ducts and winding, commutator surface, pole-tips, field-coils, bearings, frame, and the room. Resistance of the elec circuits should be measured, and average temp of the copper calculated from:

\[ t_1 = (R_1 + R_0)(234 + \omega) - 234 \]

where \( R_1 \) and \( R_0 \) are the hot and cold resistances, and \( t_1 \) and \( t_0 \) are the hot and cold temps.

(e) Compounding test. To adjust the current in series field so that a compound-wound generator will give specified voltages at no load and full load, the machine is first operated at no load and current in shunt field adjusted to give desired no-load voltage. Load is then put on, and it will usually be found that the terminal voltage is too great. Strips of German silver or other resistance metal are then connected across the series field terminals, until by shunting current from the series field the machine voltage is reduced to desired value. This “series-field shunt” is then insulated, and made up into permanent form. Before making the no-load adjustment, it is advisable to overexcite the shunt field for a moment to overcome hysteresis.

(f) Insulation tests. After the heat run the insulation is tested, first by measuring its resistance and then by applying a high-potential test. Insulation resistance is found by connecting one terminal of a 500-volt d-c circuit to the windings through a 500 voltmeter, and connecting the other terminal of the 500-volt circuit to the machine frame. If voltmeter resistance is \( R_0 \) and the deflection during above connection is \( x \), then insulation resistance in ohms is: \( R = R_0(500 - x) + x \). The value of \( R \) should be approximately one megohm (1 000 000 ohms) for each 1 000 volts of rated potential of the machine. HIGH-POTENTIAL test is made by applying an alternating high potential between each winding and the frame of the machine for 1 min, in accordance with specifications adopted by Am Inv Elec Engs. This test is usually made only at the factory and should be under supervision of an experienced person.

6. DIRECT-CURRENT MOTORS AND MOTOR-GENERATOR SETS

Shunt motor (Fig 8) has only one exciting winding, which is connected across armature terminals, and is in parallel or shunt with the armature. Field winding consists of a large number of turns of fine wire on each pole, and all poles are usually connected in series in one circuit. Field current depends upon line voltage and resistance of field winding. Resistance of field winding is made high, so that the field current will be between 1% (large motors) and 5% (small motors) of the full-load current of motor. The characteristic of the shunt motor is a fairly constant speed for all reasonable load values.

Series motor (Fig 9) has only one exciting winding, which is connected in series with the armature, and all the current flows through both field and armature. Field winding consists of a few turns of thick wire on each pole, the windings on all poles being connected in series. Field current depends upon the load; large with heavy load and small with light. Resistance of field winding is made low, so that loss of voltage and power in that circuit will be small. Characteristics of a series motor are: a speed varying with every change in load, high speed at light load, and low speed at heavy load. Efficiency is high throughout a wide range of speed. Speed will be dangerously high at no load; thus a series motor must always be connected rigidly to its load. Since torque is high at low speeds, this motor is especially adapted to work requiring frequent starting.

Compound motor. Usual form is the cumulative motor, each pole of which has both series and shunt winding, wound and connected for mutual assistance in producing the magnetic field. It is a combination of shunt and series motor, designed to give the good starting qualities of the series motor and to avoid danger of excessive speed at light loads.
DIRECT-CURRENT MOTORS

Differential motor has opposed shunt and series winding; not much used and not recommended.

Inclosed v open type referring to the mechanical housing of the motor. Open Type has all parts freely exposed to the air and is therefore well ventilated. Intended to be used indoors or in protected places. Inlosed Type is for use in exposed locations, where there is liability of dampness and dirt. Special means must be provided to circulate air inside the machine, but even then an inclosed motor is larger and more expensive than an open motor of same capacity. Relative capacities in output of open, semi-inclosed and totally inclosed motors, are shown by Table 6. Totally inclosed motor weighs about 15% more than an open motor of same capacity, notwithstanding that it is allowed by commercial convention to operate at 15°C higher temp.

Rating. Motors are rated on basis of their continuous or their intermittent capacity. Continuous Rating is the output in hp (or kw) which a motor will give continuously with a maximum temp rise (measured by thermometer above the surrounding air) not exceeding 50 or 70°C in field or armature, depending upon character of insulating material (Art 1). Intermittent Rating is the output which the motor will give for 1 hr (starting at room temp), with a maximum rise in temp above surrounding air not exceeding the above values (Standardization Rules of ASA C-50).

Voltage and current. Usual values of voltage for d-c motors are: 110-125 for small units on lighting circuits; 220-250 for motors in factories, shops, and mines, on power mains or on outside mains of a 3-wire system; 500-600 for general railway work; 1200-2400 for heavy railway work. Current in amperes required for any motor is: \[ I = \frac{(output\ in\ hp \times 746)}{(efficiency \times \text{voltage})} \]. Usual efficiencies of motors of different sizes are given in Table 7.

Applications of motors. Chief applications of d-c motors: Shunt Motor, driving shafting, machine tools, blowers, reciprocating pumps, motor-generators; Series Motor, R R, and all transportation work, hoists, cranes; Compound Motor, elevators, hoists, or machinery that is stopped and started frequently.

Speed characteristics. Shunt motor is always used when constant speed is desired. It may be obtained with characteristics such that the drop in speed from no load to full load is 5 to 10%. At full load the speed of any well-designed shunt motor may be increased to equal the no-load speed, by putting resistance into the field circuit. Variable-speed motors are of the series type; they decrease in speed as load increases, every change in load causing change in speed. Multispeed motors are of shunt type, and usually have commutating poles so that they may operate with different strengths of field without suffering from bad commutation. They may be controlled by varying the field resistance, or the voltage impressed upon the armature. By increasing resistance in series with the field of a shunt motor speed is increased, due to weakening of the field. If the motor has commutating poles, to assure good commutation, speed may be varied in ratio of 1 to 2, or even 1 to 4 in small sizes. Motor speed is stable with this mode of control and efficiency is good.

Potential control. By means of several generators and several wires, various definite voltages are available. Thus, with one main generator giving 240 volts and 3 smaller ones giving 40, 80, and 120 volts, combinations may be made giving 40, 80, 120, 160, 200, and 240 volts. By connecting the armature terminals to these voltages, the motor will run at speeds proportional to the voltages. The shunt field is left continuously connected to one circuit, usually the maximum voltage circuit. A shunt motor with normal excitation will be stable at each speed; that is, will operate at fairly constant speed irrespective of load. Efficiency will be good at all speeds. A number of wires are needed to make the different voltages available at the places where the motors are located.

Variable-speed motors. By connecting a rheostat in series with a shunt motor armature, the voltage impressed upon the armature will be reduced by an amount proportional to the current, and speed will thereby be reduced. The speed is unstable, changing with every change of load, and efficiency is poor.

Starting box (rheostat) is always employed in starting d-c motors, to reduce the voltage impressed on the armature when not running at a speed high enough to generate the
proper counter e.m.f. Fig 10 shows usual connections of a starting box to the line and motor.

Starting box contains: (a) means of opening and closing the circuit supplying current to the motor, including the field current; (b) set of resistance steps in series with motor armature, and a means of short-circuiting this resistance step by step; (c) a magnet coil connected across the motor terminals to open the circuit if impressed voltage fails (low-voltage release); (d) a magnet coil carrying main current to actuate a spring and open main circuit, if current exceeds a specified value (overload release).

Specifications. In calling for bids for d-c motors it is customary to specify: kind of service and load, method of drive, voltage, horse-power, speed, and whether open, semi-inclosed or inclosed, series, shunt, or compound-wound; if shunt-wound, whether shunt field rheostat is to be supplied; if compound-wound, whether cumulative or differential; dimensions of pulley and shaft extension, whether rails or base are required; whether starting box is to be supplied and if so, the style; temp rise for continuous full load; temp rise for 25% overload; efficiency at 25, 50, 75, 100, 125, and 150% load; starting torque required; necessity for withstanding moisture; regulation; percentage of variation in speed between no load and full load, with field resistance constant; variation in speed at full load obtained by variation of field rheostat.

Installation. (See Art 5.)

Costs. (See Art 19.)

Operation. All motors should be frequently inspected and following points noted: (a) Bearings filled with proper amount of oil; (b) brushes securely held in proper position; (c) brushes fit properly; (d) commutator smooth: look for "high mice," or projection of the insulation above the bars; (e) air gap true; (f) commutator not worn in grooves.

Troubles. Following troubles that may occur in operating d-c motors, and their causes, are stated by Crocker and Wheeler: (a) Sparking at commutator. Causes: armature carries too much load, brushes improperly spaced or not in proper position, rough commutator, poor brush contact, internal short or open circuit, field too weak, unequal strength of poles, vibration. (b) Heating of commutator and brushes. Causes: sparking, bearing trouble, bad connections, brush friction too great. (c) Heating of armature. Causes: overload, internal short circuit, moisture or ground, reversed coil. (d) Heating of field. Cause: internal short circuit. (e) Heating of bearings. Causes: bearings dry or dirty, shaft out of true, bearings out of line, thrust due to belt, unbalanced magnetic pull. (f) Noise. Causes: armature not balanced, brushes dry or not set at proper angle, armature strikes. (g) Speed too low. Causes: wrong voltage, overload, armature strikes, bearing too tight. (h) Speed too high. Causes: wrong voltage, field too weak. (i) Motor stops, or fails to start. Causes: overload, open circuit, wrong connection.

Tests. A motor is usually tested for resistance of insulation and of windings, heat run, stray power, regulation and commutation. Regulation test consists in measuring speed at no load and at full load. Other tests are the same as made on d-c generators (Art 5).

Constants. Efficiency of any particular size of electrical machine may vary widely according to its design. For weight and cost, see Art 19.

Table 7. Average or Usual Constants for D-C Machines

<table>
<thead>
<tr>
<th>Kw rating</th>
<th>1</th>
<th>5</th>
<th>10</th>
<th>20</th>
<th>50</th>
<th>100</th>
<th>200</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency at full load</td>
<td>0.80</td>
<td>0.84</td>
<td>0.86</td>
<td>0.88</td>
<td>0.90</td>
<td>0.91</td>
<td>0.92</td>
<td>0.93</td>
</tr>
<tr>
<td>Rev per min</td>
<td>2000</td>
<td>1100</td>
<td>850</td>
<td>680</td>
<td>650</td>
<td>600</td>
<td>450</td>
<td>350</td>
</tr>
</tbody>
</table>

Motor-generator set is a combination of motor and generator having separate fields and armatures, but mounted on same shaft with common base and bearings. The two machines may both be for d-c, both for a-c, or one for each, in accordance with the use to which the plant is to be put. Principal applications are:

Balancers. Two similar d-c machines mounted on the shaft, and connected in series across the mains of a 250-volt circuit. From the common connection a third wire is brought out, thus giving a 3-wire system for 125-volt lamps on each leg, and for 250-volt motors on the outside main. With compound machines the regulation on the 125-volt circuits is good.

Boosters. To raise the voltage on a particular feeder a series booster is used, consisting of a shunt motor driving a series generator, the latter being connected in series with supply and feeder. The set runs at constant speed, and the voltage increases with the current to the load. Voltage at
full load is from 10 to 20\% of the rated voltage of the circuit. The combination may be designed to neutralise losses in voltage due to drop in the feeder.

Multiple-voltage systems. Motor-generator sets are used to give the fractional voltages required for these systems. Each set consists of 2 or 3 machines operating as a balancer; that is, each may be a motor at one moment and a generator at the next, depending upon which circuit is supplying the load.

Ward-Leonard system. For regulating the speed of a motor a special generator may be provided, which, being driven by its own motor, forms a motor-generator set. By varying the field strength of the generator any voltage may be generated, from 0 to full rated voltage. If this generator supplies only the armature of the motor, the speed of which is to be regulated, its speed may be controlled from 0 to full speed by merely varying the small current flowing in the field of the special generator. Main supply circuit furnishes current for the motor of the set, and fields of the generator and the controlled motor.

Igniter sets. Where a motor must start and accelerate a heavy load frequently, as in mule hoists and rolling mills, the motor is advantageously supplied from a special set, consisting of a motor (shunt or induction) driving a special generator, with a heavy flywheel forming part of the set. For such service the set motor must have poor speed regulation. As the accelerating motor starts, it draws a heavy current from the generator, causing speed of set to drop and the flywheel to give up considerable stored energy. This energy supplies the peak demands, and when the peak load period has passed the set speeds up gradually and stores more energy in the flywheel. This combination is expensive, but is used where conditions limit the maximum demand which may be made on the electrical supply system. (See Sec 16.)

7. ALTERNATING-CURRENT CIRCUITS

Sine wave. Every generator for d c as well as for a c has induced in its own windings an alternating voltage. The commutator of the d-c machine rectifies this, giving direct or continuous voltage. Since an a-c machine has no commutator, this voltage is brought to the load in its alternating form by slip-rings.

In designing machines every endeavor is made to obtain an e m f which follows a true sine law: \(e = E_m \sin \theta\), in which \(e\) is the instantaneous value, \(E_m\) the maximum value, and \(\theta\) gives the phase time, or abscissa at which the instantaneous value is specified. All calculations of a-c circuits are based on assumption that voltage and current do follow a sine law.

Frequency. The series of values from a to c (Fig 11) constitute a cycle or period. Time in seconds required for one cycle is the periodic time \(T\), and \(1 + T\) (number of cycles per sec) is the frequency \(f\). In commercial practice frequencies of 25, 50, and 60 cycles per sec are used, the first for general power, the latter for lighting purposes. If \(\theta\) is expressed in radians, then \(\theta + t = 2\pi f\), and \(\theta = 2\pi f \times t\). Thus phase \(\theta\) is a conventional means of expressing a given instant of time \(t\). A cycle may be divided into 360°, and \(\theta\) may be the abscissa expressed in degrees.

Effective, virtual, or root mean square value of an a c is equal to that value of a d c which would produce the same heating effect or average power loss in a resistance \(R_f\).

If current follows a sine law, the effective value is equal to maximum value divided by \(\sqrt{2}\). Effective value of e m f is that which, when multiplied by the effective value of current in a simple resistance, will give the true power in watts. It is also equal to maximum value divided by \(\sqrt{2}\). Effective values of current and voltage are the values shown by all instruments, and are the only ones used in practical engineering. (See Sec 16.)

Inductive reactance, inductive circuit. Any circuit in which the presence of a current produces a magnetic flux is an inductive circuit, the quantity of inductance depending upon the number of turns and the quantity of flux produced by one ampere. When an a c flows in an inductive circuit the current lags behind the impressed e m f, and the relation between voltage and current in such a circuit is \(E = 2\pi f L I\), where \(E\) = effective value of e m f, \(f\) = frequency in cycles per sec, \(L\) = inductance in henries, \(I\) = effective value of current. \(X_L = 2\pi f L\) is the inductive reactance in ohms. \(E = X_L I\) in a circuit having inductance only, and the current will lag behind the voltage by 0.25 of a period.
Capacity reactance, anti-inductive circuit. If an alternating e m f is impressed upon a circuit having capacity only, the current which flows precedes or leads the e m f by 90°, and its value is \( I = 2\pi fC \), where \( C \) is the capacity in farads and the other quantities are as in preceding paragraph. \( X_c = 1 + 2\pi fC \), called capacity reactance, is expressed in ohms and \( E = IX_c \).

Power and power factor. In an a-c circuit containing inductance or capacity, as well as resistance, the product of effective volts and effective amperes (EI) does not give true power, because the current will be out of phase with the voltage; that is, the maximum value of current will occur either later than or before the maximum value of voltage. Therefore EI is the volt-amperes or "apparent power." Ratio of true power \( P \) to apparent power is the power factor. It may be proved that the power factor is equal to the cosine of the angle of phase difference between the voltage and current, as shown by equation: Power factor = \( \cos \phi = P / EI \), where \( \phi \) is the time difference in phase between voltage and current, expressed in angular measure.

Fig 11 shows an alternating voltage \( E \) and an a c I differing in phase by an angle \( \phi \), which means that their maximum or their zero values occur at a difference in time of \( (\phi + 360) / T \) sec, where \( T \) is the periodic time of one cycle. Fig 12 is a vector representation of these quantities, and conventionally \( I \) is said to lag behind \( E \) by an angle \( \phi \). \( E \cos \phi \) is the component of the voltage in phase with the current, and is called the "active component." The useful or heat power in watts is \( P = EI \cos \phi \). \( E \sin \phi \) is the component of the voltage out of phase with the current, and is called the "reactive component." \( Q = EI \sin \phi \) is the reactive power, as it reacts on the impressed forces without producing useful work or heat. Total volt-amperes or apparent power is \( EI = \sqrt{P^2 + Q^2} \).

Kilovolt-amperes (kva) equals 1000 volt-amperes.

Calculations. A corollary of the law of conservation of energy is that the sum of all the true (heat) power consumed in a circuit is equal to the input of true power, \( P_0 = P_1 + P_2 + P_3 \). The sum of all the reactive power consumed in a circuit is equal to the input of reactive power, \( Q_0 = Q_1 + Q_2 + \text{etc.} \)

Kirchhoff’s laws for a-c circuits. First law (for series circuits) (Fig 13 and 14): The sum of all active components of voltage (\( E \cos \phi \) = 1R) in a closed circuit is equal to zero, and the sum of all reactive components (\( E \sin \phi \) = \( I \times X \)) is equal to zero. Hence,

\[
E_0 \cos \phi_0 = E_1 \cos \phi_1 + E_2 \cos \phi_2 + \text{etc}
\]

\[
E_0 \sin \phi_0 = E_1 \sin \phi_1 + E_2 \sin \phi_2 + \text{etc}
\]

\[
E_0^2 = (E_0 \cos \phi_0)^2 + (E_0 \sin \phi_0)^2
\]

Reactive component of voltage in an inductance is positive, that in a capacity is negative. Second law (for multiple circuits) (Fig 15 and 16): The sum of all active components of current (\( I \cos \phi \) = \( E/R + Z \)) meeting at a point is equal to zero, and the sum of all the reactive components (\( I \sin \phi \) = \( E \times X \)) is equal to zero.

\[
I_0 \cos \phi_0 = I_1 \cos \phi_1 + I_2 \cos \phi_2
\]

\[
I_0 \sin \phi_0 = I_1 \sin \phi_1 + I_2 \sin \phi_2 - I_3 \sin \phi_3
\]

\[
I_0^2 = (I_0 \cos \phi_0)^2 + (I_0 \sin \phi_0)^2
\]

Reactive component of current in an inductance is negative; in a capacity, positive.

Ohm’s law for series a-c circuits (Fig 13). In a circuit having resistance \( R \), inductive reactance \( X_L \), and capacity reactance \( X_c \) in series, the impedance in ohms is: \( Z = \sqrt{R^2 + (X_L - X_c)^2} \), the current \( I = E/Z \), and the power factor \( \cos \phi = R/Z \). Voltage across the resistance \( EI \) (Fig 14) is in phase with the current. Voltage across the inductance \( IX_L \) is 90° ahead of the current, and the voltage across the capacity \( IX_c \) is 90° behind the current. These combine geometrically to give: \( E = \sqrt{E^2 + (IX_L - IX_c)^2} \), which differs in phase from \( I \) by the angle \( \phi \), the cos of which is \( E/Z \), and sin of which is \( (X_L - X_c)/Z \).
Multiple circuits (Fig. 15, 16). In multiple circuits having resistance and reactance in various branches:

Conductance \( G_0 = R_1 + R_2 + R_3 + R_4 + R_5 + R_6 \)
Susceptance \( B_0 = X_L + X_3 + X_4 + X_5 \)
Admittance \( Y_0 = 1 + Z_0 = \frac{1}{G_0 + B_0} \)
Current \( I_0 = E_0 Y_0 \) and \( \cos \phi_0 = G_0 + Y_0 \)

The negative sign is used to denote a lagging current in an inductance in multiple circuits.

Resonance. If an inductance and capacity are connected in series, the voltages across them are opposite in sign; if equal in magnitude their resultant or difference is zero. This is resonance in series circuits. If an inductance and capacity are connected in parallel, the two currents will oppose each other; if the currents are equal a large current may flow in each, but the resultant current in the supply circuit is zero or very small. This is resonance in multiple circuits. The phenomenon is utilized to regulate long transmission lines. The line has inductance, while near the load a synchronous motor is installed, which can act like a large condenser. By adjusting the excitation of the latter its capacity effect is varied until it neutralizes the line inductance, and it is possible to obtain a higher voltage at the load than is given by the generating station.

Polyphase circuits. The single-phase a-c system, while simpler to calculate and best for lighting purposes, is not satisfactory for general transmission and power purposes. This is because: (a) a polyphase machine, whether generator or motor, weighs and costs less than a single-phase machine; (b) single-phase motors will not start from rest without complicated auxiliary devices; (c) in transmission work the 3-phase system requires only 75% as much copper for given power and voltage as the single or 2-phase systems. Therefore some commercial installations use 2-phase, while the great majority use 3-phase.

Two-phase system (sometimes called quarter-phase) consists of 2 circuits, which are usually independent and come from independent circuits in the generator. Voltage of each circuit is the same, and it is endeavored to maintain same current in each. This is called balanced conditions. Generally 4 wires are required, though sometimes 3 wires are used, but the latter arrangement is undesirable as it causes poor regulation. The wiring connections of 2-phase circuit are simple, as each phase is treated as an independent single-phase circuit.

Three-phase system saves 25% of the copper required for transmission line, as compared with any other commercial system, and is in general use. Theoretically, it consists of 3 independent circuits, in which the 3 e.m.f's differ in phase by \( \frac{1}{3} \) of a period, or 120 electrical degrees. Since the currents in the 3 circuits combine to neutralize each other, the 3 return wires are not necessary, and the outgoing current in each wire returns by the other two without interference with regulation. It is, therefore, common in 3-phase machinery to connect the 3 windings inside the machine so that only 3 conductors are brought out from the machine. There are two methods of making this connection. Fig. 17 shows a Y-connected generator feeding a 3-phase line, at the other end of which is a delta (\( \Delta \)) connected motor. The different voltages in this system have definite ratios as follows: Let \( E \) be the voltage between any 2 wires of the transmission line, and \( I \) the current in each line: Generator voltage per phase = \( E + \sqrt{3} \). Line voltage (neutral) = \( E + \sqrt{3} \). Motor voltage per phase = \( E \). Generator current per phase = \( I \). Motor current per phase = \( I + \sqrt{3} \).

Choice of \( Y \) or delta-connections is a matter of convenience, except for some exceptional pieces of apparatus. To the operator it makes no difference which connection is used, and in fact it is impossible to tell without having the design drawings.

Polyphase transformations. There may be systems of 5, 6, or any number of phases, but the 1, 2, and 3-phase systems are the only ones used for transmission. Some machines have 6-phase windings, but these are always supplied by 3-phase transmission lines. For methods of converting from one polyphase system to another see Art 13.

8. ALTERNATING-CURRENT GENERATORS

Synchronous generators. Field structure consists of a number of poles, excited by coils carrying a d-c. The relative motion of armature conductors and field structure generates the voltage. Frequency of the voltage depends directly upon number of field poles and rev per min of revolving part. Revolving-field generators make more effective use of material than those with revolving armatures, and are more easily insulated for high voltages. Most generators of greater capacity than 300 kw are of the revolving-field
type. Advantages: good regulation, high efficiency, and satisfactory operation in parallel. Most alternators built at present are separately excited, because voltage regulators are now available which are simpler and more reliable than the self-excited machines formerly in use. Induction Generators are a special form of synchronous machine, having a revolving-field structure consisting of a spider with bare projecting poles, and one coil of d c which excites all poles.

Induction generators are constructed like induction motors. The magnetic field is of the rotating polyphase type, produced by a.c in same windings as the load current. An induction generator must always be connected to a synchronous generator, from which it must receive its excitation. Only a minority of the units of a station may be of the induction type. Advantage: less violent effects in case of short circuits.

Connections (single, two, and three phase). Single-phase generator is usually about 30% heavier and more costly than a polyphase of same rating. Two and three-phase generators of same capacity and voltage are practically of same dimensions, weight, and cost. By changing the internal armature connections any polyphase machine may be reconnected as a 3, 2 or single-phase machine. As transmission by 3-phase currents is more economical of copper than by 2-phase or single-phase currents, all transmission lines are 3-phase; hence, the 3-phase generator is preferable.

Voltage. Alternators are now built for voltages up to 16 000 and 22 000 between lines, either single or polyphase. For higher voltages, owing to extra cost of insulation and danger of damage, it is cheaper to install transformers with a lower voltage alternator.

Frequency depends upon speed of rotation and number of poles. If the rotative speed of revolving part is given in rev per min, the frequency is \( f = \frac{(r \times p \times m)}{120} \). Formerly it was found more economical to run alternators at high speeds. Hence frequencies as high as 133 and 125 cycles per sec were customary; but, as systems increased in size and complexity, high frequencies caused electrical difficulties. Usual frequencies are now 60, 50, 40, and 25 cycles per sec, of which 60 is standard in U S. In Europe 50 cycles are used instead of 60.

Single phase. Voltage per phase is the same as between lines, and current per phase same as current per line. The product of voltage and current = volt-ampere rating.

Two-phase or quarter-phase. Each phase supplies half the rating; thus the voltage and current per phase in the machine are the same as the voltage and current per phase of the line. The current is

\[
I = \text{Power output in watts} + 2 \times E_p
\]

where \( I \) = amperes in each line; \( E \) = volts between lines; \( p \) = load power-factor.

Three-phase machines may be either Y or delta-connected. In both cases the relation between output, current in each line, and voltage between lines is the same:

\[
I = \text{Power output in watts} + \sqrt{3} \times E_p
\]

Tests. Principal commercial tests on a-c generators are: resistance, cold and hot; friction; saturation and core loss; synchronous impedance and load loss; heat run and insulation. Friction, core loss, and saturation tests are made during one run; synchronous impedance and load loss during another. For testing, the generator is driven by a small motor of about 1/10 the capacity of the generator. Synchronous impedance is used to calculate regulation of the generator; results of the other tests give the efficiency. Losses are friction, core loss, excitation, armature \( J_2R \) or copper loss, and load loss. Efficiency is the output divided by the output plus all losses at that output. Armature \( J_2R \) and load loss vary as the square of the load; other losses are approximately constant. Heat runs may be made by operating the generator under normal load conditions, or by a compromise method in which the generator supplies current to a synchronous motor, which runs free and is under-excited, the current being wattless or reactive. Temp of windings after the heat run is determined by comparing their resistance at that time with their resistance when machine was at a known (room) temp.

Usual efficiencies at full load for different sizes of generator are given in Table 8.

These values are merely indications and vary with frequency, voltage, speed, power-factor, etc. A 60-cycle low-voltage machine will probably have a better efficiency than a machine of same rating for 25 cycles or high voltage.

Regulation of a generator is defined as the ratio of the difference in terminal voltage at no load and at full load to the voltage at full load, the field excitation being kept constant at full load value and the speed being constant. Expressed as a percentage, the regulation is \( 100 \left( \frac{V_s - V}{V_s} \right) \) + \( V \), where \( V \) is terminal voltage at full load and \( V_s \) is terminal voltage at no load, with excitation for full load. Usual value, 5 to 25%.
SYNCHRONOUS MOTORS

Operation. In the operation of an a-c generator several factors are considered:

Excitation. A-c generators of the synchronous type (that in most general use), require d-c to excite their field windings; usually obtained from an exciter, which is driven by a separate engine, or by an electric motor, or from the generator itself by belt or other mechanical connection. Usual potential for field circuit is 125 volts, though some machines are designed for excitation at 250 volts. Since most machines have revolving fields, the d-c is led into the field coils by collector rings on the main shaft. In series with exciter and field circuit a rheostat is connected, to vary the current in field coils, and thereby the excitation and voltage of the generator. Usual power for excitation is from 0.5 to 2.5% of rating. Before starting a generator its bearings are inspected, cleaned, and oiled. Machine is then brought up to speed, and bearings again inspected to see that oil rings are running properly. Exciter or excitation circuit is then put in readiness, and the rheostat in alternator-field circuit adjusted for maximum resistance. Before exciting the field the armature insulation must be thoroughly dry; otherwise, the armature is short-circuited through an ammeter, and run for several hours at a partial excitation to give about rated current in the short-circuited armature. When insulation is thoroughly dry the short circuit is removed and the excitation adjusted to give rated voltage at armature terminals at correct speed. To stop the machine, load is first removed by opening the circuit breaker; then the field rheostat is turned to maximum resistance, as is also the rheostat in the exciter field if there is an individual exciter. Field circuit is then opened.

Paralleling of generators. Before connecting a generator to the bus bars (to which one or more other generators are connected), following conditions must be satisfied: (a) frequency of generator must be the same as that of bus bars; (b) frequency of generator, and therefore its speed, must be constant for an appreciable interval of time; (c) voltage of generator must be the same as that of bus bars; (d) generator and bus-bar voltage must be in phase.

If two machines have not the same frequency, or if frequency is not constant, a condition will occur intermittently in which the voltages are 180° apart, or the machines are in series on a short circuit, and a dangerous current will flow. If voltages are not equal, a large wattless current may flow, and if they are not in phase, a large power current will flow, causing a mechanical shock. Two methods are used for determining when these conditions are favorable for connecting the machines together without disturbance; that is, for indicating when the machines are in synchronism. For synchronizing with lamps, the connections as in Fig 18a are such that the lamps remain dark when above conditions are satisfied; with connections as in Fig 18b, they will remain bright. If the frequencies are wrong, the lamps will flicker (the slower the flicker the nearer the frequencies). If voltages are wrong, lamps will glow slightly but steadily. Synchronousoscope is an instrument which indicates the relative frequencies and phases of 2 alternators; usually installed on switchboard of a station, if a number of generators are used.

Cost and weight. Generators vary widely in their specific weights and costs, that is, weight and cost per kw rating; but they may be divided into classes in which these characteristics are fairly definite. Conditions affecting specific weight are: method of rating, speed, frequency, voltage, and size. Method of rating is fundamental. For comparison, rating is taken as the output in kw which each machine will give continuously with a temp rise not exceeding 50° C. On this basis, specific weight decreases as the speed, frequency or capacity increases, and it increases with increase of voltage. A-c generators are divided into 3 classes according to their speeds and purposes: high speed, as turbine-driven generators; medium speed, as belt-driven and water-wheel driven; slow speed, or engine-driven. See Table 17, Art 19.

9. SYNCHRONOUS MOTORS

Operation. Any alternator will operate as a motor. If two synchronous alternators are connected in parallel to bus bars supplying a load, and the driving power is removed from one prime mover, the alternator connected to this prime mover will continue to run at same speed, taking power from the other alternator and driving its own prime mover or other apparatus coupled to it; this alternator thus acts as a motor. Speed of such a motor depends solely upon the speed of the generator or generators supplying electric energy to it; it is therefore said to run in "synchronism" with source of supply and is called a synchronous motor. The speed of a synchronous motor having p poles, and supplied with current of a frequency of f cycles per sec, is: r p m = 120f / p. If load on the motor increases, speed will not decrease, unless load reaches a value so excessive that
the maximum output or "pull-out torque" is reached; then the motor will drop out of
step and come to rest, while the current taken will increase to short-circuit value and
torque will decrease to a negligible value. Difference in construction between an alternator
and a synchronous motor is that the latter has, in the face of the field poles, a squirrel-cage
winding, intended to give good starting torque and prevent "hunting" while running. 

Hunting defines the occasional undesirable action of synchronous machines, of varying
in speed, current, and voltage, as a frequency observable in meters. If excessive, a short
circuit results (see Specifications below). A standard 2 300-volt generator will operate
satisfactorily as a motor at 2 080 volts, and as these are the natural values of the generated
and delivered voltages, this characteristic of the synchronous motor accords well with
customary distribution practice. A standard generator may have a squirrel-cage winding
added to its poles and become a good synchronous motor.

Number of phases. Synchronous motors may be single, 2, or 3-phase. The single-
phase motor is not self-starting, and has a considerably lower efficiency than the polyphase.
It is also more liable to hunt and be unstable, and is therefore far less desirable than a
polyphase motor. The 2 and 3-phase motors are very similar in all their characteristics.

Terminal voltage. Since synchronous motors are usually built with a revolving field
and a stationary armature, the armature winding can be insulated for voltages as high as 15
000, thus often obviating need of transformers.

Relations of voltage and current. Relations between line voltage and phase voltage
are the same as in a-c generators (Art 8). Current in each line of a 3-phase motor is:

\[ I = \frac{746 P}{\sqrt{3} \, e \, B \, \cos \phi} \]

where \( P \) = output, h p; \( E \) = voltage between lines; \( e \) = efficiency at
assumed load; \( \cos \phi \) = power factor (may be unity). Usual values for efficiency are
about the same as for a-c generators.

Advantages of synchronous as contrasted with induction motors: higher efficiency,
higher power factor, controllability of power factor with constant speed, high voltage,
lower cost. Disadvantages: need of an exciter, will not start as great a load.

Applications. To transform from a c to d c, or from one kind of a c to another differing
in frequency, potential, or phase relation, motor-generator sets, consisting of a synchronous
motor direct connected to one or more generators, are often employed (Art 8). The
potential of the secondary or distribution circuit is thus made independent of the variation
in potential of the primary circuit supplying power to the motor. In certain cases it is
desired to take power from a 25-cycle circuit and supply power at 60 cycles for lighting
purposes. Here a synchronous motor-generator set would be used; often called a " fre-
cquency changer." In some applications of electric drive by induction motor one syn-
chronous motor is installed to make it take leading current, in order to neutralize the
lagging current taken by the induction motor. This effect is produced by over-exciting
the fields of the synchronous motor. The motor may be used to drive any machinery
not requiring much starting torque. Such a motor is a "rotary phase modifier" or
"rotary condenser" (see below).

Tests of synchronous motors. The first four tests of an a-c generator (Art 8) apply also to
synchronous motors.

Phase characteristics, or V-curves at no load, full load, and any other specified load. Machine
is operated as motor with specified load kept constant throughout the run. Voltage and frequency
impressed upon the motor are also kept constant. Current in the field is varied from minimum at
which motor will operate to the maximum (from 0.25 to 1.5 normal), and the variation in current
input to armature noted. Readings are taken of load, volts armature, amperes armature, and
amperes field. A curve is plotted with amperes armature as ordinates, and amperes field as
abscissas. This gives the characteristic V-curves. At point of minimum current input for each
load the power factor is unity. At lesser values of field current the armature current lags and
power factor is poorer; at greater values the armature current leads.

Starting. All synchronous motors have a squirrel-cage winding in the faces of the
poles, which enables them to start as induction motors with a torque of 40% to 80% of
rated torque. The induction motor action brings the speed up to about 95% of syn-
chronous speed. Then the field switch is closed and a strong field supplied. This causes
the rotor to pull suddenly into exact synchronism. Frequently there, is a "Field
Breakup Switch," which is kept open during starting and closed just before pulling into
synchronism. This protects the field windings from breaking down, due to the high
voltage induced in them at low speeds. If there is considerable flywheel mass in the load
it is difficult for the motor to pull into synchronism. Special synchronous motors are
available for unusual starting requirements. After the motor has reached synchronous
speed, the full load may be applied and the field rheostat adjusted to give minimum arma-
ture current, or a leading power factor if the motor is designed for that particular operation.
INDUCTION MOTORS

Installation and operation. Precautions to be taken in installation are the same as for a-c generators (Art 8). Direct current must be provided for excitation. If a synchronous motor is operated on a polyphase system having unbalanced voltages, it will take unequal currents in the different lines and tend to balance the voltages. But these unequal currents increase the heating for a given load.

Specifications. Synchronous motors are rated in same manner as synchronous generators, and same heating limits and specifications apply (Art 8). It is customary to specify the value of current taken by the motor in starting with no load other than the friction of its own bearings; or its own friction plus that of the machine to which it is connected, in case it is part of a motor-generator set. It is sometimes stated in specifications that the motor will not hunt, provided the total resistance drop between generator and motor is less than some specified value (10 or 15%).

Dimensions, weight, and costs are given in Table 19, Art 19.

10. INDUCTION MOTORS

Principles. Induction motor is a machine having distributed windings, like those of the armature of a d-c machine, on both stationary and revolving members. One winding, the primary, receives polyphase currents from the supply circuit and thereby sets up a rotating magnetic field. This field cuts the conductors of the secondary winding, induces currents in it, and thereby drags it along with the field. The action is reversible; either member may be the primary, provided it is connected to the line. That member which remains stationary, whether it be primary or secondary, is called the stator; the other, the rotor. In U S the stator is usually primary.

Synchronous speed. Speed of rotation of the magnetic flux is called the synchronous speed. At light loads the rotor speed is nearly equal to the synchronous speed. If \( f \) is the frequency of the current, and \( p \) the number of poles of motor windings, the synchronous speed is: \( \text{rev per min} = 120 f + p \).

Slip. At any appreciable load the rotor speed is less than the synchronous speed. Difference between the actual rotor speed \( N_r \), and synchronous speed \( N \) is "slip." It may be expressed as a percentage or a fraction: \( S = (N - N_r) / N \).

Methods of rating. Amer Inst of Elec Engs recommends that the rating of an induction motor shall be the h p which it will deliver continuously at the shaft with a maximum rise in temp not injurious to its insulation (Art 1).

Starting and break-down torque. In addition to the ability to carry its rated load without excessive heating and with reasonable values for efficiency, power factor, and slip, the motor should be able to start such loads as must be brought up to speed, because good starting ability in an induction motor involves certain complications and expense. It is important also that the motor be able to carry momentary overloads without "breaking down," that is, gradually coming to a standstill. To prevent this the max motor output must be known and should be at least 50% greater than rated output.

Frequency and speed. Induction motors can be built for any frequency. The higher frequencies are satisfactory where the load never exceeds the normal. Frequencies as low as 25 are preferable where overloads are common, or large starting torques are required. Rotor speed of an induction motor at normal loads approaches within 5 to 10% of the synchronous speed, which is fixed by the frequency of the system and its number of poles (see above). Hence, for a given frequency of supply circuit, only certain speeds are available. Thus, for 60 cycles, the rev per min are: 3 600 for 2 poles; 1 800 for 4 poles; 1 200 for 6 poles, etc.

Phase connections. Two-phase or quarter-phase motors are usually wound with independent phase windings. Three-phase motors are connected in Y or delta, depending upon convenience of designing engineer. In single-phase and 2-phase motors the voltage and current per phase, are the same as voltage between lines and current in line; in a Y-connected 3-phase motor, the current per phase is equal to line current, and voltage per phase is equal to line voltage divided by \( \sqrt{3} \); in a delta-connected 3-phase motor the current per phase is equal to line current divided by \( \sqrt{3} \), and voltage per phase is equal to line voltage.

Currents taken by motors. Let: \( P_o \) = output, h p; \( I \) = current in each line; \( e \) = efficiency as a decimal fraction; \( p = \cos \phi = \)

<table>
<thead>
<tr>
<th>H p</th>
<th>25 cycles</th>
<th>60 cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Eff</td>
<td>Power factor</td>
</tr>
<tr>
<td>1</td>
<td>0.79</td>
<td>0.78</td>
</tr>
<tr>
<td>5</td>
<td>0.65</td>
<td>0.86</td>
</tr>
<tr>
<td>20</td>
<td>0.88</td>
<td>0.91</td>
</tr>
<tr>
<td>50</td>
<td>0.90</td>
<td>0.92</td>
</tr>
<tr>
<td>180</td>
<td>0.905</td>
<td>0.925</td>
</tr>
<tr>
<td>200</td>
<td>0.91</td>
<td>0.923</td>
</tr>
</tbody>
</table>
power factor as a decimal fraction; \( V \) = voltage between lines (between one outside wire and the middle wire for 3-wire, 2-phase line). Then, for 2-phase: \( I = 373 P_0 + \frac{1}{2} V \); for 3-phase: \( I = 451 P_0 + \frac{1}{2} V \).

Testing. Induction motors may be given an “input-output” test (Art. 5) at working load, from which efficiency, power-factor, slip, and maximum output may be determined; or, a no-load excitation and a no-load short-circuit test, from which all characteristics may be calculated. The former is similar to a stray-power test (Art 5) on a d-c motor, the latter to a resistance measurement. No-load tests require very little power, and are preferable for large motors, where it would be expensive to supply power and inconvenient to dissipate the energy. They are equally accurate.

Characteristic curves. Fig 19 shows examples of the usual characteristic curves of an induction motor. Typical break downs of all the curves at maximum output is shown at 300 h.p. Power-factor curve shows relation between the true power input and the apparent power, or volt-amperes. Low power factor involves no greater registration of the watt-hour meter, or cost of energy to operate the motor, but does involve poor voltage regulation of the system as a whole and a larger capacity of wiring, transformers, etc. Apparent efficiency is the product of the power factor and true efficiency, and is equal to output in watts divided by input in volt-amperes. Its value determines the actual capacity of the line and transformer supplying the motor.

Fig 19. Characteristic Curves of a Three-phase Induction Motor

Starting. To start an induction motor without injurious heating, a resistance must be connected in the secondary circuit, or the voltage impressed upon the primary must be reduced. These methods are known as Rheostatic Control and Potential Control. They are also available to control the motor speed.

Potential control consists in reducing and regulating the voltage impressed on the primary, usually by a starting compensator or auto-transformer, which provides 1 or 2 fractional voltages. For this the secondary must be of higher resistance than with other methods of starting, but no changes of connection of the secondary are necessary. Hence, a squirrel-cage rotor winding is used, made of one bar per slot, all bars being connected at both ends to solid copper rings. To start the motor the primary is connected to taps on the compensator, which give a voltage of from \( \frac{1}{2} \) to \( \frac{2}{3} \) the rated voltage if it is a small motor, and \( \frac{1}{3} \) to \( \frac{1}{2} \) if it is large. A small motor may be brought up to speed with this voltage, but a larger one may require an intermediate step. When motor is up to speed (indicated by the low, steady value of the current) it is connected to full line potential. Rheostatic control. Better apparent torque efficiency, that is, more torque for a given current is obtained by inserting in the secondary circuit a much greater resistance than can be permanently used. To do this a special starting resistance is connected in series with each of the 3 armature windings, and a switch provided for short-circuiting the resistance, either step by step or as a whole, as the motor speeds up. There are two commercial methods. The first is for use only when the torque required at starting is not great, in which case the starting resistance may be small and placed within the armature spider. The switch lever is so arranged that the resistance can be short-circuited in steps while armature is revolving, thus obviating the need of collector rings and external connections. Second method, for large starting torque, consists of bringing the 3 terminals of the secondary winding to collector rings. From brushes on these rings conductors lead to external resistances, with steps or taps, so that the resistance can be short-circuited gradually by a controller.

Speed control. Speed of an induction motor may be controlled in 5 ways: (a) By varying the potential applied to the primary of a motor having suitable permanent resistance in the secondary. (b) By varying the resistance in external circuit of the secondary. (c) By changing the internal connections of primary winding as to change the number of poles. (d) By connecting two motors in “concatenation” (similar to series connection). That is, the stator of first motor is connected to the supply, rotor of first motor is connected directly to rotor of the second, and stator of second motor is treated as its secondary. (e) By changing frequency of the applied voltage. Method (b) (rheostatic) is the most general and practical where more than 2 speeds are required; any speed may be obtained. Method (c) is best where only 1 motor is available and only 2 speeds are required. Method (d) requires 2 motors and gives 2 speeds; not as desirable as (c). Method (e) is of theoretical interest only.

Installation. Induction motors, even in large sizes, are usually self-contained; the bearings being a part of the end frame of the motor. They are either direct-connected or
belded. Belt drive is the commoner, since an induction motor can be built only for a definite speed, corresponding to a certain number of poles. Small motors need no foundation, and are often attached to the wall or ceiling, the bearings and end shield being so made that they may be turned through 90° or 180°, for proper operation of the oil rings. Most motors must have reasonable ventilation, free from dust and dirt. For severe service, as in cement mills or mines, motors are built totally inclosed ("iron-clad") and may then be even submerged in water. This increases both size and cost.

Operation. Small motors are designed to start merely by closing the main switch. With larger motors, if starting switch is in proper position, potential may be applied to the motor, and the starting resistance gradually cut out by the switch. Induction motors are very sensitive to variations in the impressed voltage. A decrease from 100 to 80 volts will cause the maximum output and starting torque to decrease from 100 to 64, with a roughly proportional increase in heating for a given load. Unequal voltages in the different phases cause decrease in maximum output, and increase in heating for a given output. An unbalancing of 25% in voltage doubles the heating effect at full load; giving the same heating as 50% overload. CAUTION IN STARTING. Before starting for the first time, see that the starting device is in operating condition and in proper position, to avoid injurious heating. Wiring must be proportioned to carry the starting current without an excessive drop in voltage (see above).

Faults. Some of the common faults in induction motors, with their indications and remedies, are:

SECONDARY OPEN-CIRCUITED. Motor will not start, and will not take a current greater than exciting current; probably due to the starting resistance not being connected in. ONE PHASE OF SECONDARY OPEN-CIRCUITED. Motor tends to remain at half-synchronous speed, although the voltage is normal. If the armature is blocked, the currents in primary will be unbalanced. ONE PHASE OF PRIMARY OPEN. Motor will not start, and current will be unbalanced. ONE ARM OF PRIMARY REVERSED. Currents in primary will be very much unbalanced when motor is running, and starting torque will be very slight. SHORT-CIRCUIT COIL IN PRIMARY. There will be humming when potential is applied to the motor and excessive local heating around the short-circuited coil. VIBRATION due to mechanical unbalancing is chiefly noticeable at high speeds, particularly in high-speed machines. If vibration is due to magnetic unbalancing, it is probably caused by inequality in the air gap at different portions of circumference, and at different positions of armature. It may be detected by measuring the air gap with taper wedges at different points around the circumference, with the armature in several positions.

Specifications. Following memoranda (from Amer Handbook for Elec Engs) will assist in framing specifications: Principal characteristics and conditions of service. Use to which motor is to be put; kind of load and method of drive; voltage and number of phases; rating, horse-power; frequency and speed. Style and description, construction details. Whether to be open, semi-inclosed or inclosed; requirements regarding pulley and length of shaft; whether rails are required; method of starting; compensator, external resistance or internal resistance; whether motor is to be run at speeds other than full speed; whether starting devices are to be supplied. Performance and tests. Final temp rise at full-rated load; temp rise in 2 hr at 25% overload applied immediately after full-load run; efficiency at 25, 50, 75, 100, 125, and 150% load; starting torque with full-load current, ft-lb; high-potential tests of insulation; requirements as to effect of moisture upon insulation.

Weight and cost of induction motors vary with type of armature winding and character of mechanical frame and housing; also with speed, frequency, and voltage. Table 18, Art 19, gives weights and costs for standard 60-cycle motors.

Single-phase motors may be of either induction or commutator type. Induction type is the commoner, as its constant-speed characteristic is more generally appropriate than the variable speed of the usual commutator a-c motor. A 2- or 3-phase induction motor may be operated as a single-phase machine after it is once up to speed; but it has lower efficiency and power factor, and smaller maximum output than it would have as a polyphase motor. Slip, for a given output, is less in a single than in a polyphase motor. Because of the poorer operating characteristics, and especially the smaller maximum output or maximum torque, the motor must be rated at lower capacity when run single phase. A single-phase motor having same frame and wt of iron and copper as a polyphase motor will rate at from 60 to 70% of the capacity. Single-phase induction motors usually consist of standard 3-phase motors with their rating changed; thus a 10-hp, 90-volt 3-phase motor would make a typical 7.5-hp, 120-volt single-phase motor. Starting a single-phase induction motor has no torque at standstill, and must be started by some means as a phase-splitting device. A common method is to connect a Capacitor in series with one phase winding of a special wound polyphase motor. This gives a good starting torque and improves the power factor under running conditions. Or, a commutator on the rotor may be used, making it possible to operate as a repulsion motor (see
below) having good starting qualities. After reaching considerable speed the brushes are removed and the secondary windings are short-circuited.

Commutator type. The several types of a-c commutator motors designed to operate on single-phase circuits differ chiefly in their electrical connections. They may be divided into series motors and repulsion motors. Both have an armature wound like that of a d-c motor and a commutator. SENSUM'S a-c motor is connected like a d-c series motor, and has the same general characteristics. Principal difference is that the a-c motor has an extra winding placed in the face of the poles and connected in series with armature and field. This winding improves the power factor. Limiting feature of most a-c commutator motors is sparking at the brushes, which is much worse than in d-c motors. REPULSION motor has a stationary structure or field (primary) with a completely distributed winding like that of an induction motor. The winding may be for any voltage. The armature or secondary is like that of a d-c commutator motor. The commutator brushes are short-circuited upon themselves, and are placed at a small angle away from the neutral. This motor acts like a combination of transformer and series motor, having the variable speed, high torque, and runaway characteristics of the series motor. It is started by applying a reduced potential to the primary, and is reversed by moving the brushes or by reversing the current in one particular portion of the primary winding known as the exciting turn. REPULSION-INDUCTION type of motor is made in small sizes to drive machinery requiring good starting torque. It is a repulsion motor with extra brushes on the commutator, the brushes being connected across a portion of the primary. This gives a constant speed characteristic like a shunt motor, and a good power factor.

11. SYNCHRONOUS CONVERTERS AND RECTIFIERS

Since it is more economical to transmit electrical energy in the form of a-c and more convenient to utilize it in the form of d-c, some means of converting it from one form to the other is desirable. For this purpose synchronous converters, motor-generator sets (Art 6) and rectifiers are available.

Synchronous converter, also called "rotary converter," is similar to a d-c generator, in which certain commutator segments, or the conductors leading from them, are connected to 2, 3, 4, or 6 collector rings. When the movable member rotates, the voltage between any 2 rings is alternating. Such a machine may be operated as an a-c generator, or as a "double-current" generator giving a-c from its collector rings and d-c from its commutator. If the rings are connected to an a-c source, the machine will run as a synchronous motor, and d-c may be obtained from the commutator brushes; that is, the machine with but one set of windings acts simultaneously as an a-c motor and a d-c generator. It therefore has the friction, core loss, and excitation loss of one machine instead of two; and since the motor and generator currents flow in the same winding, and opposite directions, they more or less balance each other, and the armature $R^2I^2$ loss is much less than in either a motor or generator alone.

Converter versus motor-generator. A converter is much more efficient, weighs and costs less than a motor-generator set of same capacity, and occupies less space. But, since only one winding is used, there is a definite relation between the voltages of the a-c and d-c terminals. Maximum value of the alternating wave bears a definite relation to the direct e.m.f. (see Art 5). The converter must therefore be supplied with a voltage of the same order as the direct voltage, which requires transformers if a high-voltage transmission line is used to supply the converter. Efficiency of a converter approximates 93%, and of the transformers, 97%; the efficiency of the combination is therefore about 90%. Efficiency of a synchronous motor is about 93% and of a d-c generator, 92%; hence the combination motor-generator set has an efficiency of 85.5%. If the supply voltage is greater than 13,000 volts, transformers will also be needed for the motor-generator set, the net efficiency being then 83%.

Application of converters is commonest in electric railway work. Nearly all motors for electric traction are of d-c series type, operating at 500 to 600 volts. For this service the energy is transmitted over long distances, requiring a high-voltage a-c transmission line and converters to link the d-c distribution with the a-c transmission.

Phases and rings. SINGLE-PHASE CONVERTER has 2 collector rings, each connected to the windings by as many equally spaced taps as there are pairs of poles. The taps for the 2 rings alternate
SYNCHRONOUS CONVERTERS AND RECTIFIERS

at equal spaces. A single-phase converter is therefore a 2-ring converter. Three-phase converters have 3 rings and 3 equally spaced taps (one for each ring) for every pair of poles. A 4-phase or quarter-phase converter has 4 rings and 4 taps, and a six-phase converter has 6 rings and 6 taps per pair of poles.

Shunt and compound-wound converters. A converter may be shunt or compound wound, depending upon the service. Series winding is intended to make the converter take leading current when the load increases, and thus increases the voltage at the a-c terminals, but the ratio of the a-c terminal voltage to the d-c voltage remains unaltered.

Inverted converter converts from d-c to a-c. It works satisfactorily, but its speed depends upon nature of the a-c circuit. An inductive load in the a-c circuit causes the armature to demagnetize the field, with a resultant increase in speed. It is therefore dangerous to operate an inverted converter on an inductive load, unless it is provided with a speed-limiting device. This does not occur when the machine operates as an a-c motor, since its speed is fixed by the frequency of the supply circuit.

Connections and voltage ratios. The ratio of voltage on the a-c side to that on the d-c side depends upon the number of rings and type of connection (Table 10). In practice the current on input side must be greater than that given in the table, in order to supply the converter losses, and the a-c will also vary inversely as the power factor, which is taken as unity in the table. There are other losses besides R1, hence practical figures for output differ slightly from those in the table.

Table 10. Voltage, Current, and Capacity Relations of Converters

<table>
<thead>
<tr>
<th>D-C generator</th>
<th>2 ring</th>
<th>3 ring</th>
<th>4 ring</th>
<th>6 ring diametrical</th>
<th>6 ring double delta</th>
<th>12 ring</th>
</tr>
</thead>
<tbody>
<tr>
<td>D C, volts</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>A C, volts between lines</td>
<td>71</td>
<td>61.2</td>
<td>71</td>
<td>61.2</td>
<td>71</td>
<td></td>
</tr>
<tr>
<td>A C, volts between rings</td>
<td>71</td>
<td>61.2</td>
<td>50</td>
<td>35</td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>A C, amperes</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>A C, amperes in line</td>
<td>141</td>
<td>94</td>
<td>71</td>
<td>47</td>
<td>47</td>
<td></td>
</tr>
<tr>
<td>A C, amperes in winding</td>
<td>71</td>
<td>55</td>
<td>50</td>
<td>47</td>
<td>47</td>
<td></td>
</tr>
<tr>
<td>Relative R1 loss</td>
<td>100</td>
<td>137</td>
<td>55</td>
<td>37</td>
<td>26</td>
<td></td>
</tr>
<tr>
<td>Relative output, unity power factor</td>
<td>100</td>
<td>134</td>
<td>165</td>
<td>197</td>
<td>197</td>
<td></td>
</tr>
<tr>
<td>Relative output, 87% power factor</td>
<td>99</td>
<td>115</td>
<td>129</td>
<td>129</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Testing. Converter tests are practically the same as those on a synchronous motor (Art 9), with the addition of a test on ratio of a-c to d-c voltage, taken at no load and at full load.

Regulation. A converter, like a synchronous motor, may be used to cause a rise in voltage in the transmission line supplying it. It is done by over-exciting the field. The voltage on the d-c side will rise correspondingly, and thus the machine may be compounded. For this to take place there must be considerable inductance between generating station and converter.

Fig 20. Transformer Connections and Vector Relations of Synchronous Converters

Operation. As a converter exerts no appreciable mechanical torque, its structure and foundations are light. Fig 20 shows usual modes of connecting transformers to supply converters. The transformer secondaries must give a voltage which is a definite fraction of the direct voltage desired (Table 10).

Starting. A converter may be started by either of the methods described for synchronous motors, or it may be speeded up as a shunt motor, and then synchronised with the a-c supply circuit like an alternator (Art 8). All converters are supplied with a "field break-up switch," which opens the field circuit in several places to avoid the strain of the high potential induced in field windings during starting, and to reverse direction of field current after the machine is up to speed, in order to reverse the polarity if necessary. This is usually a double-throw switch with several poles. For normal operation it is thrown down to "running" position. To change the polarity it is thrown to "reverse" position and left closed only for a moment; then it is returned to "running" position. Speed-limiting device. If a converter be disconnected from the main a-c supply circuit, and still remain connected to the d-c circuit, it will tend to operate as a
d-o motor, and its speed might become dangerously high. To avoid this a centrifugal governor placed on the shaft opens the main d-o switches of the converter.

Rectifiers. The operation of a mercury-arc rectifier depends on the facts that: (1) a tube containing mercury and mercury vapor under low pressure (less than 0.01 mm), having one electrode in the mercury (the cathode) and the other of some conductor, usually graphite (the anode), offers very high resistance to a current tending to flow from the mercury to the anode, but (2) offers very little resistance to a current flowing from anode to cathode, provided the current is once started by forming an arc inside the tube. An alternating e.m.f impressed on this tube will cause a unidirectional current to flow in separate pulses. With two anodes and one cathode, with suitable connections, the pulses are largely smoothed out, and with some inductance in the circuit a unidirectional current with but little variation is obtainable. In practice a 3-phase alternating current is usual, with 3, 6 or 12 anodes in the tube, producing a direct current of almost no pulsation.

Losses. In such a rectifier there is a loss in voltage of 20 to 30 volts, no matter what the working voltage or current, and the product of this voltage and the current used gives the rectifier loss in watts. There is practically no other loss in the rectifier, but there are losses in the auxiliary apparatus, transformers, vacuum pumps and cooling water, circulator. An auxiliary "starting anode" is necessary. This draws an arc giving the initial ionisation to the mercury vapor; after which the working current maintains the ionised conditions.

The anode tank is of steel, insulated from the ground, with letz connections to the several electrodes carried through the tank walls by special "insulating seals," of porcelain or a special glass, in which the different materials have the same heat expansion coefficient. This tank is surrounded by another tank and between them circulates water for cooling. The inner tank is maintained at a vacuum of 1 to 5 microns (the upper limit of successful operation being 10 microns, or 0.010 mm) by two pumps in series, a mercury condensation pump operating continuously for fine adjustment and a rotary pump for coarse work. The latter operates only occasionally.

Applications. Mercury-arc rectifiers are chiefly used to supply direct current to railways at voltages of 600 and greater. They are at their best at high voltages, because their efficiency is higher, but operate satisfactorily at 200 volts with a lower efficiency and greater bulk and cost per kw.

Hot-cathode mercury rectifier, known as "phanotron," has a hot cathode of a suitable metal which emits electrons, and contains a small amount of mercury in form of vapor. This operates as a rectifier with much smaller values of current than the pool type, but with about half as much loss in voltage and therefore with a higher efficiency at low voltages, and is suitable for circuits of 125-250 volts, though not yet in very general commercial use.

Tungsten rectifier is similar to the preceding, except that it uses argon gas in a glass tube and is suitable for lower voltages, 50 volts or less, and small currents, 15 amp or less. It is useful for charging storage batteries and is cheaper.

Copper-oxide rectifier is a very simple device, consisting of a pile of copper plates whose surfaces have been treated in a particular manner. It can rectify alternating voltages of the order of a few volts, but has current capacity up to hundreds of amperes.

12. ELECTRIC POWER PLANTS (See also Sec 16)

Location of an electrical power plant is governed by: form of power; distribution of load; cost of ground; possibility of good foundations; room for extension; convenience of coal, and of water supply for evaporation and condensing; limitation of voltage used.

Form of power, whether steam or water, is usually definitely determined by local conditions. Choice between steam, gas, or oil depends chiefly on relative cost of fuel and of maintenance of an oil or gas engine. If steam is to be used, the choice between turbines and reciprocating engines is governed largely by size of units; in large sizes the steam turbine costs less per h.p and is cheaper to operate, while in small sizes the reciprocating engine is more economical. In designing a power plant and selecting the number and size of units, it is important that the total capacity be sufficient to carry the maximum load with margin, and that it be divided into units of a size to carry average load economically. Each unit is usually capable of carrying 25 or 50% overload for 2 hr. There should be at least 4 units in a large plant, and nothing is gained by having more than 8 units. A sufficient number of exciters are necessary to carry the peak load, with one exciter to spare. Transformers are commonly arranged in groups, one group for each generator. In hydro-electric plants it is often advisable to install 1 or 2 steam-driven units and boilers, to serve if water supply should fail (see also Sec 16).

Alternating vs direct current. Choice depends upon length of transmission line and value of energy. For utilizing all the energy within a short distance of the generating
station d-c is preferable, because d-c motors (particularly in small sizes) are more convenient, easier to control, and are available in greater variety of form and characteristics than a-c motors. But the voltage obtainable from a d-c generator is limited by the commutator to about 600; and, for transmission to a considerable distance by d-c, the quantity of copper becomes prohibitive; hence a c is used, and with the a-c transformer the transmission line potential is independent of the voltage at either generators or motors. The dividing line between the best fields for d-c and for a-c plant is not clear cut, and can be determined only by careful calculation and comparison of costs. Some installations use a-c generators and a c for transmission, but these are converted into d-c in substations near the point of utilization, and at a distance from the generating station. When the sub-station cost is less than the difference between the cost of the copper requisite for d-c and for a c, the a-c system with sub-station is preferable. If the a-c system be chosen, 3-phase generators are advisable, as 3-phase transmission requires 25% less copper than 2 phase or single phase, and there is no advantage in the 2 phase over the 3 phase. If the power plant is for a varied service, including lights as well as motors, the frequency should be 60 cycles, because incandescent lights operated at 60 cycles are satisfactory, while at 25 cycles the flickering is harmful to the eyes. Transformers for 60 cycles are considerably cheaper than those for 25 cycles.

Voltage. The most convenient and widely used voltage for a local power plant is the 220–240 volt 3-wire system, in which two 110-volt generators are connected in series, or a 220-volt generator and a balancer set provide the 3 voltages. In this case the electric lights and small motors are connected to the 110 volts from the neutral to either of the outside wires, while all the large motors receive 220 volts from the 2 outside wires, thereby saving in copper. If 110 volts were used, either an excessive amount of copper would be required, or the voltage on the lamps would vary enough to cause dissatisfaction. For a number of large motors, 500 volts is generally used, but the lighting problem then becomes difficult, as the lamps must be connected in groups of 4 in series, and if any one of the 4 burns out, all in that group go dark. 500 volts is also undesirable in damp places, as in a mine, because there is danger of an unpleasant shock, particularly to horses or mules. The 220-volt, 3-wire system is therefore best, if d c be used.

For the 3-phase a-c system the distribution circuits are best run with 4 wires, with 208 volts between the outside wires and 125 volts between each phase and the neutral. Lights are connected between each phase and the neutral, balancing the load on the 3 phases as nearly as possible, and 3-phase 208-volt motors used on the 3 phases.

Lowest standard voltage for transmission is 2200, which will take care of reasonable loads within a radius of 1 or 2 miles from the power station, stepdown transformers being used to supply the different sections of the area.

Arrangement. It is common practice to divide the power station, if steam or gas driven, into two parts, separated by a fireproof, dustproof wall. On one side are the boilers or gas producers; on the other, the prime movers, generators, and all electrical apparatus. In the simplest form the boilers are set in a single row along one side of this wall, and the generating units along the other side, the piping being so arranged that any engine may be supplied from any boiler. If transformers are used, they are generally placed in the room with the generators, but on opposite sides and on the lowest level, the switchboard being in a gallery above. Cables from generators to switchboard are laid underneath the floor and running up the side of the wall.

Switchboards are of 2 kinds: direct control, in which case the current is carried by bus bars immediately behind the switchboard panel, the opening and closing of switches in this circuit being effected directly by the operator; and remote control, in which the current is carried by conductors placed in brick compartments in the basement, and the connections are made by electrically operated switches controlled by a small relay circuit coming from control switches on a benchboard above. If potential is 2200 or less, and power is less than 5000 kw, direct control is satisfactory and feasible, but for greater voltage or power the remote control system is preferable.

Switchboard is divided into a number of units, each known as a panel. There are generator panels, reactor panels, and feeder panels, and at one end of the switchboard is a voltmeter; also, in an a-c station, a synchroscope is placed on a swinging bracket, which may be distinctly seen from any part of the switchboard. A circuit-breaker is a switch which opens the circuit when current is excessive; operated by hand or automatically by the current itself. While the make-up and arrangement of the different panels may vary greatly according to individual ideas, the essentials are as shown above.

D-c feeder panel, 2-wire system: 1-circuit-breaker at top of board, 1 ammeter, 1 hand-wheel for rheostat, 1 field rheostat back of board, 1 single-pole field switch, 1 triple-pole main switch (or 1 double and 1 single-pole) for equalizer, 1 4-point voltmeter receptacle.

A-c feeder panel, 2-wire system: 1 single-pole circuit breaker, 1 ammeter, 1 double or 2 single-pole main switches, 1 4-point voltmeter receptacle, 1 watt-hour meter. A-c generator panel, 3-phase: 3 ammeters, 1 3-phase wattmeter, 1 field ammeter, 1 double-pole
field switch, 1 handwheel for rheostat, 1 synchronising receptacle, 1 potential receptacle, 1 3-phase oil switch, 3 disconnecting switches, 2 current transformers, 1 potential transformer, 1 voltmeter for group, 1 synchroniser for group. A-C F E E D E R O R O U T G O I N G L I N E P A N E L, 3-phase: 3 ammeters, 1 3-phase oil switch, 3 disconnecting switches, 1 polyphase watt-hr meter, 3 current transformers. A V O L T A G E R S U B S T A N T I A L may be used, requiring an independent panel.

Costs. See Art. 19.

13. ELECTRIC TRANSMISSION

Types. Transmission may be in form of single-phase, 2-phase or 3-phase a-c, or as d-c. Single-phase and d-c systems require 2 wires; 3-phase, 3 wires; 2-phase, 4 wires. For given voltage between wires the relative weights of copper are: single-phase and 2-phase, 100; 3-phase, 75; d-c, 50. Because of the limited voltage at which d-c is obtainable, it is not applicable to long distances. Single-phase system is used where the object is lighting only, on account of its simple connections. For important transmission problems the 3-phase system would be chosen (Sec. 16).

Line drop is the difference between voltage at generating station and the load. It is usually expressed as a percentage of the delivered voltage, and most transmission lines are designed for 10% drop when transmitting full or rated load power. In general, the weight of copper required varies inversely as the line drop allowed. This is not strictly true in a-c systems, but is exact in d-c systems, and the relation may be written: 

\[ W = \frac{125 P D^3 + KE^2}{D + d}, \]

where \( W \) = wt of copper, lb; \( P \) = power delivered, watts; \( D \) = distance one way, in thousands of ft; \( K \) = ratio of power lost in line to power delivered; \( E \) = voltage delivered.

In an a-c system the inductive reactance must be considered, as well as the resistance. Resistance for a certain length of given size of wire is obtained from a wire table, and is prorated for the given distance. Inductance in henries per mile for one wire of a transmission system is given by:

\[ L = 74 \times 10^{-4} \times \log_2 (2D + d), \]

where \( D \) = distance between wires, and \( d \) = diam of wire, both in inches. Reactance in ohms is \( x = 2 \pi fL \), where \( f \) is the frequency. In a single-phase transmission the total resistance and reactance are twice the above values. In a 2-phase circuit, the resistance and reactance per phase are twice the above values. In a 3-phase circuit, the resistance and reactance per line or per Y-phase are used, and these are the values given by the above formulas.

Line regulation depends upon: line resistance and reactance, the current, and power factor of the load. It may be calculated by: 

\[ E_2^2 = (pE_1 + IR)^2 + (IX + qE_1)^2, \]

where \( E_0 \) = voltage at generating end; \( I \) = load current per line; \( p = \cos \phi \) and \( q = \sin \phi \) at the load; \( qE_1 \) is negative for anti-inductive load; \( E_1 \) = voltage at receiving end; \( X \) = reactance of line; \( R \) = resistance of line. For single-phase, \( E_1 \) is the voltage at the load, and \( R \) and \( X \) are taken as the sum of outgoing and return circuits. For 2-phase, \( E_1 \) is the voltage per phase at the load, and \( I \) is the current per phase in a 2-phase system (Art. 7); \( R \) and \( X \) being taken for the complete circuit of one phase, outgoing and return. For 3-phase, \( E_1 \) is the voltage to neutral at the load = 0.57 \times \text{voltage between lines}; \( I \) is the current per line, or \( Y \) current; \( R \) and \( X \) are taken for one line, one way. This gives \( E_0 \), the voltage to neutral at generating station. Voltage between lines is then 1.73 \( E_0 \).

Size of wire for an a-c transmission. Select first a wire which gives an allowable resistance drop (\( IR = 5 \) to 10%), and then find loss in voltage \( E_0 \) (generator - \( E_1 \) (load)) due to combined effect of \( R \) and \( X \). If loss be too great, select a larger wire and try again. To obtain a solution in one calculation is too complicated a problem except for experts. Remember that the impedance drop in the line (\( IZ \)) is usually much greater than the difference between generator and load voltage due to vector relations. Usual voltages for transmission work are: 2,000, 6,000, 13,000, 19,000, and 33,000 volts between lines, whether single, 2 or 3-phase. A rough rule for choice of voltage is to allow 1,000 volts for each mile of distance between generating station and load. Usual sizes of wire, from No. 4 to No. 6000 B & S gauge in solid conductors and larger sizes in stranded conductors (Table 4). Smaller wire than No. 4 has insufficient mechanical strength. Wires larger than No. 0000, if solid, would be too stiff, and would break from the repeated bending to which they are subjected.

- Stranded conductor. Gage number or rating of a stranded conductor is that of a solid conductor having same cross-section of metal. Resistance and weight of a stranded conductor are greater for a given length than of an equivalent solid conductor, due to the twisted path (and hence greater length) of the individual wires. Actual length of path of the current is increased by about 7%. In spacing the 2 wires of a line, it is usual to allow about 1 ft for every 10,000 volts.

- Transformer, commonly called static transformer, is used to transform a-c of given voltage to a higher or lower voltage. Single-phase transformer consists of 2 electrical circuits, usually of a large number of turns, interlinked with a common magnetic circuit of iron. Since the power is approx. the same in both windings, the currents are inversely proportional.
proportional to the voltages. Polyphase transformer is essentially two or more single-phase transformers, made into a single piece of apparatus; and so designed that at least part of the magnetic circuit is common to all the phases. A 3-phase transformer has 3 high-tension and 3 low-tension windings, arranged on an iron core (Fig 21). The winding by which energy enters the transformer is the PRIMARY; that by which it leaves, the SECONDARY. Since either winding may be connected to the source of energy, these terms are not definite unless the manner of connection is also stated. HIGH-TENSION WINDING and LOW-TENSION WINDING are used to distinguish the two windings, the high-tension being the one with the greater number of turns. When the high-tension winding is connected to the source of supply, it is a STEP-DOWN TRANSFORMER; when the low-tension winding is so connected, it is a STEP-UP TRANSFORMER.

![Diagram of core-type and shell-type transformers](image)

**Fig 21. Core-type Transformers**

**Fig 22. Shell-type Transformers**

**Classification of transformers.** (A) According to operating characteristics. Constant-potential transformers are intended to give an approx constant potential on the secondary side; constant current, to give an approx constant current on the secondary, for arc lamps. Both are designed to operate on a constant-potential supply circuit. Series transformers are connected in series with the main circuit and receive the line current in the primary. The secondary circuit includes only a meter and the secondary current will be inversely proportional to the transformer ratio. They are used to step down very heavy currents for purposes of measurement by low-reading ammeters and wattmeters. Auto-transformers or compensators, sometimes called single-circuit transformers, consist of one electric circuit interlinked with a magnetic circuit and a tap brought off from some part of the winding. As the voltage between this tap and either terminal of the circuit is a fraction of the total, a fractional voltage may be secured. Windings on each side of the tap are usually proportioned to the current to be carried. Auto-transformers are desirable where the ratio of voltages approximates unity, as they then require much less copper than regular transformers. Potential regulators are transformers in which the voltage of one member may be varied from zero to a fixed maximum, either by changing the direction of the magnetic flux or by changing the phase of the e.m.f of the secondary with respect to that of the primary.

(B) According to construction. There are two methods of arranging the electric and magnetic circuits of transformers, the corresponding construction being called "core-type" and "shell-type." Core-type transformer (Fig 21) has a single magnetic circuit interlinked with 2 electric circuits, each electric circuit containing primary and secondary coils. It is best adapted to small sizes or high voltages and to oil-cooling, and is the commoner. The 3-phase core-type is a combination of 3 single-phase transformers into one, to save material and space. Shell-type (Fig 22) has 3 magnetic circuits in parallel, interlinked with 1 electric circuit containing primary and secondary. Best for air cooling and large currents. Three-phase shell-type is a consolidation of 3 transformers into one.

(C) According to method of cooling. As a transformer is a very compact piece of apparatus, the problem of carrying away the heat is important. Naturally-cooled type has no special means of cooling, but relies upon ordinary circulation of air. Only used in very small sizes, as for meters. In the on-cooled, the core and windings are submerged completely in a tank of oil, and are subdivided by ducts so that oil may circulate and absorb heat from internal parts. The heat is carried to surface of tank containing the transformer, and then dissipates into the surrounding air. Tank must be specially designed, with deep corrugations or projecting vanes or tubes, to provide large air-cooling surfaces. In the air-blast type there are passages through which air is forced by a blower. Water-cooled transformer resembles the oil-cooled type, but a coil of pipe carrying running water is submerged in the oil. Transformers artificially cooled by oil are used when the size is too great for the self-cooling oil type and no water is available. Oil circulates through external coils or tanks, to afford greater cooling surface.

Transformer connections commonly used in lighting and power service are: Single-phase system with 2-wire secondary (Fig 23), standard in household lighting with a-c system, the neutral wire being grounded on the low-tension side, the primary side not being grounded. Lamps or motors operating at 110 volts are connected between the neutral and either side. Maximum potential between any secondary and ground is 110 volts, but if either outside wire becomes grounded a short-circuit occurs on that half of the transformer. Two-phase, or quarter-phase 4-wire system. The standard is essentially 2 independent single-phase systems, which are
usually electrically independent throughout. Two-phase 3-wire system is occasionally used for distribution of power in small systems. Return wire is common to both circuits. There may be a slight saving in copper, but the chances of unbalanced voltage and bad regulation, especially with an inductive load, render it objectionable. THREE-PHASE Y AND DELTA CONNECTIONS (Fig 24, 25). Transformation in a 3-phase system, with 3 single-phase transformers or one 3-phase transformer, having 3 primary coils and 3 secondary coils, is accomplished by connecting the primary either in Y or in delta, and the secondary either in Y or in delta. Following relations exist between voltage per transformer winding and voltage between lines, current in transformer windings, and current in lines. Power in the 3 transformers in any case is $3 \times 0.58 \times EI = 1.73\, EI$. THREE-PHASE OPEN DELTA, or V-connection, saves expense by omitting one transformer from the delta connection. It is recommended only for low voltages, as 2 300. Regulation and efficiency are poor, as one phase of the load receives power from 2 transformers in series. Aggregate capacity of the transformers should be 15% greater than the load. TWO-PHASE TO 3-PHASE (Fig 26). Scott, or T-connection, consists of 2 transformers which, on the 2-phase side, are connected in normal 2-phase manner. On the 3-phase side one transformer has a tap at the middle point, the other a tap giving 87% of full-transformer voltage. Fig 26 shows method of connecting, and the currents in primary and secondary with balanced loads. Total transformer capacity must be 15% greater than the load.

EFFICIENCY is equal to the power output divided by output plus core loss plus total copper loss, and is very high. "All-day efficiency" is equal to the energy output for a day divided by the input; with short periods of load it is low, because core loss goes on when there is no load. If $P$ is the load in watts for $h$ hr per day, $A$ the core loss, and $E$ the copper loss, the all-day efficiency is $100\, (AP + (AP + 24A + hB))$ in percentage.

Regulation is $(E_0 - E) + E$, where $E_0 = $ secondary voltage at no load and $E = $ secondary voltage at full load. It should be from 1 to 4% for load of 100% power factor, and is poorer for inductive loads. Fig 27 shows efficiency and regulation at full load of a line of 60-cycle lighting transformers for 2 300 volts.

Installation. Transformers require no special foundations, but merely provision to carry their dead weight. They must be in a dry place, unless of the totally enclosed "subway" type. They are often placed on poles. They must be thoroughly cooled.
Substation is a building containing an equipment for transforming or converting the energy of transmission line into a convenient form for use in small units. Since the energy may be used as a.c. or d.c., there are 2 general types of substations: a.c. to a.c. and a.c. to d.c. In either case the energy must be distributed to the various consuming devices at a much lower voltage than that of transmission, sometimes at a different frequency, and sometimes in an entirely different form. The substation is therefore the dividing point between the transmission and distribution systems.

A-c substation in simplest form comprises step-down transformers for lowering the voltage, and incidental regulating and protective devices. There may be a group of 3 single-phase transformers, or one 3-phase. Single-phase transformers are preferable for moderate sizes, as they require a smaller reserve. Since the transmission system is always 3-phase, these groups provide low-voltage 3-phase currents for different groups of motors, or the individual phases may be wired separately for lighting purposes. If transmission system is 25 cycles it may be necessary to install motor-generator sets (Art 6) (frequency changers) to give 60-cycle current for lighting. These usually consist of a synchronous motor driving an alternator. If the distribution system voltage must be kept constant, some form of voltage regulator is installed, which will keep the voltage constant on each individual circuit, or on the 3-phase circuit as a whole. A switchboard with the necessary switches and measuring instruments is requisite. D-c substation consists of step-down transformers, converters, motor-generator sets, or rectifiers with incidental regulating and protective devices. The converter (Art 11) is cheaper and more efficient than the motor-generator set, and is advisable in absence of any local reason for using motor-generators. Converters may be arranged to give constant voltage irrespective of load, or may be over-compounded. The substation then resembles a d-c generating station.

Lightning arresters are to protect the apparatus of a station from natural lightning discharges, and from "internal lightning" caused by sudden changes in current or voltage conditions in the system itself. A lightning arrester permits a current to flow from conductor to ground, whenever the potential exceeds the normal, and stops this current when the excess voltage ceases to exist. This is usually done by letting the excess voltage break down a spark gap, by means of an arc which stops as soon as the voltage drops below a critical value depending upon the width of gap.

Types of arresters. HORN-GAP ARRESTER is simplest and is commonly used for high voltages, but is not sensitive enough for moderate and low-voltage systems. It consists of 2 copper rods, bent like horns, separated by a fraction of an inch at the nearest point and diverging from there. The arc starts at the small end of gap, lengthens as it rises, and finally breaks. The "Autovalve" and the "Thynite" lightning arresters are two new commercial forms of the valve type; that is, they can discharge a very large current for a short time with a very small increase in line potential and can shut off this current as soon as the line potential returns approximately to normal. Each arrester consists of three functional parts, all in series in the circuit from line to ground: (a) an air gap, set so as to spacing of terminals that it will break down and discharge a very large current when the line potential rises to a point 20-50% above normal. This initiates the discharge; (b) a set of porous blocks or disks, made up of finely divided porcelain and carbon; and (c) a quench gap whose duty is to open the circuit and shut off all current as soon as the discharge has diminished to a reasonable value and the dangerous voltage has been eliminated.

Functional part (b) is always used, but in medium-voltage applications (c) may not be used and for 600 volts neither (a) nor (c) is necessary.

14. ELECTRIC DISTRIBUTION

Principles. Three fundamental considerations determine the cross-section and weight of copper conductors for a particular purpose (see also Art 13): (a) Voltage lost in the line, or IR drop. This depends upon the line current and the resistance of outgoing and returning lines. It is important in affecting the saleability of the energy and desirability of the apparatus served. It causes considerable variation in the light given by lamps, and a variation in speed of motors. (b) Energy lost in the line due to PR, which represents an actual money loss. (c) Current density in conductors. This determines their temp rise, which, if excessive, causes danger of fire.

Usual loss in voltage allowed in distribution systems is less than in transmission; it varies from 2 to 5% of the delivered voltage. In a d-c system the proper cross-section of conductor in circular mils (Table 4) is given by: cm = (21.6D) + a, where D = distance one way, ft; I = current, amperes; a = specified loss, volts. In a a-c system the drop due to resistance of wire is usually the determining factor; resistance drop is probably negligible, as the wires are strung close to each other. Choice between a-c and d-c for distribution work depends upon character of the load apparatus and the available current. D-c motors are generally preferable, and therefore d-c distribution systems are used, unless the cost of the converting substation is too great.
Examples

Series-arc system (Fig 28). Problem: 80 arc lights, requiring 10 amperes at 50 volts each in a single series circuit. Allow 3% loss. Voltage consumed = 50 \times 80 = 4000. Let \( R \) = resistance per 1000 ft of wire. Length of wire in thousands of feet = 5 \times 0.25 = 1.25. Voltage loss = 4000 \times 0.03 = 120 = 10 \times 12.6 = 8; hence \( R = 0.455 \). From Table 4, the nearest size of wire is No 7 B & S.

![Fig 28. Series-arc Distribution](image)

Multiple system (Fig 29). Problem: two loads at 500 and 1000 feet respectively from distribution center. Each load, 10 amperes. Allowable maximum drop, 5 volts. Find size of wire.

Let \( R \) = resistance per 1000 ft of wire. Then, \( 5 = 50 \times 2 \times 0.2 + \frac{10}{2} \times 0.3 + \frac{10}{2} \times 0.5 \times R; \) hence \( R = 0.166 \). Choose No 2 B & S wire, of which \( R = 0.165 \).

Anti-parallel system. Problem: find size of wire to give a maximum drop (on middle group) of 5 volts on loads shown in Fig 30. Let \( R \) = resistance per 1000 ft of wire. Then, \( 5 = 50 \times 0.3 + 50 \times \frac{0.2}{2} + 50 \times \frac{0.3}{2} + 50 \times 0.6 \times R; \) hence \( R = 0.155 \). Choose No 2 B & S wire.

![Fig 30. Anti-parallel Distribution](image)

Tapered conductor. Problem: given 3 loads as in Fig 31, and maximum drop of 5 volts, to find sizes of wires. Assume drop proportional to distance: \( AB = 2.5, \ BC = 1.25, \ CD = 1.25 \). Then,

\[
\begin{align*}
2.5 &= 40 \times 2 \times 0.2 \times R_1; \text{ hence } R_1 = 0.156 \text{ per 1000 ft; choose No 2 wire.} \\
1.25 &= 20 \times 2 \times 0.1 \times R_5; \quad R_5 = 0.312 \quad \text{" } 1000 \quad \text{" } 5 \quad \text{" } \\
1.25 &= 10 \times 2 \times 0.1 \times R_8; \quad R_8 = 0.625 \quad \text{" } 1000 \quad \text{" } 8 \quad \text{" }
\end{align*}
\]

Feeder and main. Problem: given loads as in Fig 32, and max drop of 10 volts. Find size of wire. Assume drop to junction point = 8 volts (0.75 of total).

Feeder, \( R = 15 \times 2 \times 0.2 \times R_1; \) hence \( R_1 = 0.266; \) choose No 4 wire.

Main, \( 2 = 5 \times 2 \times 0.2 \times R_5; \quad R_5 = 1.0 \quad \text{" } 10 \quad \text{" }
\]

![Fig 32. Feeder and Main Distribution](image)

Three-wire system. Principle: at any given distance from generator the sum of outgoing currents equals sum of returning currents (Fig 33). Problem: Given 3 loads, 200 and 400 ft from generator, as shown. Neutral or middle wire to be same size as outside wires. Max drop, 5 volts. Let \( R \) be resistance per 1000 ft. \( 5 = 10 \times 0.4 \times R + 10 \times 0.2 \times R + 10 \times 0.2 \times R; \) hence \( R = 0.555 \). Choose No 7 wire.

Construction. Distribution systems may be overhead or underground. Underground systems cost about 5 times as much to install as the overhead, but less to maintain. Steel poles are used for high voltage or regular transmission systems, but wooden poles are satisfactory for ordinary distribution. Cedar, chestnut, pine, and cypress are good, costing $10 to $20 per pole, according to location. They are usually 35 to 40 ft long, have a taper of 1 in in 5 to 8 ft, are 7 to 8 in diam at top and set 5 to 8 ft in ground. Spans, from 75 to 125 ft. Poles are guyed to anchors on curves, at ends, and at every 20th pole, to take care of breaking of wires. Glass insulators on cross arms are used for moderate voltages, porcelain insulators for higher. In stringing wires, sag must be adjusted with reference to the temp; a large sag in summer, small in winter.

In cities most of the distribution is laid underground in elaborate conduits, which are expensive and unnecessary for mining work. Good results are obtained by laying a lead-covered double conductor cable in a shallow trench and covering it with earth.

Interior wiring of buildings. Defines methods, practices, and regulations covering installation of distributing circuits are based on following considerations: (a) avoidance of danger from fire or risk of shock; (b) limitation of losses of power and energy; (c) maintenance of reasonably constant voltage at the load; (d) assurance of reasonable mechanical strength; (e) compliance with local specific regulations. Standard voltages: for lighting and incidental power, 100 to 130 volts; for power and lighting on 3-wire system, 230 to 260 volts; for power alone, 550 volts. Usual allowances for drop in building wiring, 3%. Local regulations to be observed: National Electric Code, etc.
obtaining insurance on buildings; Municipal Inspection in cities; regulations of local Light and Power Co., if energy is purchased. These regulations are so elaborate that any one expecting to be responsible for an installation of wiring must be acquainted with the National Electric Codes, on which most of the other regulations are based. ALLOWABLE CURRENT-CARRYING CAPACITY OF WIRE. Voltages, Part 3 are for rubber-covered wire installed indoors. For other installations, and for exterior work, somewhat greater curit is allowed. In laying out a distribution system, a current or fuse must be inserted at every junction where size of wire changes, and there must not be more than 660 watts in lamps on any one fuse. Larger motor loads are cared for by a CIRCUIT-BREAKER.

Methods of indoor wiring. OPEN WIRING ON CEILS. Wire must be insulated with material resisting fire, and dampness and corrosive vapors, if present. Wires must be separated from each other and from any nearby surface by specified distances and the cleats may be spaced not more than 4.5 ft apart (local regulations). No 14 is the smallest allowable wire. In a dry distribution system, a Cu wire or FUSE must be inserted at every junction where size of wire changes, and there must not be more than 660 watts in lamps on any one fuse. Larger motor loads are cared for by a CIRCUIT-BREAKER.

Methods of indoor wiring. OPEN WIRING ON CEILS. Wire must be insulated with material resisting fire, and dampness and corrosive vapors, if present. Wires must be separated from each other and from any nearby surface by specified distances and the cleats may be spaced not more than 4.5 ft apart (local regulations). No 14 is the smallest allowable wire. In a dry distribution system, a Cu wire or FUSE must be inserted at every junction where size of wire changes, and there must not be more than 660 watts in lamps on any one fuse. Larger motor loads are cared for by a CIRCUIT-BREAKER.

Conduit. Best but most expensive method is to run the wires in conduits, built into the walls, floors, or framework of building. Conduit may be line or not, which has a bearing on amount of insulation required on the wires. Conduit may be rigid or flexible; the former is better and more expensive, and is often required in large cities. ARMORED CABLE, commonly known as "BX," may be used in buildings not provided with conduits, and where very reliable installation is required. Lead- armored cable is used where dampness is expected.

Metering. Charges for electric energy are based upon the kw-hr, which is the total integrated amount of energy delivered in 1 hr to a circuit in which the average power is 1 kw. Cost per kw-hr varies from 1¢ in large quantities, to 10 and 15¢ for small quantities. The ampere-hr is not an accurate measure of energy, unless the circuit voltage remains absolutely constant. See also Sec 16.

Instrument used for measuring electric energy is the watt-hr meter, sometimes called integrating wattmeter. Electric connections are similar to those for wattmeters used in measuring power. MEASUREMENT OF TOTAL POWER OR ENERGY: (a) in d-c or single phase a-c circuit, by one meter having its current coil in series with the load and its potential coil in parallel with the load; (b) in a 3-wire d-c or in a 2-phase circuit, balanced or unbalanced, by 2 meters connected as if in 2 independent single-phase circuits (total power being the sum of the 2 readings); (c) in a balanced 3-phase system, by 1 meter connected in 1 of the 3 receiving circuits (its reading being multiplied by 3) or by 1 meter connected with its current coil in 1 of the line wires and its potential coil connected from 1 line wire to the neutral (total power being obtained by multiplying the reading by 3); (d) in an unbalanced 3-phase system, balanced or unbalanced, by 2 meters, connected as in Fig 34. Total power is the sum of the 2 readings, if the power factor be greater than 0.5, or the difference of the readings if it be less than 0.5, in which case the potential leads of 1 meter must be reversed, to bring the pointer on the scale.

Watt-hour meter consists of 3 parts: (a) a small electric motor, of commutator, mercury and disk, or induction type, which runs at a speed proportional to the power; (b) a brake or governor system, usually consisting of an aluminum disk revolving in the field of permanent magnets to give a drag by eddy currents proportional to the speed; (c) a train of gears driving pointers for recording number of revolutions. While the type of motor varies with the make and purpose of the meter, the brake and recording devices are common to all. COMMUTATOR TYPE consists of a small d-c motor, the field being excited by the load current in current coil and the armature connected in potential coil carrying a current proportional to potential. It is operative on both d-c and a-c circuits, but is used only on d-c, the induction type being cheaper and better for a-c. MERCURY-VAPOR watt-hr meter contains a motor consisting of a disk of copper or aluminum floating in a well of liquid mercury. Main current is led to the mercury, but passes through the disk because of its lower resistance. This forms an elementary armature. Potential coils are on an iron core; they form the motor field and produce a torque in the armature which revolves it. Operative on both a-c and d-c circuits, but the induction type is preferable for a-c. INDUCTION TYPE watt-hr meter is similar to a 2-phase induction motor, the current coils forming 1 phase, the potential coils the other. This gives a rotating magnetic field which drives a metal disk rotor. Operates only on a-c. Cheaper than either of the other types, and more reliable and accurate. POLYPHASE WATT-HR meter contains 2 current coils and 2 potential coils, connected as 2 wattmeters would be connected; but both elements are on the same shaft and drive same set of gears, thus mechanically taking care of any positive and negative readings in either element, and giving correct total energy in one reading. Sometimes a single-phase watt-hr meter is used on a balanced 3-phase circuit (such as one containing motors only). Its current coil is connected in one phase, and its potential coil is connected between one line and a neutral obtained by connecting 3 equal high resistances in Y. Total energy is 3 times the reading.

Meter capacity. In dwellings it should be 50% of the total capacity of the connected load; in offices, 75%; for elevators, hoists, etc., 100% of the load.
Installation. Watt-hr meters must be installed on a rigid support free from vibration, and must be level. They should be at least 15 in between centers, and must not be near iron girders nor steam pipes, nor conductors carrying large currents. They must be protected from mechanical shock, weather, heat, dirt, vermin, and dampness.

Sources of error. Adjustments are provided to take care of normal friction loss. Variation in friction of brushes or bearings causes error. Mechanical shock, dirt, or dampness may alter the friction. External magnetic fields cause variation in adjustment. In induction meters variations in frequency, voltage, or load power factor may cause a slight error. Meters should be inspected and calibrated at least once a year. To calibrate a watt-hr meter, connect it to a constant known load and count revolutions of the disk per min. Note the constant K painted on the disk, and substitute in formula: watts \(= 60 \text{ rpm} \times K\).

15. ELECTRIC LIGHTING

Light distribution follows the law that the intensity is inversely as the square of the distance, providing the greatest dimension of the light source is less than 0.1 of the distance between source and object.

Definitions. Intensity of light is the relative amount of luminous energy given by any source and is measured in candles or candle power. Candle power (c p) is a measure of light intensity, determined by comparison with a well-seasoned incandescent electric lamp, that has been accurately checked with a standard lamp at the National Bureau of Standards, Washington. Illumination is measured in ft-candles. One ft-candle is intensity of illumination on a surface 1 ft distant from a source of one c p. At 2 ft distance the illumination would be 0.25 ft-candle. Light is the means; illumination, the end.

Intrinsic brilliance of a source is measured in c p per sq in. When excessive it is harmful to the eye. Intrinsic brilliancy of tungsten lamp is 1000 c p per sq in. A light source generally gives different intensities in different directions. Hence, c p means nothing unless direction is specified. Mean horizontal candle power (m h c p) is the average c p of a lamp in all directions in a horizontal plane passing through center of the source, and is usually obtained by rotating the lamp about a vertical axis. Mean spherical candle power (m s c p) is the average c p of a lamp in all directions, or the c p of a uniform source giving the same total flux of light. It is directly proportional to the total light given by the lamp, and is measured by taking intensity readings in all directions, or by placing the lamp in a hollow dull white sphere and measuring average intensity. Flux of light is measured in lumens and is the quantity emanating from a source of unit intensity (one c p) and contained in a unit-soled angle. There are 4\(\pi\) or 1256 lumens emanating from a source of unit intensity and 1256 N lumens from a source of N spherical c p. Luminous effic is expressed in lumens per watt consumed and is from 10 to 20 in modern incandescent lamps, the higher values for the larger lamps (see mfr guarantees).

In applying the laws of photometry to the calculation of a problem in illumination certain qualifications are necessary: source of light must be small compared to the distance of the object illuminated; luminous surface must be at right angles to the line of direction from the object to be illuminated; reflection and refraction must be negligible. The most useful and general application of the law is expressed by: \(I_A = (c p + H^2) \cos^2 \alpha\); where \(I_A\) = intensity of illumination in ft-candles at a given point p (Fig 35) on any horis plane; \(c p\) = intensity of light source in given direction, expressed in candles; \(H\) = height in ft of lamp above plane containing point p; \(\alpha\) = angle from vertical.

General illumination of reasonable intensity (0.5 to 1.0 ft-candles) facilitates a general view and perspective of the surroundings, while a greater intensity (1 to 5 ft-c) facilitates reading or work. In uneven illumination light comes from all directions, casting no deep shadows; extreme diffusion gives flat lighting and may be monotonous. To protect the eye some diffusion is usually desirable, for it tends to remove glaring reflection from objects in view; thus, when reading from glazed paper or working on polished metals light must not be strongly directional. In direct illumination, shadows are dark, contrasts great, and forms are clearly outlined. Details are best brought out by a light rich in the color corresponding to that of the object viewed. Direct lighting unit sends most of its light at once to the object to be lighted. Semi-indirect unit consists of a diffusing medium between the lamp and the object, which directs most of the light to the walls and ceiling, from which it is reflected. Totally indirect unit directs all light from the lamp to the walls or ceiling, from which it is reflected. While more light is lost with the indirect system it is easier on the eyes, glare is avoided, the eyes are more sensitive, and vision is improved.

Flux are generally in large units (1000 c p), are among the most efficient sources. Have high first cost and high maintenance cost, compared to incandescent lamps.
ELECTRIC LIGHTING

They operate on either d-c or a-c circuits (but are not interchangeable), and may be of series or multiple type. The d-c lamp is usually a little more efficient and more reliable than the a-c. **Series-type arcs** are in series on one circuit, supplied by a generator or transformer designed to give a constant current irrespective of the lamps in operation. **Multiple-type arcs** operate either singly or in pairs in series, on the usual constant-potential circuits with motors and incandescent lamps. Arc lamps other than the mercury and sodium-vapor type are becoming obsolete.

Mercury-vapor lamp is used on d-c multiple circuits; 110 volts with individual auxiliary starting and regulating device gives a blue green light, an effic of 15 to 20 lumens per watt and comes in units of 300 to 500 watts. Sodium-vapor lamp is a new development, particularly adapted to highway lighting. It requires considerable auxiliary apparatus, gives a yellow light and has very high effic. Operates in multiple on 125-volt a-c circuits.

Incandescent lamps are made in many forms and sizes and for many voltages and currents, for operation in multiple or series. The multiple type for 115, 120 or 125 volts, either a c or d c, is the most common. They consist of a coiled filament of fine tungsten wire, encased in an inside frosted bulb containing an inert gas, nitrogen or argon.

Rating of incandescent lamps. All multiple lamps are now rated in watts input, and in lumens rather than candle power; thus the 25-watt lamp gives 250 lumens; the 40-watt 420; 60-watt, 750; 100-watt, 1500. The useful life is from 1000 to 1200 hr; that is, at end of this time the output of light is reduced to 50% of the original value. All incandescent lamps are very sensitive to variations in impressed voltage, respecting life, as well as effic and candle power. The smaller sizes give 10-15 lumens per watt when new.

Fluorescent lamp consists of a mercury-vapor arc in a tube with fluorescent or phosphorescent coating, which gives the light a wide range of agreeable colors; it operates on a c or d c, more efficiently on a c. It is more efficient than the incandescent lamp.

Fixtures, known as luminaires, are very important. The direct type sends all the light downward, the indirect type sends the light upward and depends upon a good, reflecting ceiling. There are many intermediate types. Utilisation factor of a fixture for a room is the ratio of the useful lumens of light delivered to the working planes to the total lumens output of the lamps. It varies from 0.15 to 0.7; mean value, 0.5. The reflecting qualities of the surroundings have an important bearing. To determine the number and rating of lamps required: $F = AE + u$, where $F =$ total lumens required; $A =$ horis area to be illuminated, sq ft; $E =$ desired illumination in ft-c (Table 11); $u =$ utilisation factor for the particular surroundings. Choosing the number of units desired, based upon the uniformity of illumination required, gives the lumens per lamp.

Cost per hr of supplying a given illumination comprises cost of lamp and of energy:

$$ C = \frac{P_n + \frac{n \cdot w \cdot K}{L}}{1000} $$

where $C =$ total cost of light required, cts per hr; $P =$ price of lamps, cts per lamp; $n =$ number of lamps required obtained as above; $L =$ aver life of lamps, hr; $w =$ watts per lamp; $K =$ price of energy, cts per kw-hr.

Interior Illumination. Interiors are generally illuminated by incandescent lamps on multiple circuits, and to satisfy general illumination of even intensity a number of medium size units (60 to 250 watts) are usually preferable to one large unit. Units should be placed or shaded so as to be out of line of sight of eye. Best method of distribution is to divide the room into equal squares, having sides of 10 to 20 ft, depending upon degree of illumination desired and height of ceiling, and placing a source of light at ceiling in center of each square (not at corners). The side of each square should not exceed twice the height of the lamp above the working plane. Any local concentrated illumination may be provided by special local fixtures. Diffusing globes should be used on all lamps in line of vision, and frosted lamps in all fixtures unless completely shaded. Customary criterion for good interior lighting of factories by Mazda lamps is to supply 1 to 2 watts per sq ft of floor space; the higher value when work is exacting or walls are of dark color. This is based on an illumination of from 3.5 to 7.0 ft-candles on a plane 30 in above floor, using tungsten lamps.

**Table 11. Usual Intensities of Illumination (Ft-candles) in Plants, as Mine Plant**

<table>
<thead>
<tr>
<th>Service</th>
<th>Ft-candles</th>
<th>Service</th>
<th>Ft-candles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desk work</td>
<td>5-30</td>
<td>Steel works: Unloading yards...</td>
<td>2-5</td>
</tr>
<tr>
<td>Factory; general</td>
<td>3-5</td>
<td>Open-hearth floors...</td>
<td>4-10</td>
</tr>
<tr>
<td>Local bench, for fine work.</td>
<td>25-100</td>
<td>Blast furnaces...</td>
<td>2-5</td>
</tr>
<tr>
<td>Local bench, for coarse work.</td>
<td>6-20</td>
<td>Rolling mills...</td>
<td>4-10</td>
</tr>
<tr>
<td>Machine tools</td>
<td>10-20</td>
<td>Wire drawing...</td>
<td>3-5</td>
</tr>
<tr>
<td>Pattern shops</td>
<td>10-20</td>
<td>Threading, pipe mills...</td>
<td>2-5</td>
</tr>
<tr>
<td>Power house</td>
<td>5-30</td>
<td>Warehouse, Wharf...</td>
<td>2-5</td>
</tr>
</tbody>
</table>

**Mining lighting.** Tunnels, shaft stations, and all places of traffic, are usually lighted by 40- or 60-watt Mazda lamps, with weatherproof sockets and steel porcelain enamel reflectors. In gasous
mines. Lamps are enclosed in heavy vapor-tight glass globes protected by iron guards. 300 to 800-volt circuits are used in mines, for which voltage lamps are available. Working places may be lighted by portable storage battery lamps, carried on the cap with separate battery or in the hand with battery combined (Sec 23, Art 10). To be approved by the Bureau of Mines these lamps must be free from possibility of igniting gas, must be of light weight (not over 6 lb) and must not spill of leak electrolyte. They must illuminate a 7-ft circle, give about 0.7 c p, and are usually for 2 volts (Bureau of Mines Schedule 6).

Reflectors should be used with all lamps. Reflector for arc lamps for general lighting is an integral part of lamp, and designed to throw the light downward and outward. Reflectors for incandescent lamps may be extensive, intensive, or focusing; extensive throws the light downward, within a solid angle of about 90°; intensive in an angle of 60°, and focusing in an angle of 20° to 40°. Industrial reflectors may be made of white enameled steel, aluminum, or painted metal; for interior use, plain glass or prismatic glass. Latter uses the principle of refraction to send downward the rays that would normally pass through the glass. Reflectors and lamps must be cleaned regularly, to prevent loss of efficiency. Tungsten lamp should be cleaned while the current is on, as there is less liability of breaking the filament.

16. APPLICATIONS OF ELECTRIC TRANSMISSION TO MINE SERVICE
   (See Sec 16 for details)

17. ELECTROCHEMISTRY

Equivalent weight or chemical equivalent of any substance is its molecular weight divided by its highest valency: thus, equivalent weight of copper in CuSO₄ is 31.78, being the atomic weight of copper 63.57 divided by its valency 2. Equivalent weight of the SO₄ radical is [32.07 + (4 X 16)] + 2 = 48.03. Equivalent weight gives the relative weights of various substances deposited in electrolytic work by a given current.

Gram molecule or mol is the number of grams of a substance which are equal to its molecular weight; thus, 1 gram molecule of CuSO₄ is 159.64 gm. Gram Equivalent is the number of grams of a substance which are equal to its equivalent weight; or to its mol divided by its valency. The gram equivalent of CuSO₄ is 159.64 + 2 = 79.82.

Electrolyte. When an electric current passes through certain substances, chemical action takes place at the points where the current enters and leaves the substance. Such substances are called electrolytes and the chemical action produced is electrolysis.

Electrodes are the conductors by which the current enters and leaves the electrolyte. Anode is the electrode by which the current enters; cathode, that by which it leaves. The anode is connected to the positive terminal of the generator. Hydrogen and metal atoms of salts flow to cathode and are called cathions; oxygen, and acid and basic radicals flow towards anode and are called anions. All anions and cations are called "ions."

Electrochemical equivalent of an ion is the mass in gm of the ion which would be deposited by one coulomb (Art 1) of electricity. Electrochemical constant or Faraday (F) is the number of coulombs required to liberate one gram equivalent of any ion; value is 96,450 coulombs for all ions.

Faraday's Law. Quantity of an electrolyte decomposed by an electric current is directly proportional to total quantity of electricity which passes. Rate of decomposition is directly proportional to current. Quantity decomposed is theoretically independent of voltage, current density, size of electrodes, and concentration of electrolyte. In practice, local reactions cause deviation from this law. A given quantity of electricity always decomposes equivalent weights of different electrolytes in definite proportions for different elements. Total weights of different substances deposited by a given current in a given time are proportional to the equivalent weights of those substances. Some elements, as copper, may have different valencies in different combinations. Weight of such substances deposited is inversely proportional to the valency.

Electrochemical equivalent of a substance is the number of gm of the substance deposited by 1 ampere flowing for 1 sec. The ampere is the unit of electric current, which will deposit 0.0011118 gm silver in 1 sec. For calculating weights deposited by different currents in commercial practice it is more convenient to use the value of grams deposited by 1 ampere in 1 hr (Table 12).

The electrochemical equivalent of any ion may be calculated by dividing the gram equivalent of the ion by the Faraday. Thus, grams deposited in 1 sec by 1 ampere equals the gram equivalent of the ion + 96,450. Weight of any substance in gm deposited in 1 hr is obtained by multiplying the values given in Table 12 by the current in amperes.

Decomposition or critical voltage is the minimum potential which must be impressed to cause decomposition of a substance. With lesser potential no action takes place; with greater potential action is proportional to current. This value depends upon chemical composition of the electrolyte, and is a function of the chemical energy of the process.
Table 12. Electrochemical Equivalents of Common Elements Deposited per Ampere-hr

<table>
<thead>
<tr>
<th>Element</th>
<th>Grams</th>
<th>Element</th>
<th>Grams</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>0.337</td>
<td>Lead</td>
<td>3.865</td>
</tr>
<tr>
<td>Bromine</td>
<td>2.981</td>
<td>Magnesium</td>
<td>0.454</td>
</tr>
<tr>
<td>Calcium</td>
<td>0.7476</td>
<td>Nickel (val = 2)</td>
<td>1.993</td>
</tr>
<tr>
<td>Chlorine</td>
<td>1.322</td>
<td>Oxygen</td>
<td>0.2984</td>
</tr>
<tr>
<td>Copper (val = 1)</td>
<td>2.371</td>
<td>Platinum (val = 2)</td>
<td>3.640</td>
</tr>
<tr>
<td>(val = 2)</td>
<td>1.186</td>
<td>Silver</td>
<td>4.024</td>
</tr>
<tr>
<td>Gold (val = 1)</td>
<td>7.36</td>
<td>Sodium</td>
<td>0.8576</td>
</tr>
<tr>
<td>(val = 2)</td>
<td>2.453</td>
<td>Tin</td>
<td>1.107</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>0.0375</td>
<td>Zinc</td>
<td>1.219</td>
</tr>
<tr>
<td>Iron (val = 2)</td>
<td>1.042</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(val = 3)</td>
<td>0.6944</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 13. Decomposition Voltages of Solutions used in Metallurgical Industries

<table>
<thead>
<tr>
<th>Solution</th>
<th>Volts</th>
<th>Solution</th>
<th>Volts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acid, hydrochloric</td>
<td>1.31</td>
<td>Hydrate, potassium</td>
<td>1.67</td>
</tr>
<tr>
<td>nitric</td>
<td>1.69</td>
<td>sodium</td>
<td>1.69</td>
</tr>
<tr>
<td>oxalic</td>
<td>0.95</td>
<td>Nitrate, lead</td>
<td>1.32</td>
</tr>
<tr>
<td>perchloric</td>
<td>1.65</td>
<td>potassium</td>
<td>2.17</td>
</tr>
<tr>
<td>phoshoric</td>
<td>1.70</td>
<td>silver</td>
<td>0.70</td>
</tr>
<tr>
<td>sulphuric</td>
<td>1.67</td>
<td>sodium</td>
<td>2.15</td>
</tr>
<tr>
<td>Chloride, nickel</td>
<td>1.85</td>
<td>Sulphate, cadmium</td>
<td>2.03</td>
</tr>
<tr>
<td>Chloride, sodium</td>
<td>1.98</td>
<td>nickel</td>
<td>2.09</td>
</tr>
<tr>
<td></td>
<td></td>
<td>zinc</td>
<td>2.35</td>
</tr>
</tbody>
</table>

Values given in Tables 12 and 13 are useful in checking efficiency of electrolytic action; for, with these constants, the theoretical value of grams separated per kw-hr may be calculated and compared with the results obtained in practice. Thus, if $A$ is the value of grams deposited per ampere-hr (Table 12), and $B$ is the critical voltage for that substance (Table 13), then the theoretical grams per kw-hr is $(A + B) \times 1000$. Example. Copper is deposited from a cupric solution at the rate of 1.186 gm per ampere-hr ($A$), and requires 1.59 volts to maintain the action ($B$). Therefore the maximum possible recovery is $(1.186 \times 1000) + 1.59 = 748$ gm per kw-hr. Similarly, zinc is decomposed at rate of 1.219 gm per ampere-hr ($A$), and requires a critical voltage of 2.35 ($B$). Hence, a primary battery consumes a minimum of $(1.219 \times 1.000) + 235 = 520$ gm per kw-hr. The kw-hrs required to deposit 1 kg of material are given by the formula: kw-hr = $B + A$

18. BATTERIES, STORAGE AND PRIMARY

Lead storage battery consists of 2 lead electrodes in dilute $\text{H}_2\text{SO}_4$. The positive plate has lead peroxide supported by a grid of pure lead; the negative is lead sponge similarly supported. The chemical reaction is:

\[
PbO_2 + 2\text{H}_2\text{SO}_4 + Pb = \text{PbSO}_4 + 2\text{H}_2\text{O} + \text{PbSO}_4^-
\]

Reading from left to right gives the action of discharging; from right to left gives charging. There are 2 types, the Plante and the Faure. Plante type consists of plates of pure lead with surface area increased by roughening by webs, ribs or grooves, and formed by charging electrolytically. There are 3 forms of construction of Plante plates: central web, cast lead, and pellet. In general, Plante cells are heavier and more bulky than Faure cells, but last longer. Faure type (paste type) has active material consisting of a paste containing litharge (PbO) or red lead (Pb$_3$O$_4$) applied to all grids and dried. Plates are then formed by being charged and discharged. Faure cells are lighter and therefore preferable for vehicles. Positive plates are those from which the current flows to the load during discharge. They have a dark chocolate color when charged, with hard smooth surface. Negative plates are gray, with softer surface. The electrolyte $\text{H}_2\text{SO}_4$, diluted with distilled or pure water, should have sp gr of about 1.15 when new, but different values are used for different services. It must be free from chlorine, nitrates, copper, iron, mercury, arsenic, acetic acid, and platinum, and should be made for the particular purpose. When cell is fully charged, the sp gr is 1.21 to 1.3; when discharged, about 1.15. Open-circuit voltage is 2.
Capacity of a lead battery is stated in ampere-hr. Normal discharge current is that which the cell will give for 8 hr. Ampere-hr rating is this current multiplied by 8.

Special ratings may be stated for a 1-hr or 4-hr discharge. Rate of charge and discharge varies from 6 to 10 amperes per sq ft of plate area, not including area obtained by corrugating. Any current may be obtained from a cell by putting enough plates in multiple. Watt-hr efficiency is the ratio of output to the input necessary to bring the battery back to its original condition. It is 90 to 92% for a battery floating on the line, and 75 to 90% for a battery completely discharged before recharging. A cell is discharged until its terminal voltage while discharging has decreased to 1.8 volts, and is charged until it requires 2.5 volts to force rated current through it. If a cell is discharged so that its voltage at normal current is less than 1.75, PbSO₄ may form, making it difficult to charge again.

Care of lead storage batteries. All terminals and electric connections of a lead cell must be of lead; joints are formed by burning, or are lead covered. Instructions for care of batteries are given by makers, and should be followed carefully according to conditions and service. Electrolyte must be free from the injurious substances mentioned above, must be of definite sp gr for each condition, and must cover all plates. Cells must be cleaned before any deposit of sediment on bottom is high enough to touch the plates. Exterior of the cells must be cleaned and kept dry to prevent grounding and deterioration of terminals. Any leak must be repaired at once. Charge as soon as possible after cell has been discharged, at a current slightly in excess of the 8-hr discharge current, continuing until the negative plates give off gas steadily; then stop. In discharging, stop when terminal voltage drops to 1.8 for normal 8-hr current and 1.6 volts for the 1-hr rate. Keep temp of the battery below 105°F. Cells to be put out of commission for some time should first be fully charged, electrolyte removed and replaced by pure water. Then discharge through a very low resistance, until practically discharged (avoiding heating of cells). Electrolyte is then removed, plates washed, dried, and put away.

Edison storage battery contains positive plates consisting of perforated steel tubes heavily nickelized and filled with alternate layers of nickel hydroxide and thin flakes of pure metallic nickel. Tubes are supported by a grid of cold-rolled nickel steel. Negative plates consist of a nickel-steel grid, holding rectangular pockets filled with powdered iron oxide. All plates are insulated from each other and from steel container. Electrolyte consists of a 20% solution of potash in distilled water. Chemical reaction is:

\[
2 \text{NiO}_2 + 2 \text{KOH} + \text{Fe} = \text{Ni}_2\text{O}_3 + 2 \text{KOH} + \text{FeO} + \text{plate} - \text{plate} + \text{plate} - \text{plate}
\]

Read from left to right for discharge; from right to left for charge.

Rating. Batteries are rated at the current which they will give for 5 consecutive hr. Ampere-hr rating is this current \( \times 5 \) hr. Charging current is same as discharging, but time is about 7 hr instead of 5. Ampere-hr capacity is practically independent of rate of discharge, as battery is not injured by reasonable overload and may be discharged to 0 volts. Watt-hr efficiency is 60 to 65%. Average voltage per cell at normal rate of discharge (5 hr) is 1.2, varying from 1.45 to 1.0 volt. During charging at normal rate voltage is 1.55 to 1.55.

Operation. Steel containers must be insulated from each other, kept clean and dry, and plates kept covered with electrolyte. Charge at 75 to 85°F; discharge at 120 to 125°F. Sp gr of electrolyte should be constant at 1.2. Batteries are shipped with plates discharged, and after setting up should be charged at their normal rate for 12 hr. This overcharge should be repeated after the first 30 and 60 days, and thereafter whenever electrolyte is renewed. Battery may stand idle indefinitely if level of electrolyte is above the plates. It should be ventilated, as the hydrogen gas given off is explosive. As in case of all storage batteries the maker's instructions must be carefully followed.

Weight and cost. Lead storage batteries rated on 8-hr basis cost about $50 per kw-hr of capacity, or the cost may be $500 to $600 per kw capacity on 8-hr basis. Weight: 120 lb per kw-hr for portable style, 260 lb in glass jars, 370 lb in lead-lined tanks. Nickel storage batteries rated on 5-hr basis cost about $75, and weigh about 90 lb per kw-hr capacity. On this basis the cost per kw rating is about $400. The nickel-iron storage cell gives about 12 watt-hr per lb of gross weight per charge; portable type of lead cell, about 8 watt-hr per lb.

Primary batteries consume zinc or other metal by H₂SO₄, KOH, or similar electrolyte, and produce electrical energy. Zinc is usual for negative pole, and carbon or copper for positive. Polarity results from new chemical substances (usually hydrogen) at the poles, causing a back e m f. Depolarisers are chemical reagents used to combine these substances and prevent or reduce back e m f. There are 2 general types, wet, dry, and standard. Wet cells are being superseded by dry cells on account of their convenience. Typical wet cells are: Daniell, giving 1.07 to 1.14 volt; Gravity, 1 volt;
Bunsen, 1.9 volt; Edison-Ilanodes, 0.75 volt; LeClanche, 1.5 volt. The Daniell and Gravity are similar, and are good for continuous small currents. LeClanche cell is good for intermittent service, as its depolariser takes time to operate. It is the commonest wet battery. Dry cells are of LeClanche type, consisting of a zinc container which is also the negative pole. A carbon rod forms the positive pole, the electrolyte being sal-ammoniac and zinc chloride held in blotting paper, saw dust, or the like. Manganese peroxide is used as a depolariser. Voltage is 1.5 to 1.6. Internal resistance is 0.05 ohm new and 0.5 ohm after 10 months. The short-circuit current through an ammeter of 0.01-ohm resistance should be from 18 to 30 amperes. High temp increases the current. Potential decreases with age, due to drying out. Cells are not good after 10 to 12 months, even if not used. Their ampere-hr capacity is 24 to 30; higher on intermittent service, but capacity and life are very poor on continuous service. Life of cell depends greatly upon relative external and internal resistance, a matter requiring careful consideration. By putting 2 cells in parallel their combined life may be much more than twice the life of one alone on the circuit. Usual size of cell is 6 in high by 2.5 in diam. Cost is 10 to 40¢ each, depending upon quantity and quality purchased. (Standard Cell, see Art. 1.)

19. COSTS (as of 1938)

The war has altered all price schedules, but the 1938 data indicate relative costs and show weights of various sizes.

D-c generators are usually of the compound-wound type, and comprise 3 classes: high speed, to be belted to prime mover; moderate speed and low speed, to be direct-driven by an engine. The last class is least important. Table 14 gives costs and weights of the first 2 classes, for 125 or 250 volts. Machines to operate at lower speeds cost more. Add about 10% for installation.

<table>
<thead>
<tr>
<th>Kw</th>
<th>Speed</th>
<th>Wt, lb</th>
<th>Cost</th>
<th>Speed</th>
<th>Wt, lb</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>1 450</td>
<td>1 090</td>
<td>$ 790</td>
<td>850</td>
<td>1 825</td>
<td>$ 930</td>
</tr>
<tr>
<td>50</td>
<td>1 550</td>
<td>2 035</td>
<td>$1 250</td>
<td>700</td>
<td>3 550</td>
<td>$1 800</td>
</tr>
<tr>
<td>75</td>
<td>850</td>
<td>3 550</td>
<td>$ 757</td>
<td>575</td>
<td>4 900</td>
<td>$ 2 550</td>
</tr>
<tr>
<td>100</td>
<td>700</td>
<td>4 900</td>
<td>$ 2 250</td>
<td>575</td>
<td>6 160</td>
<td>$ 3 000</td>
</tr>
<tr>
<td>150</td>
<td>575</td>
<td>7 500</td>
<td>$ 3 100</td>
<td>500</td>
<td>7 620</td>
<td>$ 4 300</td>
</tr>
</tbody>
</table>

D-c motors. Shunt motors, usually rated at the output they will give continuously without injury to themselves, are divided into classes according to speed (small high- and moderate-speed units, Table 15). For installation, excluding freight, add 5 to 10%.

<table>
<thead>
<tr>
<th>H p</th>
<th>Speed</th>
<th>Wt, lb</th>
<th>Cost</th>
<th>Speed</th>
<th>Wt, lb</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>1 750</td>
<td>105</td>
<td>$ 60</td>
<td>1 150</td>
<td>130</td>
<td>$ 74</td>
</tr>
<tr>
<td>1</td>
<td>1 750</td>
<td>160</td>
<td>115</td>
<td>1 150</td>
<td>200</td>
<td>141</td>
</tr>
<tr>
<td>2</td>
<td>1 750</td>
<td>285</td>
<td>225</td>
<td>1 150</td>
<td>350</td>
<td>280</td>
</tr>
<tr>
<td>5</td>
<td>1 150</td>
<td>485</td>
<td>370</td>
<td>850</td>
<td>570</td>
<td>430</td>
</tr>
<tr>
<td>10</td>
<td>1 150</td>
<td>1 000</td>
<td>600</td>
<td>700</td>
<td>1 300</td>
<td>770</td>
</tr>
<tr>
<td>25</td>
<td>850</td>
<td>1 500</td>
<td>1 100</td>
<td>690</td>
<td>1 800</td>
<td>1 300</td>
</tr>
<tr>
<td>100</td>
<td>850</td>
<td>2 450</td>
<td>1 600</td>
<td>690</td>
<td>3 200</td>
<td>1 950</td>
</tr>
</tbody>
</table>

Table 16. Weight, Cost and Usual Speed of Series Motors for 230 Volts

<table>
<thead>
<tr>
<th>H. p</th>
<th>Speed</th>
<th>Wt, lb</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>725</td>
<td>790</td>
<td>$ 696</td>
</tr>
<tr>
<td>25</td>
<td>575</td>
<td>1 670</td>
<td>$ 1 042</td>
</tr>
<tr>
<td>50</td>
<td>500</td>
<td>2 970</td>
<td>$ 1 551</td>
</tr>
<tr>
<td>75</td>
<td>475</td>
<td>3 900</td>
<td>$ 2 052</td>
</tr>
<tr>
<td>100</td>
<td>460</td>
<td>5 000</td>
<td>$ 2 600</td>
</tr>
</tbody>
</table>

Series motors are usually of the “Mill Motor,” totally enclosed type, rated at the output they will give for 1 hr without injury.

Table 17 gives data on a line of slow-speed, 60-cycle, three-phase generators, for 440 to 2 200 volts. For installation and cost of exciters add about 15%.

<table>
<thead>
<tr>
<th>Kva</th>
<th>R p m</th>
<th>Wt, lb</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>450</td>
<td>4 400</td>
<td>$ 2 300</td>
</tr>
<tr>
<td>200</td>
<td>450</td>
<td>6 500</td>
<td>$ 3 400</td>
</tr>
<tr>
<td>400</td>
<td>400</td>
<td>10 000</td>
<td>$ 5 000</td>
</tr>
<tr>
<td>800</td>
<td>400</td>
<td>13 000</td>
<td>$ 7 000</td>
</tr>
</tbody>
</table>
Three-phase induction motors for 60 cycles are standard. In Table 18 costs and weights are given for a standard line having the good starting characteristics obtained by a definite wound secondary. Squirrel-cage motors are slightly less expensive. Single-phase motors cost 30% more for given output and speed. Installation is simple for most a-c motors and its cost can be taken at 4% to 8% of first cost.

<table>
<thead>
<tr>
<th>HP</th>
<th>Speed, rpm</th>
<th>Wt, lb</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1800</td>
<td>137</td>
<td>$95</td>
</tr>
<tr>
<td>2</td>
<td>1800</td>
<td>175</td>
<td>135</td>
</tr>
<tr>
<td>3</td>
<td>1800</td>
<td>280</td>
<td>210</td>
</tr>
<tr>
<td>5</td>
<td>1800</td>
<td>410</td>
<td>300</td>
</tr>
<tr>
<td>10</td>
<td>1800</td>
<td>825</td>
<td>580</td>
</tr>
<tr>
<td>25</td>
<td>1800</td>
<td>1400</td>
<td>800</td>
</tr>
<tr>
<td>50</td>
<td>1800</td>
<td>2100</td>
<td>1150</td>
</tr>
</tbody>
</table>

Costs of synchronous motors for 60 cycles, three-phase, are given in Table 19. Cost of installation and an exciter must be added, aggregating 10%.

<table>
<thead>
<tr>
<th>HP</th>
<th>Speed, rpm</th>
<th>Wt, lb</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>450</td>
<td>1465</td>
<td>$750</td>
</tr>
<tr>
<td>50</td>
<td>450</td>
<td>1625</td>
<td>900</td>
</tr>
<tr>
<td>100</td>
<td>360</td>
<td>2200</td>
<td>1200</td>
</tr>
<tr>
<td>200</td>
<td>300</td>
<td>3000</td>
<td>1700</td>
</tr>
</tbody>
</table>

Motor-generator sets, with 2 d-c machines, or 1 a-c and 1 d-c, cost about $23 per kW rated output for a 200-kw set running at 750 rpm; more for smaller sets. Flywheel sets and specially controlled sets cost more because of special features.

Table 20. Cost of Oil-cooled Transformers for 60 Cycles

<table>
<thead>
<tr>
<th>Kva</th>
<th>Voltage</th>
<th>Wt, lb</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>2400</td>
<td>170</td>
<td>$116</td>
</tr>
<tr>
<td>5</td>
<td>2400</td>
<td>225</td>
<td>144</td>
</tr>
<tr>
<td>10</td>
<td>2400</td>
<td>330</td>
<td>205</td>
</tr>
<tr>
<td>25</td>
<td>2400</td>
<td>535</td>
<td>360</td>
</tr>
<tr>
<td>50</td>
<td>2400</td>
<td>1000</td>
<td>580</td>
</tr>
<tr>
<td>100</td>
<td>2400</td>
<td>1350</td>
<td>800</td>
</tr>
</tbody>
</table>

Cost of operation of power plants varies so widely with local conditions that great detail is necessary for accurate estimates. A value of 0.5¢ per kw-hr (excluding fixed charges) is low, and is attainable only in large plants. 1¢ per kw-hr delivered to bus bars is common where load factor is reasonable, say 0.3 to 0.4, and is a figure commonly used for preliminary estimates. Load factor is the ratio of average load for some period (as 24 hr) to maximum load during that time. Duration of peak load must be specified (as 1 min or 15 min); it is usually a short period during which the machinery may carry the overload without injury. Total cost of a kw-hr, including fixed charges, is high when the load factor is low and vice versa.

BIBLIOGRAPHY

Allmand, Applied Electro-Chemistry, Longmans-Green
Annert, Electrical Machinery, McGraw-Hill
Arruda, Storage Batteries, Van Nostrand
Braymer and Roe, Rewinding Motors (4 vols), McGraw-Hill
Croft, Wiring for Light and Power, McGraw-Hill
Gandy & Schalch, D-C Motor and Generator Troubles, McGraw-Hill
James, Controllers for Electrical Motors, Van Nostrand
Morsecraft & Helms, Vol I, Continuous Currents; Vol II, Alternating Currents, John Wiley & Sons
Pender-Delmar, Electrical Engineer's Handbook, John Wiley & Sons
Rowland, Applied Electricity for Practical Men, McGraw-Hill