# *Electric Power Equipment*

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ELECTRIC POWER EQUIPMENT

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# PREFACE TO THE THIRD EDITION

Eighteen years have gone by since "Electric Power Equipment" first appeared in the list of technical books. During this period there have been many changes and developments in the power-equipment field. It has, therefore, been necessary to revise the text at frequent intervals. In order to guard against increasing its size, it has been necessary to delete some material to make room for newer developments. In some cases the treatment has been expanded in the interest of clarity. The general plan of the book has been retained, namely, a "bird's-eye view" of the power field from the point of generation to the customers' meter center.

In the last eighteen years this volume has been used primarily as a college textbook for senior classes in electrical engineering. The author is at present using the volume as a textbook for junior students in electrical engineering in a course that consists of two lecture hours per week and a two-hour period per week extending over two-thirds of the standard nine months academic year. The two-hour period is used for experimental work in the dynamo or transmission laboratories or for computational work dealing with some of the reports outlined in Appendix II. Such a course gives the junior student in college a good background that reflects exceedingly well when he reaches the more advanced theoretical senior courses dealing with the several phases of power machinery and transmission.

The author is greatly indebted to those who have used the volume and have from time to time been kind enough to offer suggestions for its improvement.

Thanks are also due manufacturers and others who have been kind enough to supply information for this revision.

J. G. TARBOUX.

ITHACA, N. Y.,
*July*, 1946.

# PREFACE TO THE FIRST EDITION

This work is designed primarily as a textbook or reference book for students in electrical engineering, who have already had a fundamental course covering electrical circuits and machinery. It is the belief of the author that students in electrical engineering should have a general knowledge of the details, operation, and application of some of the more common types of electrical power equipment which are now available.

The scope of this book is broad, starting with a brief survey of power resources, a study of prime movers, the relation of steam to water power, a discussion of loads and load graphs, then taking up such topics as generating equipment, synchronous generator excitation, power-plant circuit layouts, switching equipment, transformers, meters and measurements, switchboards, the calculation of short-circuit currents, current-limiting reactors, switches and circuit breakers, transmission lines, relays, lightning arresters, substations, distribution systems, and closing with a short chapter on the economics of electrical service.

There are a large number of good books which cover in detail most of the above topics; however, into this volume has been gathered what is thought to comprise the most essential elements of all of the above subjects, in order that the student may obtain a "bird's-eye view" of the entire field of electrical power equipment.

The author is grateful to Director P. M. Lincoln of the School of Electrical Engineering for his valuable suggestions as to the details and method of presentation of the subject and also for reading of the manuscript.

The author is also indebted to the many manufacturing and operating companies who very kindly supplied illustrations and information concerning their equipment.

J. G. TARBOUX.

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*June*, 1927.

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# ELECTRIC POWER EQUIPMENT

## CHAPTER I

## GENERAL INTRODUCTION

**1. Influence of Power on Present-day Civilization.**—It is practically impossible to estimate the actual magnitude of the part that *power*, as the term is used today, has played in the building up of present-day civilization. One can catch a general vision of the effect of power upon society by looking back over the history of the world.

Every advance in civilization has been due to some outstanding engineering invention. In the early periods of savagery man was limited to his own individual strength. Fire, the bow and arrow, pottery, domestication of animals, the manufacture of iron, the written alphabet, explosives, and the invention of printing are some of the stepping-stones to present-day civilization. The manufacture of power, or rather the transformation of potential energy to useful energy, means that we are no longer limited to human and animal strength. Power can be had where and when it is needed. Whatever the measure of a single machine, that machine can be used to make a greater one.[1]

The total electrical energy produced and distributed annually in the United States, from 1902 to 1944, is shown in Fig. 1. In the year 1944, the total production was approximately 231 billion kw.-hr., of which 67.5 per cent was produced in fuel-burning plants and 32.5 per cent in hydro-plants. The approximate regional distribution of this energy is shown in Table I. The installed generators capacity for 1944 included 15 million kw. in hydro-plants and 35 million kw. in fuel-burning plants.

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[1] Morison, George S., "The New Epoch," 1913.

**2. Historical Development of Power Systems.**[1]—Water power was utilized many centuries ago in China, Egypt, and Assyria. The first large installations of water wheels on this continent took place in 1822 on the Merrimac River, at Lowell, Mass., and later at Manchester, N. H., and Lawrence, Mass. The capacities of the plants at Manchester and Lawrence were about 10,000 hp. each. Several noteworthy water-power projects followed rapidly, some of the most important being at Cohoes, N. Y., in 1828; Lewiston, Me., in 1849; Holyoke, Mass., on the Connec-

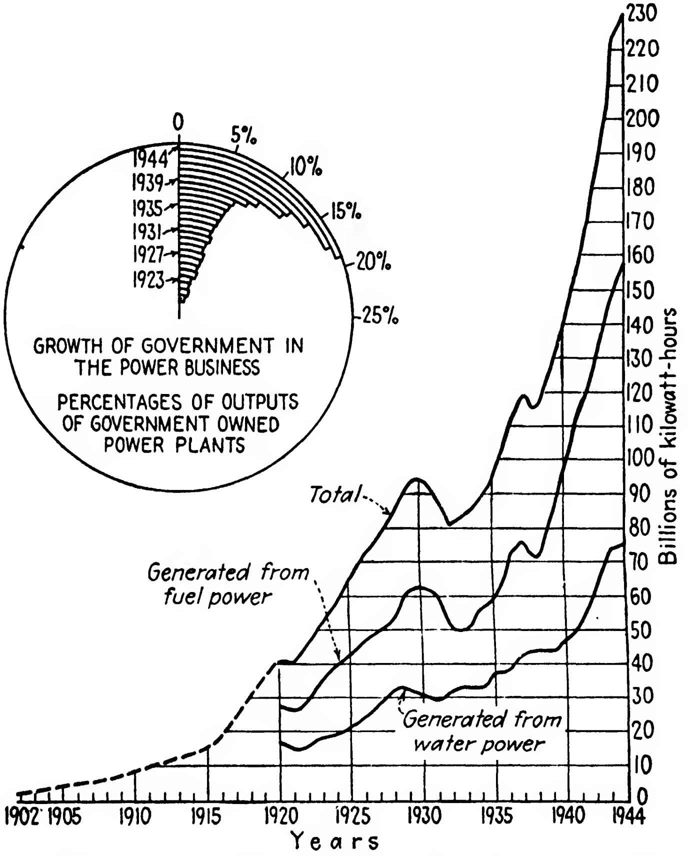

FIG. 1.—Growth of generated energy and growth of government in the power business. (*Elec. World*, Jan. 20, 1945.)

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[1] See RUSHMORE and LOF, "Hydroelectric Power Stations," and MARTIN and COLES, "The Story of Electricity."

ticut River in 1848; Rochester, N. Y., on the Genesee River in 1856; and Minneapolis, Minn., on the Mississippi River in 1857. These plants were used mainly for the manufacture of cotton goods, paper, and flour. In 1861 the development of the mighty power of Niagara Falls was begun. The original development consisted only in supplying different industries with water to drive their own water wheels, but in 1881 a central power plant was built, the energy being transmitted to the factories along the cliff by means of ropes, belts, and shafts.

TABLE I.—ESTIMATED ENERGY GENERATED IN 1944, MILLIONS OF KILOWATT-HOURS[1]

| Region | Fuel power | Water power | Total |
|---|---|---|---|
| New England | 9,359 | 3,076 | 12,435 |
| Middle Atlantic | 40,963 | 8,747 | 49,710 |
| East North Central | 50,573 | 3,142 | 53,715 |
| West North Central | 9,269 | 2,989 | 12,258 |
| South Atlantic | 20,752 | 7,553 | 28,305 |
| East South Central | 5,097 | 10,830 | 15,927 |
| West South Central | 13,202 | 1,078 | 14,280 |
| Mountain | 1,614 | 11,523 | 13,137 |
| Pacific | 5,556 | 25,589 | 31,145 |
| Total U. S. | 156,385 | 74,527 | 230,912 |

[1] *Elec. World*, Jan. 20, 1945.

Steam as a motive power became available through the invention of the steam engine by Watt in 1769.

In 1831 Michael Faraday discovered the principle of electromagnetic induction, thus laying the foundation for the electric generator and motor. Gramme was probably the first one to show that electrical energy could be transmitted from place to place. In 1873 at the Vienna Exposition, current was supplied from a Gramme generator and transmitted 550 yd. to a motor driving a pump. In 1876 Charles F. Brush developed the first commercial series system, made up of Brush series generators supplying arc lights for street lighting. This development marked the birth of commercial activity in electrical enterprises. Edison's development of the incandescent lamp in 1879 did more to stimulate the electrical industry than any other event. In the year 1882 two systems were installed, one known as the Pearl Street Station of the Edison Electric Illuminating Company of New York and the other at Appleton, Wis. The Pearl Street Station was a steam-driven plant, and the one at Appleton, Wis., was driven by a water wheel.

Up to this time the only commercial load was lighting, but about 1884 Sprague produced a commercial motor to operate on the Edison system. Meanwhile the three-wire system had been introduced, thereby allowing greater expansion of the distribution lines. The next great step forward came in 1885 with the advent of the transformer, which made possible the first alternating-current system, built at Great Barrington, Mass., by William Stanley. Following the transformer came the induction motor, which was developed by Nikola Tesla.

Alternating-current transmission originated in 1886 with a line 17 miles long supplying Rome, Italy. In 1887 the capacity of the plant supplying this line was 2,700 hp. The first three-phase line was put into operation in 1891 between Lauffen and Frankfort, a distance of 112 miles. The voltage used was 12,000 volts. Alternating-current transmission in the United States started in 1889 at Oregon City. Power was generated by two 300-hp. Victor wheels belted to 4,000-volt single-phase generators and transmitted a distance of 13 miles to Portland. Following this development came that of the Telluride Power Company in Colorado. In this case two 150-kw. single-phase generators direct-connected to Pelton water wheels operating under a head of 500 ft. supplied power at 3,000 volts to the city of Telluride over a line 5 miles long. The first three-phase line in the United States was installed in 1893 in California by the Redlands Electric Light and Power Company (now the Southern California Edison Company).

Up to this time the most common frequency was 133 cycles per sec., but in 1891 the advisability of a standard frequency was realized and 60 cycles per sec. was established as one standard. Later, in 1893, 25 cycles was introduced, and today these two are considered as the standard for this country.

In 1895 the first 5,000-hp. generators, which were then the largest ever built, were installed at Niagara Falls. From that date on, the growth of the electrical industry has steadily progressed. In 1896, 25,000-volt transmission was used by the Pioneer Electric Power Company of Utah. In 1903, 60,000 volts was used by the Guanajuato Power and Electric Company of

Mexico for its system. The first company to use 110,000-volt transmission was the Au Sable Electric Company of Grand Rapids, Mich. In 1913 the Pacific Light and Power Company installed their first 150,000-volt transmission line, which has since been raised to 220,000 volts.

The highest voltage used in the United States for power transmission is 275,000 volts, which is used on the Boulder Dam–Los Angeles line. This line was put into operation in 1936.

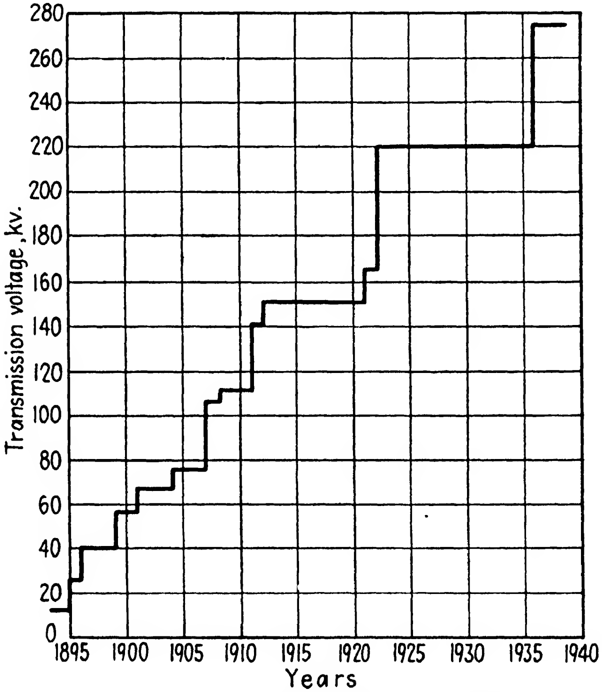

FIG. 2.—Commercial transmission line voltages.

Figure 2[1] shows the rate at which the voltages used for transmission lines have increased from 1894 to 1940.

Up to 1903 all the steam power was obtained from steam engines, which had developed to very large sizes and very efficient performances, but they had reached a limit; hence the steam turbine was produced. The first all-steam turbine plant was put into operation about this time.

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[1] Originally published by RUSHMORE and LOF, "Hydroelectric Power Stations."

In 1920 the Niagara Falls Power Company installed the first 32,500-kva. generators; in 1921 the Hydroelectric Power Commission of Ontario began operation of a 45,000-kva. unit; and in 1923 the Niagara Falls Power Company installed the first 65,000-kva. water-wheel generator.

**3. Trend of Modern Practice.**—The real function of a power engineer is to deliver power on the station busbars at the lowest possible cost per kilowatt-hour and still maintain a high grade of service without interruptions; hence it is in the analysis of the elements that go to make up the cost per kilowatt-hour that the real answer is found as to the most profitable trend for future power-station development. The total cost of each kilowatt-hour delivered on the station busbars is made up of the following four items:

1. Operating labor and superintendence.
2. Maintenance.
3. Fuel cost.
4. Fixed charges.

In the case of steam plants the two highest items are fixed charges and fuel costs. Fixed charges cannot be decreased very much; hence the main problem of the steam-plant engineer is to decrease the fuel costs by the adoption of more efficient methods.

The tendencies in the design of steam generating stations may be classified under the following four heads:

1. Tendencies that improve the reliability of the power station, increase its cost, but do not appreciably affect the operating efficiency; for example:

   *a.* The use of house turbines, auxiliary generators, and storage batteries for ensuring the auxiliary power supply.
   *b.* Isolated-phase layout and the use of reactors and other protective devices in the switch house.
   *c.* The duplication of auxiliaries and provision of excessive amounts of spare capacity in boilers and turbines.

2. Tendencies that decrease the coal consumption per kilowatt-hour and increase the cost of the power station; for example:

   *a.* The use of higher steam pressures (900 lb. per sq. in. or higher) taken together with steam reheating durings its expansion.

*b.* The use of pulverized-fuel-burning equipment.
*c.* The use of adjustable-speed motors for driving auxiliaries where saving in power consumption at light loads is the consideration.
*d.* The use of air heaters or economizers usually falls in this classification.
*e.* The use of an excessively large amount of surface in the surface condensers for the main turbines.

3. Tendencies that decrease the coal consumption per kilowatt-hour and also result in a reduction in the cost of the power station and perhaps in the cost of operating labor; for example:

*a.* The use of electrically driven auxiliaries.
*b.* The use of moderately high steam pressures without reheating.
*c.* The use of the highest steam temperatures that are possible with existing materials.
*d.* The use of large turbines and large boilers.
*e.* The use of three- or four-stage bleeding for raising the temperature of feed water.
*f.* The use of large mills for pulverizing coal.

4. Tendencies that add to the cost of the station without either improving its reliability or appreciably decreasing its coal consumption; for example.

*a.* Insufficient care given to grouping of equipment and waste space in power-station building.
*b.* Too many architectural frills.

That economy of fuel has been obtained is shown by Fig. 3. A further increase of economy has been obtained with the mercury-vapor steam cycle. There are at least three major possibilities immediately ahead. These are as follows:

1. The further development of commercial equipment for use in the application of the mercury-vapor steam cycle.

2. The development of superheaters, high-pressure steam piping, valves, and turbines for operation in connection with steam temperatures of 900°F. or higher.

3. The use of hydrogen or some equally suitable gas as the cooling medium in connection with closed ventilating systems for

turbogenerators, and the development of new generator designs that will take advantage of all the possibilities of this new cooling medium.

In hydroelectric power plants fixed charges make up the most important item in the final cost of energy; hence the main

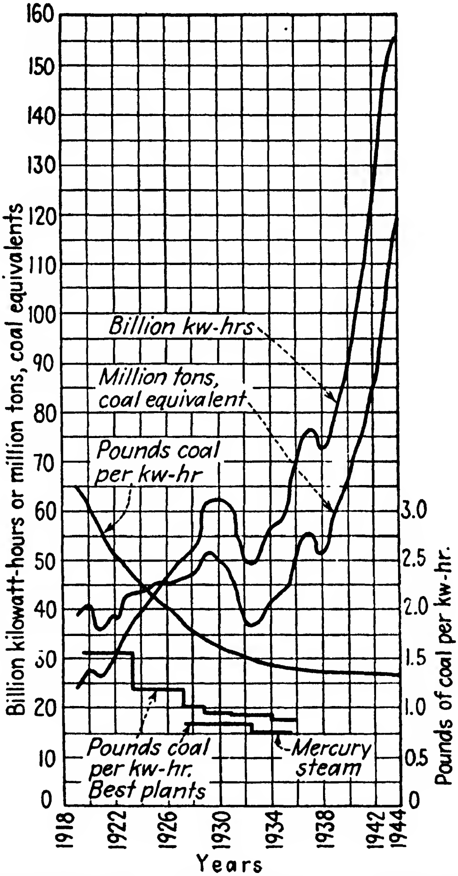

FIG. 3.—Trend in fuel economy. (*Elec. World*, Jan. 13, 1940, Jan. 24, 1942, and Jan. 20, 1945.)

objective of the designer is not higher efficiency but lower cost per unit of installed capacity. In order to obtain this lower cost per unit of capacity, the sizes of water-wheel units have been steadily increasing. There are probably five factors that will limit the size of units, namely:

1. Shipping facilities.
2. Material size limits.
3. Economical generator speeds.
4. Manufacturing limits.
5. Strength and life of parts.

The maximum size of water-wheel turbines for different heads is given by Fig. 4. The values of this curve are based on past experiences in the operation of water wheels. The maximum size of units for different speeds is given in Table II.

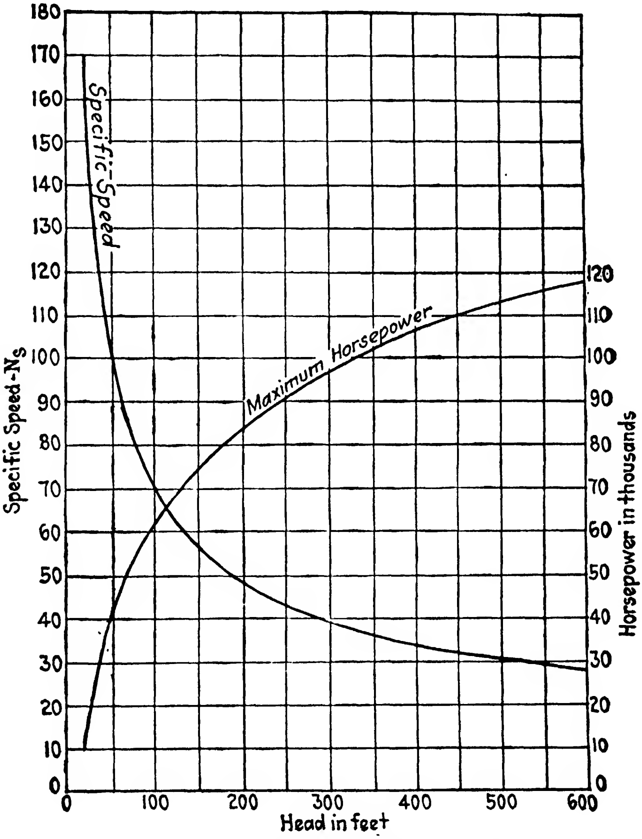

Fig. 4.—Curves showing specific speed and maximum capacity for water-wheel turbines designed for different operating heads.

It is interesting to note that theoretically it is possible to build a 130,000-kva. unit at 100 r.p.m., but the physical size of such a unit would make its cost excessive; hence the economical limit for 100 r.p.m. appears to be 75,000 kva.

TABLE II.—ECONOMICAL LIMITS OF VERTICAL WATER WHEELS

| Kilovolt-amperes | Revolutions per Minute |
|---|---|
| 10,000 | 720 |
| 20,000 | 600 |
| 30,000 | 514 |
| 55,000 | 400 |
| 80,000 | 300 |
| 110,000 | 200 |
| 75,000 | 100 |

The best answer to the power situation of this country is obtained by a proper use of both steam and hydroelectric plants. Such a system can be made to give the most economical output and also maximum reliability.

**4. Conservation of Natural Fuel Resources.**—The best performance of steam plants had by 1930 dropped to slightly less than 1 lb. of coal per kilowatt-hour. The water-power generation for 1944 amounted to 74,500,000,000 kw.-hr. At the fuel rate of the best plants, the above hydro-energy corresponds to a saving of 37,200,000 tons of coal per year.

As has been pointed out, the development of a hydroelectric power plant is generally a great deal more costly than the original investment for a steam power plant of the same capacity. Furthermore, it must be remembered that the 15,000,000 kw. of water power that has already been developed comprises those sites which could be most economically developed. Further expansion of water power plants must be made at localities not so suitable for development; hence the initial investment for future developments will probably increase as it becomes necessary to develop the less desirable water powers. On the other hand, the economy of steam power plants is increasing steadily. Better conservation of natural resources is being accomplished by using high-voltage interconnected transmission networks into which is fed the generator outputs of economical steam plants and efficient hydro-stations. Transmission networks span large areas including many states, so that energy can be relayed from state to state with considerable ease. Thus it is possible to obtain maximum use of existing hydro capacity with a minimum of fuel energy.

## Questions for Class Discussion

**1.** How has power influenced present-day civilization? Discuss briefly.

**2.** Name the two most important scientific discoveries that laid the foundation for the electrical engineer.

**3.** What were the first two central stations of the United States? How were they operated?

**4.** Name four factors that go to make up the total cost of each kilowatt-hour of electrical energy delivered to the station busbars. Which of these factors are most important in the case of (*a*) steam power plants, and (*b*) hydro-power plants?

**5.** Name a few tendencies that improve the reliability of the steam power station but do not appreciably affect the operating efficiency.

**6.** Name a few tendencies that decrease the coal consumption per kilowatt-hour of steam stations and increase the cost of the power station.

**7.** Name a few tendencies that decrease the coal consumption per kilowatt-hour of steam stations and also result in a reduction in the cost of the station.

**8.** Name a few tendencies that add to the cost of a station without either improving its reliability or decreasing its fuel consumption.

**9.** Name three possible methods by which better economy can be obtained in a steam plant.

**10.** Name a few factors that determine the maximum size of water-wheel units.

**11.** Discuss some of the future possibilities of electric power developments.

# CHAPTER II

## TYPES OF POWER PLANTS

**5. Different Types of Prime Movers.**—The most important types of prime movers that are suitable for the generation of electricity can be classified as follows:

| | |
|---|---|
| *a.* Steam | Reciprocating engines<br>Turbines |
| *b.* Hydraulic | Impulse wheel<br>Reaction wheel<br>Propeller wheel |
| *c.* Internal combustion | Oil, diesel<br>Gas |

*a. Steam Drive.*—The reciprocating engine is rapidly disappearing from use in power plants, not so much on account of its lower economy as on account of the large floor space required, high first cost, the necessity of very large foundations, and limitations in manufacture. For power-plant service the steam turbine has entirely replaced the reciprocating engine even in the very small sizes as used for power-plant auxiliaries. The principal advantages of the steam turbine are as follows: (1) low first cost, (2) low maintenance and attendance, (3) economy of space and foundation, (4) absence of oil in condensed steam, (5) freedom from vibration, (6) uniform angular velocity, and (7) high efficiencies for large variation in load.

As a direct contrast to the reciprocating engine, turbines of 70,000 kw. in a single unit are no longer uncommon, while triple units of 235,000 kw. have been built, and designers have been thinking of units of much greater capacity. As the turbine requires no internal lubrication, oil does not come in contact with the steam, and the condensed steam from the condensers is available for boiler-feeding purposes without purification. The possibility of reusing the condensed steam effects a great saving in cost of feed-water equipment and in the expense for maintenance and cleaning of boilers. The speed regulation of turbines is exceedingly good as compared with the speed regulation of any type of piston engine, particularly large slow-speed units. The efficiency of the turbine is higher for a greater range of loads than that obtained by the best piston engines. A typical steam-turbine installation is shown in Fig. 5.

*b. Hydraulic Drive.*—There are three standard types of water-wheel runners that are applicable to conditions found in practice:

1. The impulse wheel (Figs. 6 and 7).
2. The reaction wheel (Figs. 8 and 9).

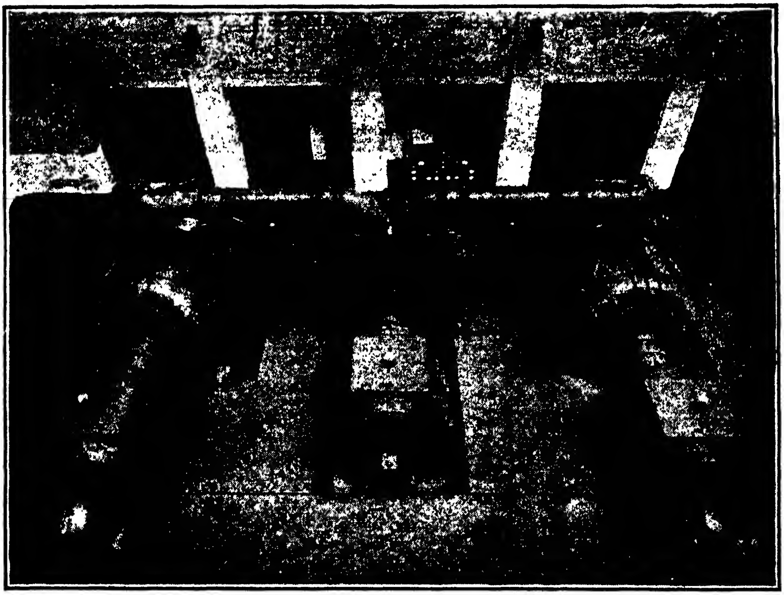

Fig. 5.—General view of 60,000-kw. unit of the Colfax Station of the Duquesne Light Company. The central or high-pressure element receives steam from the boilers at 265-lb. pressure and exhausts it into the branched overhead pipe through which it passes at about 55 lb. to the two outside low-pressure elements. A butterfly valve in each branch of this pipe permits this steam passage to be closed. Each element is of 20,000 kw., the center element operating at 1,800 r.p.m. while the two outside elements operate at 1,200 r.p.m. The frequency of the set is 60 cycles per second. (*Westinghouse Electric Corporation.*)

3. The propeller and adjustable-blade-type wheel. (Fig. 10.)

The impulse wheel is suitable for very high heads. The reaction wheel has a much wider limit, being applicable to a large class of developments generally spoken of as medium-head developments. The last class of runner, which has been introduced in the last few years, is the propeller type. As a general rule its efficiencies are a little below those of the reaction wheel. This wheel has been developed to fill the demands of very low-head developments.

From these three classes there are available water turbines that will answer the requirements of the highest to the lowest heads developed. In some cases particular conditions may be such that it is not easy to decide which of two types to use, as for example, there is no exact dividing line between the reaction and the propeller type that would indicate that all developments above a certain value of head must use the reaction wheel, or that developments below such value of head must use the propeller type of wheel.

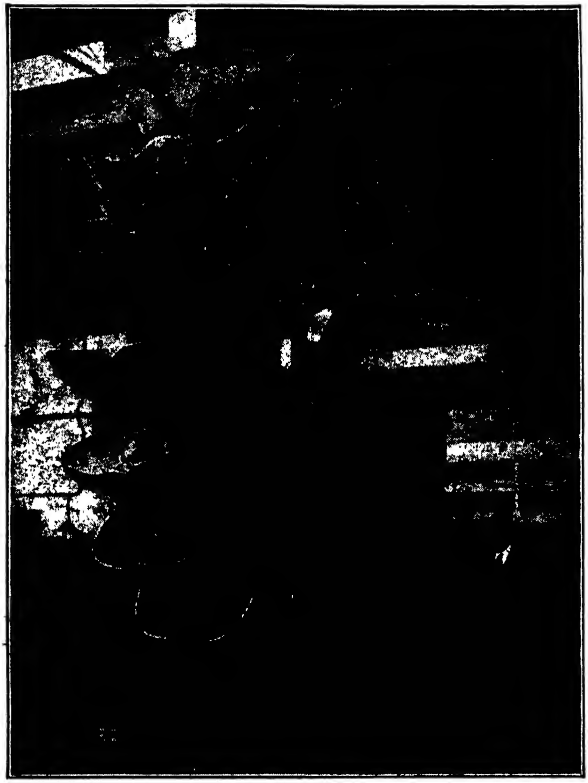

Fig. 6.—Bucket wheel for 30,000-hp. units, built for Great Western Power Company's Caribou Plant, California. Weight of assembled wheel 25 tons. (*Allis-Chalmers Manufacturing Company.*)

An empirical equation that may be used to determine the proper specific speed for best operation for a given head is as follows:

$$N_s = \frac{5{,}050}{H + 32} + 19 \qquad (1)$$

where

$N_s$ = specific speed
$H$ = head in feet on turbine

Specific speed is that speed which a given wheel will attain when reduced homologously to such a size that it will develop 1 hp. under 1-ft. head at its best efficiency.

FIG. 7.—Needle regulating nozzles for 30,000-hp. impulse-turbine units. Built for Great Western Power Company's Caribou Plant, California. (*Allis-Chalmers Manufacturing Company.*)

This equation[1] was obtained from a curve plotted between specific speeds and head for practically all the noted plants in the United States, discarding those plants which had any trouble due to pitting of the runners or any other unsatisfactory operation that was in any way dependent on the specific speed. In Fig. 4 is shown such a curve, the values of specific speed being

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[1] See WHITE, W. M., Advances in the Art of Water-wheel Design and Settings, *Trans. A.I.E.E.*, 1921.

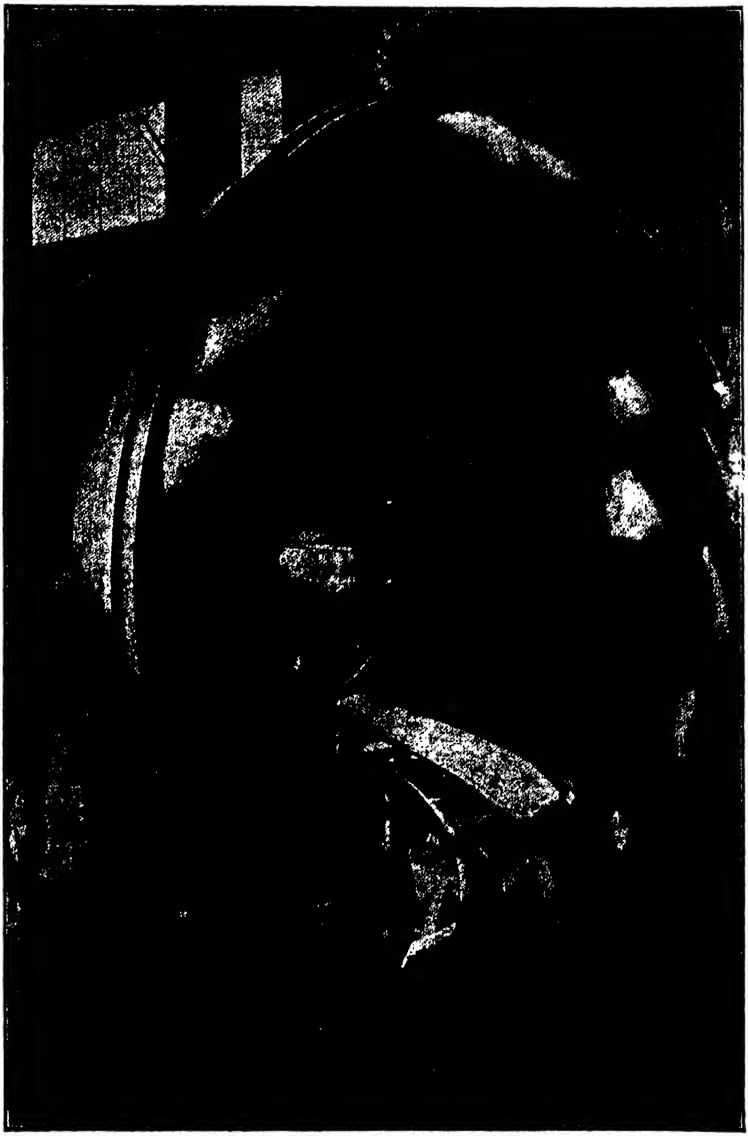

FIG. 8.—A 30,000-hp. reaction water wheel. This finished casting weighs 95,000 lb. (*Allis-Chalmers Manufacturing Company.*)

slightly higher than those obtained from the above equation, particularly for the lower values of head. The best operating speed of such a unit can then be determined from the following relation:

$$\text{r.p.m.} = \frac{N_s H^{5/4}}{\sqrt{\text{hp.}}} \qquad (2)$$

FIG. 9.—Shop assembly of a 40,000-hp., 257-r.p.m., 421.5-ft. head, single-runner, vertical-shaft, cast-steel spiral-cased turbine. The first of two built for the Pacific Gas and Electric Company Plant No. 1, Pit River Development, Mt. Shasta Power Corporation, California. Integral governor shown mounted on top of regulating cylinders. (*Allis-Chalmers Manufacturing Company.*)

A few typical hydraulic turbine installations in the United States are as follows:

1. High-head impulse type.
   Big Creek—70,000 hp. at 2,200-ft. head., 250 r.p.m., pitch diameter 162 in.
2. Medium-head reaction type.
   Boulder Dam—115,000 hp. at 475 ft. head, 180 r.p.m., inlet diameter, discharge diameter 132 in. Norris—66,000 hp. at 165-ft. head, 112.5 r.p.m., inlet diameter 161 in., discharge diameter 165.5 in.

3. Low-head propeller types:
   - *a*. Adjustable-blade type: Bonneville—66,000 hp. at 50-ft. head, 75 r.p.m., diameter 280 in.
   - *b*. Fixed-blade type: Wheeler—45,000 hp. at 48-ft. head, 818 r.p.m., diameter 264 in.

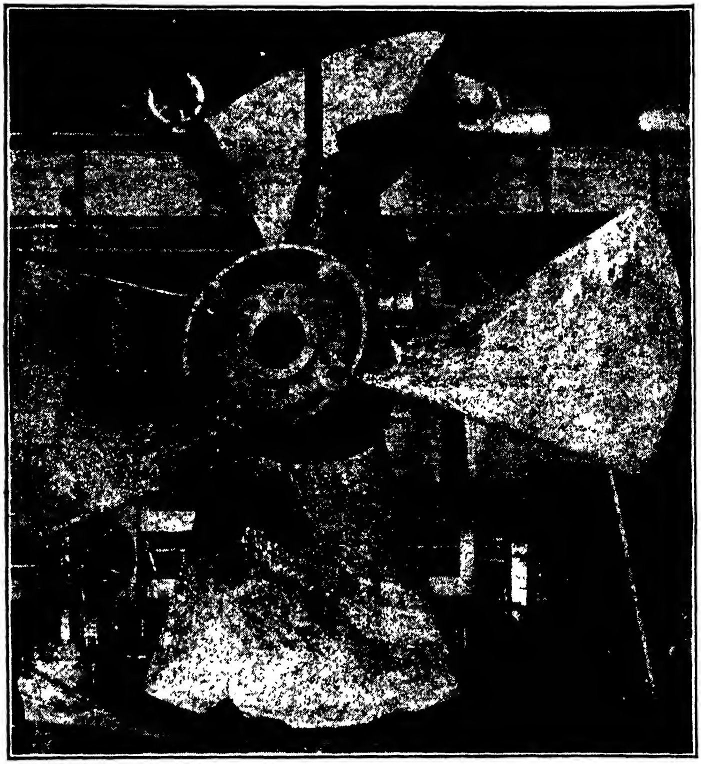

FIG. 10.—A 156-in. diameter, 2,000-hp., four-blade, cast-steel, Nagler high-speed runners. Weight 17,000 lb. each, head 13 ft., speed 80 r.p.m. (*Allis-Chalmers Manufacturing Company.*)

The interior of a typical high-head plant is shown in Fig. 11. The sectional view of a combined generator and water-wheel unit is shown in Fig. 12.

Typical medium- and low-head hydraulic developments are shown in Figs. 13 to 15.

*c. Internal-combustion-engine Drive.*—This class of prime movers includes the diesel engine and the gas engine. The diesel engine is adaptable to rather small power plants, particularly those which have a very low load factor. A considerable expense is involved in a steam plant when under no load, on account of the fact that steam must be kept circulating through turbines and other equipment. A diesel engine, on the other hand, can be started up cold and loaded to its full capacity without any appreciable drop in efficiency. They are used to a considerable extent in sections of the country where oil can be obtained readily and cheaply. In the case of small plants the maintenance and operating costs are very low, lower than those obtained with a steam plant.

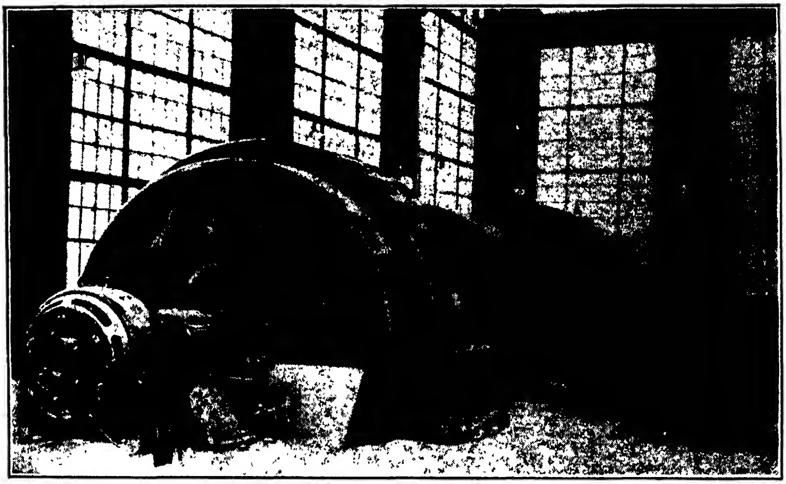

FIG. 11.—Interior view of El Dorado power house, Western States Gas and Electric Company, containing two Allis-Chalmers 14,000-hp., 1,750-ft. hydraulic, 300-r.p.m. single overhung impulse wheels. (*Allis-Chalmers Manufacturing Company.*)

The use of gas engines is limited to power plants supplying those industries which obtain gas as a by-product. In this country there are a few of such installations at large steel mills, in which cases the gas is obtained from smelting furnaces.

**6. Hydro versus Steam Power Plants.**—When it becomes necessary to build a new power plant to meet the power demands of a large system or community, the engineer is often confronted with the question as to whether a hydroelectric or steam-electric plant would best fulfill the requirements. It is important, therefore, to investigate some of the factors involved. Invariably conditions are such that a steam plant can be built very near to the load center, while a hydro-plant must be built at a considerable distance away; hence high-voltage transmission lines must be used to connect the hydro-plant to the load center. The most important factors that should be considered are as follows: (*a*) cost of energy at the load center, (*b*) continuity of service, and (*c*) reliability of service.

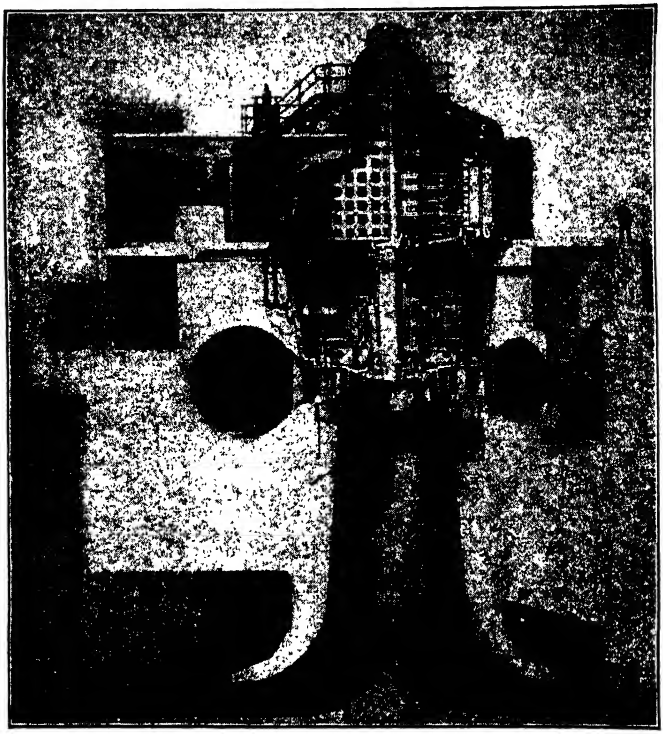

FIG. 12.—Combined hydroelectric unit designed and built by the Allis-Chalmers Manufacturing Company for the Niagara Falls Power Company. Rated 70,000 hp., 213-ft. head, 65,000 kva., 12,000 volts, 25 cycles, 107 r.p.m., rotating weight over 700,000 lb. (*Allis-Chalmers Manufacturing Company.*)

*a. Cost of Energy at the Load Center.*—The cost of energy per kilowatt-hour delivered at the load center is determined always by the sum of the fixed charges on the initial investment plus fuel cost, maintenance cost, operating labor, and superintendence costs. As has already been pointed out in Art. 3, fixed charges are higher in the case of the average hydroelectric plant than in the case of a steam plant. On the other hand, the other elements entering into the final cost of energy are generally less in the case of the hydroelectric plant than in the case of the steam plant. To the costs of energy involved in the hydroelectric plant must be added the cost involved in the transmission line, which is made up of the following items:

1. Fixed charges.
2. Maintenance.
3. Cost of energy loss in line.
4. Operating labor and superintendence.

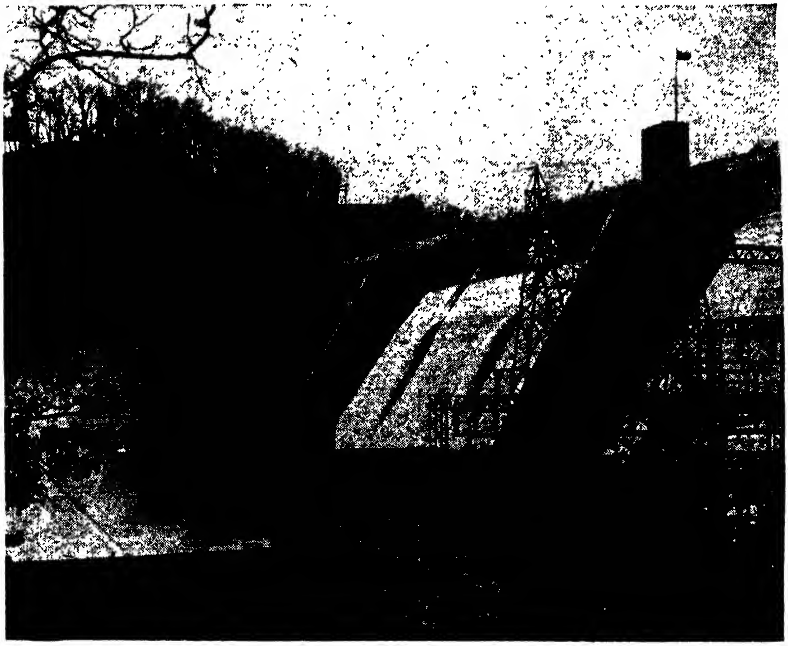

FIG. 13.—Norris Dam of the Tennessee Valley Authority. Dam is 265 ft. high, 1,860 ft. long. Reservoir area is 40,200 acres with useful storage of 2,020,000 acre-feet. Power house is of conventional type. (*Tennessee Valley Authority.*)

An extensive study of the cost of transmitting electrical energy over long transmission lines has been made by many engineers. A transmission line can be considered economical if the costs of transmission are less than the cost of shipping fuel of the same equivalent capacity a distance equal to the length of the transmission line. In other words, if the cost of energy (fuel costs of steam plant not included) at the station busbars is the same for the hydroelectric and steam-electric plants, the most economical project will be determined by the relative cost of transmitting the required energy, whether electrically over a transmission line, or as fuel shipped by railroad.

*b. Continuity of Service.*—In any system, continuity of service is of paramount importance, as any interruption of service means a financial loss to both the operating company and the customer. The larger a network, the greater is the chance for trouble to develop; hence the transmission line necessary with a hydroelectric project must be very carefully designed to minimize the possible number of interruptions. In the case of a steam plant, ample storage space for fuel must be provided in order that there may be no interruption of service due to lack of fuel which might be caused by delayed shipment or other unavoidable causes.

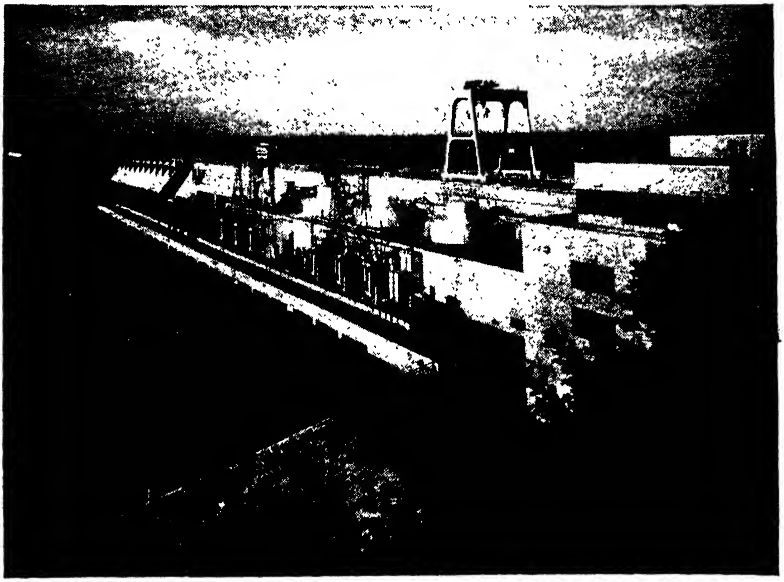

FIG. 14.—Wheeler Dam of the Tennessee Valley Authority. Example of outdoor type of power house. Dam is 72 ft. high and 6,342 ft. long. (*Tennessee Valley Authority.*)

*c. Reliability of Service.*—It is essential to the proper operation of a system that the voltage variation at the load centers be kept down to a minimum value. It is readily recognized that the farther away a power plant is located from the load center, the more precautions must be taken to maintain constant voltage over the system. In the case of the hydroelectric plant and long transmission line, it is often necessary to install synchronous condenser equipment in order that constant voltage may be maintained. Such installations increase the cost of energy delivered to the consumer.✓

There is a general impression in the mind of the public that electricity generated and distributed from a hydroelectric plant should be sold for very much less than electricity obtained from steam plants, but it must be remembered that, even though in some cases power can be generated more cheaply in hydroelectric plants, the generation expense is a very small portion of the total cost involved in delivering energy to the customer.

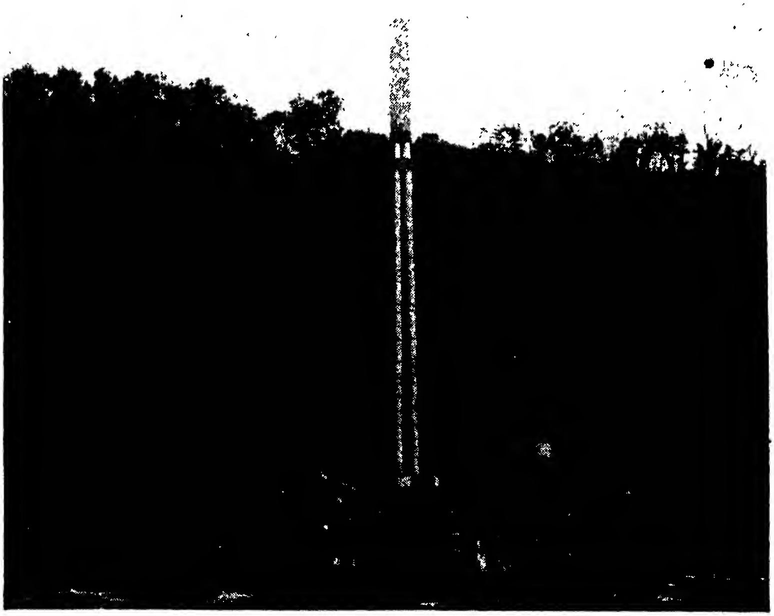

Fig. 15.—Santeetlah power house of the Carolina Aluminum Company. Plant capacity, 50,000 kva. Two 450-r.p.m. units. Total hydraulic head, 660 ft. (*Carolina Aluminum Company.*)

✓ **7. Size and Number of Units.**—The proper choice of the number and size of each unit for a power plant requires considerable study. The most important factors having to do with the proper choice of units are classified as follows:

1. Steam-electric power plants:
    - *a.* Nature of the system.
    - *b.* Nature of the load.
    - *c.* Location of plant.
    - *d.* Capacity of plant.
    - *e.* Economy and efficiency.
    - *f.* Cost of energy.
    - *g.* Available sizes.
    - *h.* Control equipment.
2. Hydroelectric power plants:
    - *a.* Nature of the system.
    - *b.* Nature of the load.
    - *c.* Topography of site.
    - *d.* Geology of site.
    - *e.* Available sizes.
    - *f.* Possible sizes of headworks and conduits.
    - *g.* Cost of energy.
    - *h.* Control equipment.
    - *i.* Capacity of plant.

The conditions involved in determining the minimum cost per kilowatt-hour may be summarized as follows:

1. To deliver a given peak load, the total installed capacity of a plant increases as the number of units is decreased, if a reserve unit is provided in each case.

2. For a given installed capacity of plant the fixed charges increase with the increase of number of units.

3. For a given installed capacity of plant the maintenance charges increase with an increase of number of units.

4. As a general rule large units have better efficiency than small units.

5. For a given total capacity of stand-by equipment, the stand-by losses increase with the number of units, particularly in a steam plant.

6. For a given installed capacity of plant the operating costs increase with an increase of number of units.

7. The total cost per kilowatt-hour decreases as the load factor (ratio of average power to maximum demand) of the load increases.

As a system expands, the maximum capacity that can be obtained out of one plant is soon reached, and power plants are then built at other advantageous points in the system. In a large interconnected network it is more economical to use the more efficient plants on the constant base load of the system, and use the older and less efficient plants to take care of the variable peaks of the load. It is also evident that it is more economical to use a few large units for such base-load plants, instead of a large number of small units. As the number of plants in a system increases, the necessity of a reserve unit in each plant becomes less pronounced, because the load normally delivered by any damaged or idle unit can be absorbed by the plants of the system without overloading any one generator very much.

Very often the location of a plant becomes the controlling factor in the choice of units; as for example, contrast a steam plant built in a congested city district with a steam plant several miles from the nearest city. It is evident that for a given capacity of plant the floor space required is generally less for a few large-capacity units than for a large number of small-capacity units. In many cases units of very large capacities have been used, and larger ones would have been installed if the manufacturers had been able to build them. Shipping conditions often limit the possible size of equipment. The problem of controlling some of the large units of present-day power plants is one requiring every precaution. The amount of money invested in each unit is so great that very complex control systems must be used to provide protection against every possible trouble. Auxiliary equipment, such as oil circuit breakers, must be capable of controlling such large units; hence the size of generators or other apparatus must not be larger than the capacity of the control system.

In the case of hydroelectric plants local conditions of topography or geology may dictate the number and size of units which are best suited. Further, hydraulic demands are of greatest importance in the case of hydroelectric plants. The size of headworks, conduits, valves, and turbine settings may be the determining factors.

**8. Location of Power Plants.**—No general rule can be given by which the best location of a plant can be determined; each particular project must be analyzed carefully on its own merits and considered in the light of its particular demands. A few more or less self-evident factors that must always be considered in determining the proper location of any plant are tabulated below:

1. Steam-electric power plants:
    *a.* Accessibility.
    *b.* Coal and ash handling.
    *c.* Water supply.
    *d.* Stability of foundations.
    *e.* Facility of extensions.
    *f.* Cost of real estate.
    *g.* Restrictions due to surroundings.
2. Hydroelectric power plants·
    *a.* Water privileges.
    *b.* Required fall.
    *c.* Water supply.
    *d.* Stability of foundations.
    *e.* Facility of extensions.
    *f.* Accessibility.

**9. Steam Power and Its Relation to Water Power.**—In Fig. 16 is shown a typical load curve of a system. In times of maximum river flow it is best to carry the base load on the hydraulic plants as illustrated and thereby effect a saving in fuel cost in the steam plants that will carry only the peaks of the load. For the sake of analysis it is assumed that during normal river flow the basic 50 per cent of the maximum load is carried by the hydraulic plants and the peaks by the steam plants.

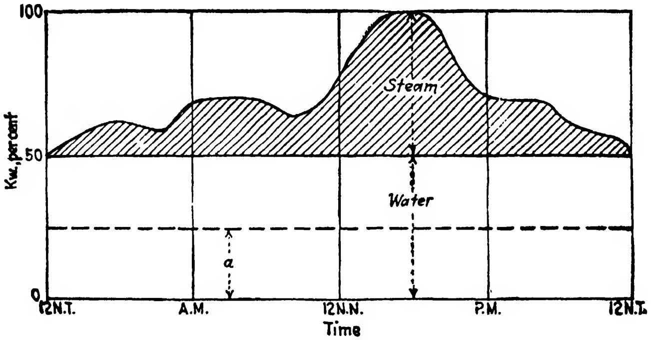

Fig. 16.—Steam power and its relation to water power.

In times of low water let it be assumed that only 25 per cent of the peak load can be carried by the hydraulic plants continually. It is therefore evident that if the hydraulic plants carry the base load as before, there must be provided an additional 25 per cent steam-plant capacity in order that the peak load may be carried. On the other hand, if the steam plants are placed on the base load and carry 50 per cent of the maximum demand continually, it is perfectly possible for the hydraulic plants to carry the peaks, provided the total daily energy as indicated by the shaded portion of the load curve of Fig. 16 does not exceed the energy corresponding to 25 per cent of the maximum demand carried continually. For the most economical operation of the system, therefore, it is essential that the hydraulic plants carry the base load during high-water periods and that the steam plants carry the base load during low-water periods.

### Questions for Class Discussion

**1.** Give a complete classification of prime movers as used for the generation of electrical power.

**2.** Why has the steam turbine practically replaced the reciprocating steam engine for central-station use?

**3.** Give a few noteworthy installations of steam turbines.

**4.** Name three types of water turbines, and state the field of application of each type.

**5.** What is the meaning of the term "specific speed" as referred to water turbines?

**6.** What demand does the internal-combustion plant fulfill? Explain briefly.

**7.** A community requires electrical power. Either a steam or hydroelectric station can be built. What factors must be considered in making a choice?

**8.** Name some of the factors that must be considered when determining the number and size of units for a particular plant. Consider particularly a steam and a hydroelectric plant.

**9.** What consideration would effect the choice of prime movers, for example, a unit of high first cost and good fuel economy, *versus* a cheap or second-hand machine operating at low efficiency?

**10.** What factors influence the choice of location of a power plant (*a*) for a steam plant and (*b*) for a hydraulic plant?

**11.** Compare the performance of steam-electric and diesel-electric plants with respect to operating and fuel economies. How do gas- and oil-fired boiler stations compare with coal-burning stations?

**12.** What is the relation of water power to steam power in a large system containing both steam and hydraulic plants. How can economy be best obtained at all seasons of the year?

**13.** Discuss briefly the operation and field of application of automatic generation stations.

**14.** What factors do you think influence such large power plants as the Windsor Plant in West Virginia and the Colfax Plant[1] on the Alleghany River to locate their generating stations adjacent to a coal mine and also a river?

**15.** In a steam power plant, is the quality of the water as important as the quantity? For condensers? For boilers?

**16.** What are the outstanding advantages of a large central station?

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[1] See *Power*, Vol. 47, pp. 210–216, 282, January–July, 1918; *Elec. World*, Apr. 2 and 16, 1921.

# CHAPTER III

## LOAD GRAPHS AND THEIR SIGNIFICANCE

**10. Typical System Load.**—Most of the systems of today are very complicated, and the loads supplied are very different in their nature. In Fig. 17 is shown a typical system, involving practically every type of load and necessitating the use of practically every type of power equipment. In this system the energy is generated entirely by steam units, at 60 and 25 cycles, thereby necessitating the use of frequency changers. Lighting, industrial, and railway loads are supplied by this system. A certain amount of the load is supplied with direct current calling for the use of rotary converters or other converting equipment. All generators are connected three phase, but power is distributed single, two, and three phase.

**11. Typical Load Graphs.**—A load graph, or load curve, is a graphic record showing the power demands for every instant during a certain time interval. Such a record may cover 1 hr., in which case it would be an hourly load graph; 24 hr., in which case it would be a daily load graph; a month in which case it would be a monthly load graph; or a year, in which case it would be a yearly load graph. In Figs. 18 to 26 are illustrated a few examples of daily load graphs. As seen from these, the area under a load curve is equal to the energy or kilowatt hours delivered to the particular load. A power plant supplying any load must have an aggregate installed capacity at least equal to the maximum demand represented on the load curve.

The importance of keeping load graphs as part of the records of power-plant operation is that a load graph indicates at a glance the general character of the load that is being imposed on the plant. Such a clear representation of the load demand cannot be obtained from tabulated figures. It is evident that the more nearly the graph of a load approximates a horizontal line, the nearer will the conditions be ideal. In other words, for a given total energy delivered in a given period, less installed total capacity of generating equipment is needed for that plant which has

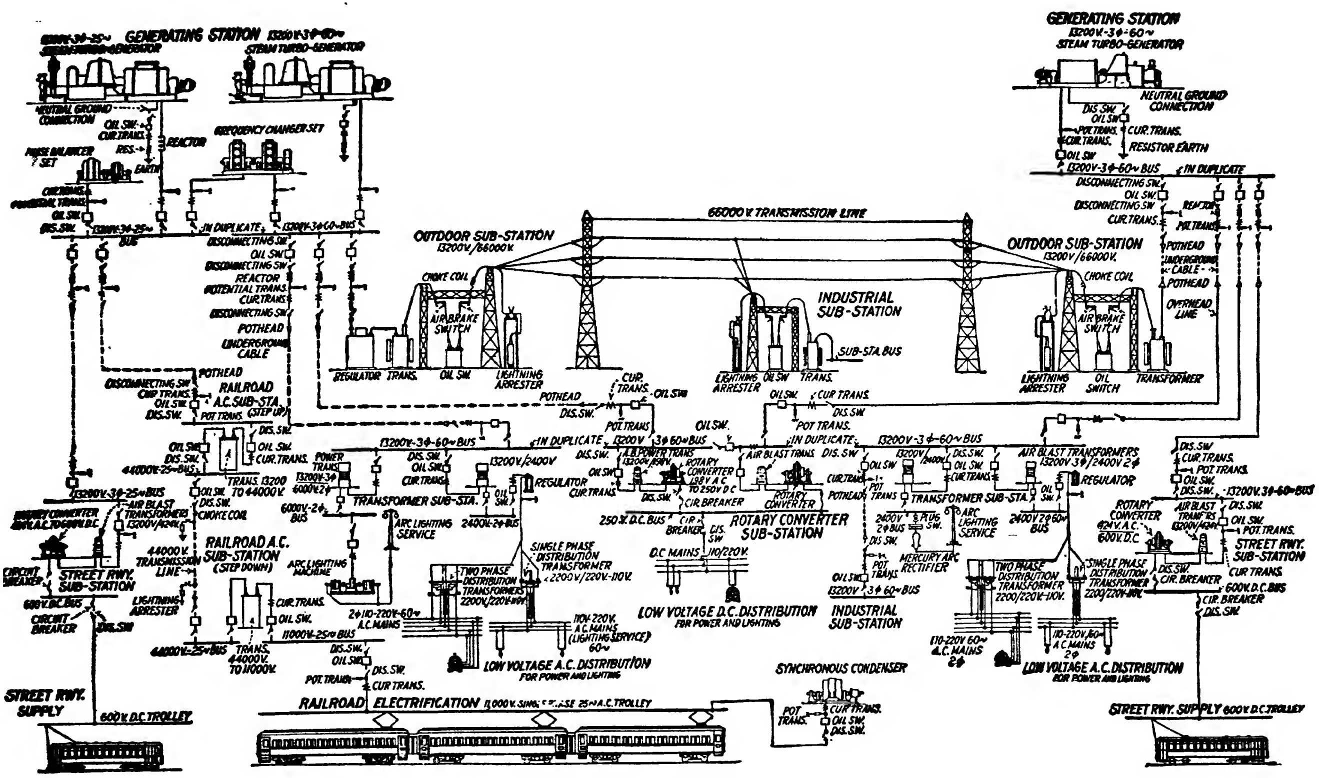
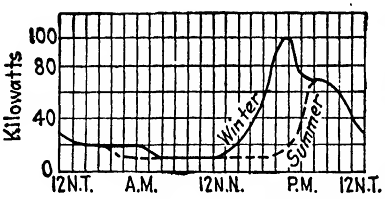


FIG. 17.—Typical system load.

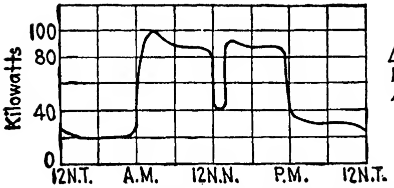


DAILY LOAD FACTORS
Winter 35%
Summer 32%
Average 33%

WEEKLY LOAD FACTORS
Winter 30%
Summer 27%
Average 28%

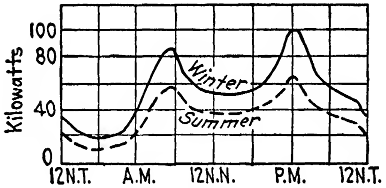
Annual Load Factor 23%

Fig. 18.—Lighting load graph.



| | | |
|---|---|---|
| Daily Load Factor | | 56% |
| Weekly " | " | 48% |
| Annual " | " | 46% |

Fig. 19.—Industrial load graph.

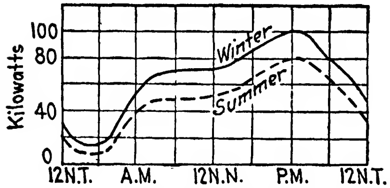


DAILY LOAD FACTORS
Winter 52%
Summer 52%
Average 52%

WEEKLY LOAD FACTORS
Winter 50%
Summer 50%
Average 50%

Annual Load Factor 35%

Fig. 20.—City street-railway load graph.

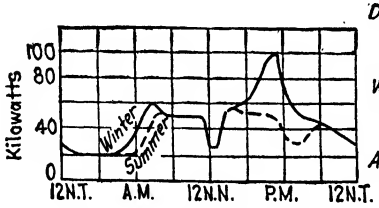


DAILY LOAD FACTOR
Winter 62%
Summer 59%
Average 60%

WEEKLY LOAD FACTOR
Winter 60%
Summer 57%
Average 58%

Annual Load Factor 47%

Fig. 21.—Interurban-railway load graph.



DAILY LOAD FACTOR
Winter 49%
Summer 71%
Average 64%
WEEKLY LOAD FACTOR
Winter 45%
Summer 65%
Average 59%
Annual Load Factor 40%
DIVERSITY FACTOR
Winter 1.07
Summer 1.54

Fig. 22.—Lighting and industrial load graph.

fewer number of valleys and peaks in its load graph. There are two methods by which load graphs of a power plant may be obtained. The most common method is by the use of recording

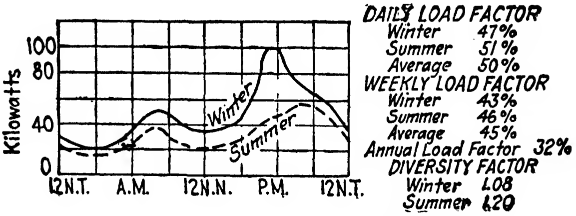


FIG. 23.—Lighting and city-railway load graph.

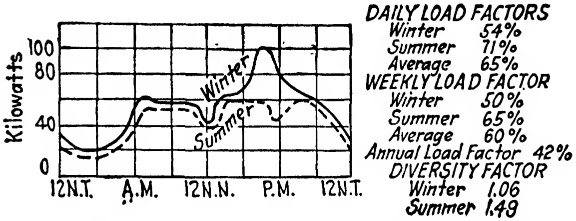


FIG. 24.—Lighting, industrial, and interurban-railway load graph.

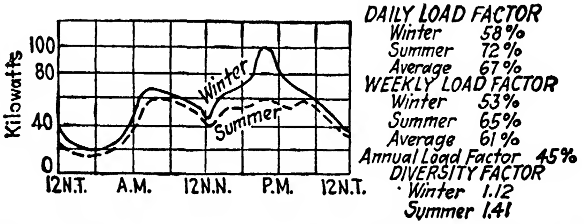


FIG. 25.—Lighting, industrial, interurban, and city-railway load graph.

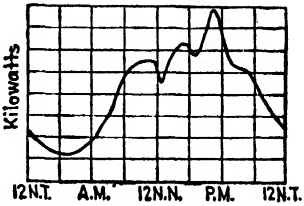


FIG. 26.—Load graph of a large power system. Daily load factor, 50 per cent.

graphic meters such as a graphic wattmeter. The other method is to plot values of power that have been obtained from indicating wattmeter readings which have been taken at equal time intervals. Graphic records are of such importance in the proper operation of power plants that all the larger central stations use a great variety of such recording instruments.

**12. Modified Load Graph.**—A modified load graph, which is obtained directly from a standard load graph, is shown in Fig. 27. This curve has some decided advantages over the standard type in that it shows the total energy in kilowatt-hours corresponding to a particular kilowatt capacity. Such a curve may be drawn for any period of time, such as a day, month, or year. Point *D* corresponds to the maximum kilowatt demand and also to the total energy delivered. Point *E* corresponds to the minimum kilowatt demand and the energy corresponding to the minimum demand at 100 per cent load factor. The portion *AE* is a straight line, and the portion *ED* has been found to approach quite closely the shape of a parabolic curve tangent at points *E* and *D*. This means that, to construct a modified load curve, data for only two points, namely, *D* and *E* must be known.

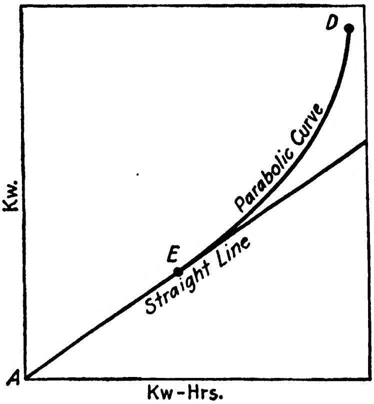


Fig. 27.—Modified load graph.

**13. Definitions.**—In order properly to interpret the load graphs of different systems it is necessary that the student become familiar with a few terms which are defined by the A.I.E.E. as follows:

*a. Connected Load.*—The connected load on any system, or part of a system, is the combined continuous rating of all the receiving apparatus on consumers' premises, which is connected to the system, or part of the system, under consideration.

*b. Demand.*—The demand of an installation or system is the load that is drawn from ~~the source of~~ supply at the receiving terminals averaged ~~over a~~ suitable and specified interval of time. Demand is expressed in kilowatts, kilovolt-amperes, amperes, or other suitable units.

*c. Maximum Demand or Peak Load.*—The maximum demand of an installation or system is the greatest of all the demands that have occurred during a given period. It is determined by measurement, according to specifications, over a prescribed time interval.

*d. Demand Factor.*—The demand factor of any system, or part of a system, is the ratio of the maximum demand of the system, or part of a system, to the total connected load of the system, or of the part of the system, under consideration.

*e. Load Factor.*—The load factor is the ratio of the average power to the maximum demand. In each case, the interval of maximum load and the period over which the average is taken should be definitely specified, such as a "half-hour monthly" load factor. The proper interval and period are usually dependent upon local conditions and upon the purpose for which the load factor is to be used.

*f. Diversity Factor.*—The diversity factor of any system, or part of a system, is the ratio of the sum of the maximum power demands of the subdivisions of the system, or part of a system, to the maximum demand of the whole system, or part of the system, under consideration, measured at the point of supply.

*g. Utilization Factor.*—The utilization factor is defined as the ratio of the maximum generator demand to the generator capacity.

*h. Plant Factor.*—Plant factor is defined as the ratio of the average generator load to the total rated capacity of the equipment supplying the load.

**14. Discussion of the Above Definitions.** *a. Connected Load.*—A lighting connected load is equal to the sum of the wattages of all the lamps in the installation. A motor connected load is equal to the sum of the continuous rated output of all the motors connected to the system. Motors are generally rated in horsepower output; hence it is usually convenient to convert the horsepower connected load to an equivalent kilowatt connected load, since, as a general rule, the load graphs and other factors that are used in connection with load graphs are given in terms of kilowatts. A combined lighting and motor connected load is equal to the sum of the lighting connected load and the motor connected load of the particular system under consideration.

*b. Demand.*—It should be noticed that the definition of demand states that "the load is averaged over a suitable and specified interval of time." There is no such thing, therefore, as an "instantaneous demand." Instantaneous loads are not very important, since most electrical equipment will stand heavy overloads for short periods of time. In other words, the choice of equipment for a particular system should not be made on the basis of what the maximum instantaneous load might be, but on the basis of the averaged load over a suitable interval of time.

*c. Maximum Demand.*—When speaking of demand or maximum demand, it is essential that the time interval over which the particular demand was averaged be specified. The time interval chosen depends on particular conditions of the system. There is no definite agreement between central stations on a standard interval, but the ones that are most common are 1, 15, and 30 min.

*d. Demand Factor.*—Expressing the definition mathematically,

$$\text{Demand factor} = \frac{\text{maximum demand}}{\text{connected load}} \tag{3}$$

It is evident that the particular time interval used in obtaining the maximum must be specified in connection with the demand factor; otherwise the term will be obscure in its meaning. In Tables III to VI are given typical values of demand factors applying to alternating- and direct-current motor installations. These values are based on a maximum demand of a 30-min. interval.

TABLE III.[1]—APPROXIMATE DEMAND FACTORS FOR ALTERNATING-CURRENT MOTOR INSTALLATIONS

| Class of service | Number of motors in installation | Total motor horsepower of installation | Demand factors in per cent | |
|---|---|---|---|---|
| | | | Probable range | Probable fair average value |
| Single-phase and three-phase motors | 1–10 | 1–75 | 80–110 | 90 |
| General factory and other motors.... | 10–20 and over | 1–150 | 75–95 | 85 |
| Small single-phase motors.......... | 1–20 | 1–50 | 80–100 | 90 |
| Elevator and crane motors......... | 1–2 | ..... | 90–110 | 100 |
| | 3–5 | ..... | 60–80 | 70 |
| | over 5 | ..... | 50–70 | 60 |

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[1] CROFT, TERRELL, "Central Stations."

*e. Load Factor.*—Expressing the definition mathematically,

$$\text{Load factor} = \frac{\text{average load}}{\text{maximum demand}} \tag{4}$$

It is evident that a load factor may refer to the average load and the maximum demand of any period of time; hence it is necessary to state the period of time along with the load factor, as, for example, 30-min. daily load factor, 30-min. weekly load factor, 30-min. monthly load factor, or 30-min, annual load factor. It should be realized that by daily load factor is understood a period of 24 hr., and by a yearly load factor a period of 365 days of 24 hr. each. The average load of a particular graph

TABLE IV.[1]—APPROXIMATE DEMAND FACTORS FOR DIRECT-CURRENT MOTOR INSTALLATIONS

| Class of service | Number of motors in installation | Total horse-power of installation | Demand factor in per cent | |
|---|---|---|---|---|
| | | | Probable range | Probable fair average value |
| General factory and other service | 1 | 1–5 | 75–95 | 85 |
| | 1 | 6–10 | 65–85 | 75 |
| | 1 | 11–20 | 55–75 | 65 |
| | 1 | Over 20 | 50–70 | 60 |
| | 2 | 1–5 | 70–90 | 80 |
| | 2 | 6–10 | 65–86 | 75 |
| | 2 | 11–20 | 60–80 | 70 |
| | 2 | Over 20 | 45–65 | 55 |
| | 3–5 | 1–5 | 60–80 | 70 |
| | 3–5 | 6–10 | 55–75 | 65 |
| | 3–5 | 11–20 | 50–70 | 60 |
| | 3–5 | Over 20 | 40–60 | 50 |
| | 6 and over | 1–5 | 55–75 | 65 |
| | 6 and over | 6–10 | 50–70 | 60 |
| | 6 and over | 11–20 | 45–65 | 55 |
| | 6 and over | Over 20 | 25–55 | 45 |
| Machine-shop individual drive | 10 and over | Over 20 | 35–60 | 40 |
| Elevator and crane motors | 1–2 | ....... | 90–110 | 100 |
| | 3–5 | ....... | 60–80 | 70 |
| | Over 5 | ....... | 50–70 | 60 |

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[1] CROFT, TERRELL, "Central Stations."

may be obtained by any recognized method of averaging, such as by planimeter, by graphical methods, or some other rule, as, for example, Simpson's equation.

In Figs. 18 to 26 are illustrated a few typical load graphs of different types of loads. The daily, weekly, and annual load factors of these loads are given in the same figures. In Tables V and VI are given the approximate 30-min. annual load factors and demand factors for different types of consumers of a large city.

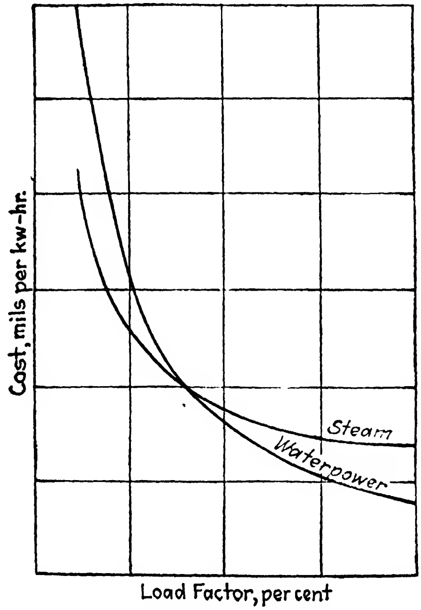

Fig. 28.—Typical cost curves for steam and water power.

It is evident that, for a given installed capacity of system, the total costs of generation per kilowatt-hour will increase with a decrease of load factor. This is illustrated by Fig. 28. It is of interest to note how the load factor affects steam as well as hydroelectric plants. In the case of hydroelectric plants the fixed charges form the major part of the total cost per kilowatt-hour, while in the case of steam-electric plants the fuel, operating, and maintenance cost form the major part of the total expenses. Considering only the power plant and no transmission lines, the total cost per kilowatt-hour at high load factors is generally higher in the case of steam-electric plants. The actual costs of generation in a hydroelectric plant are practically constant, independent of load factor, since the cost is mainly due to the fixed charges on the initial investment. On the other hand in the case of steam-electric plants, as the load factor decreases, a saving of fuel is obtained; hence the actual costs of generation will decrease with a decrease of load factor. This fact is clearly shown in Fig. 28. Even though the total costs per kilowatt-hour for the steam-electric plant are higher than for the hydroelectric plant at high load factors, the costs per kilowatt-hour at low load factors become less in the case of the steam plant as compared with the hydro-plant. This fact explains why it is more economical to carry the base load of a system on the hydro-plants and the fluctuations in the load by the steam plants.

*f. Diversity Factor.*—Expressing the definition mathematically,

$$\text{Diversity factor} = \frac{\text{sum of individual maximum demands}}{\text{maximum demand of entire group}} \qquad (5)$$

TABLE V.[1]—LOAD FACTORS AND DEMAND FACTORS OF LIGHTING CONSUMERS

| Kind of business | Annual load factor, per cent | Demand factor, per cent | Kind of business | Annual load factor, per cent | Demand factor, per cent |
|---|---|---|---|---|---|
| Banks | 16 | 67 | Stores, dry goods | 8 | 77 |
| Churches | 12 | 56 | Stores, drug | 19 | 79 |
| Hotels | 24 | 28 | Stores, furniture | 6 | 70 |
| Houses | 8 | 43 | Stores, grocery | 10 | 73 |
| Offices, business | 9 | 64 | Stores, hardware | 11 | 40 |
| Offices, personal | 7 | 64 | Stores, jewelry | 15 | 64 |
| Pool and billiards | 17 | 65 | Stores, shoes | 10 | 67 |
| Printers and engravers | 15 | 59 | Stores, clothing | 7 | 53 |
| Restaurants | 23 | 52 | Small hotels | 26 | 67 |
| Shops, barber | 12 | 70 | Laundries | 10 | 68 |
| Shops, machine | 9 | 37 | Theaters | 17 | 49 |
| Shops, tailor | 8 | 59 | Warehouses | 12 | 41 |
| Stables, livery | 22 | 52 | Wholesale houses | 19 | 47 |
| Stores, book | 12 | 66 | Manufacturers | 10 | 54 |
| Stores, cigar | 17 | 65 | Hospitals | 13 | 42 |
| Stores, house furnishing | 8 | 52 | Flats | 7 | 54 |

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[1] Based on data presented before a National Electric Light Association Convention by E. W. Lloyd. See CROFT, TERRELL, "Central Stations."

TABLE VI.[1]—LOAD FACTORS AND DEMAND FACTORS OF LARGE COMBINED POWER AND LIGHT CONSUMERS

| Kind of business | Annual load factor, per cent | Demand factor, per cent |
|---|---|---|
| Butter and creamery | 20 | 60 |
| Brass and iron beds | 20 | 60 |
| Biscuit manufacturers | 35 | 55 |
| Boots and shoes | 25 | 65 |
| Brass manufacturing | 28 | 50 |
| Boiler shops | 18 | 45 |
| Can manufacturers | 30 | 70 |
| Candy manufacturers | 18 | 45 |
| Clothing manufacturers | 15 | 55 |
| Clubs, large | 40 | 85 |
| Department stores, large | 30 | 55 |
| Electrical manufacturing | 25 | 55 |
| Express companies | 40 | 60 |
| Electroplating | 25 | 75 |
| Engraving and printing | 19 | 60 |
| Fertilizer manufacturing | 75 | 40 |
| Furniture manufacturing | 28 | 65 |
| Foundries | 15 | 75 |
| Forge shops | 30 | 49 |
| Grain elevators | 10 | 75 |
| Glove manufacturing | 25 | 55 |
| Grocers, wholesale | 20 | 55 |
| Hotels, small | 35 | 50 |
| Hotels, large | 50 | 40 |
| Ice cream manufacturing | 45 | 75 |
| Jewelry manufacturers | 18 | 50 |
| Laundries | 25 | 70 |
| Machine shops | 26 | 55 |
| Newspapers | 20 | 75 |
| Packing houses | 30 | 75 |
| Paints, lead, and ink manufacturers | 23 | 45 |
| Paper box manufacturers | 25 | 50 |
| Plumbing and pipe fitting | 26 | 55 |
| Post offices | 50 | 30 |
| Power building | 27 | 40 |
| Refrigeration | 50 | 90 |
| Railroad depots | 50 | 50 |
| Pneumatic tube | 50 | 90 |
| Soap manufacturers | 25 | 60 |
| Seed cleaners | 25 | 55 |
| Screw manufacturers | 30 | 75 |
| Spice mills | 20 | 55 |
| Saw manufacturers | 30 | 55 |
| Structural steel | 22 | 40 |
| Sheet metal manufacturing | 18 | 70 |
| Stone cutters | 17 | 55 |
| Twine mills | 30 | 60 |
| Theaters | 16 | 60 |
| Large restaurants | 50 | 60 |
| Small restaurants | 30 | 70 |
| Woolen mills | 27 | 80 |
| Wood working | 28 | 65 |
| Textile mills | 20 | 65 |

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[1] Based on data presented before a National Electric Light Association Convention by E. W. Lloyd. See CROFT, TERRELL, "Central Stations."

The significance of diversity factor is illustrated by Figs. 29 and 30. In Fig. 29 a power and lighting load are combined, or in other words these two loads are supplied from the same station. The peak load of the resultant curve is 430 kw. In case each load were supplied from independent plants, the total rating of the equipment in the two plants would have to be equal to 300 + 270, or 570 kw. Hence, the diversity factor of such a combination is

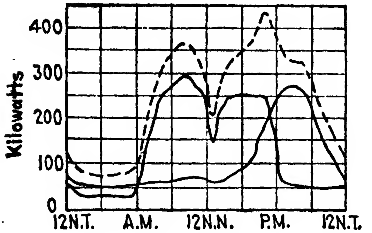
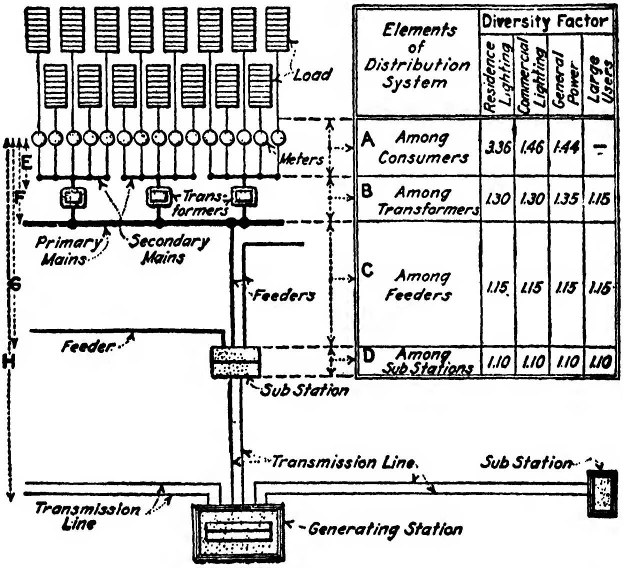


Fig. 29.—Load graphs, showing diversity between power and lighting loads.

$$570/430 = 1.33$$

In Fig. 30 is shown the effect of diversity among different components of a system, and the table given with the figure illustrates typical values of diversity factors for different types of consumers. This figure indicates that a great saving of equipment can be obtained by interconnecting a large variety of loads



| Elements of Distribution System | Diversity Factor | | | |
|---|---|---|---|---|
| | Residence Lighting | Commercial Lighting | General Power | Large Users |
| A Among Consumers | 3.36 | 1.46 | 1.44 | – |
| B Among Transformers | 1.30 | 1.30 | 1.35 | 1.15 |
| C Among Feeders | 1.15 | 1.15 | 1.15 | 1.15 |
| D Among Sub Stations | 1.10 | 1.10 | 1.10 | 1.10 |

Fig. 30.—Diversity of demand among different components of a distributing system.

and supplying the entire network from a few large efficient plants.

### Questions for Class Discussion

**1.** What three distinct types of loads may a central station supply? Discuss briefly.

**2.** Sketch three typical load graphs for (*a*) lighting, (*b*) industrial, and (*c*) railway loads. What are the prominent features of each type? How would the summer and winter curves differ in each case?

**3.** Are there any advantages in supplying different types of load from the same central station? Illustrate by adding the graphs for different types of load. Which combination is the most desirable?

**4.** Suggest methods of improving the load curve of a city. Why can a power company afford to sell blocks of power at low rates during off-peak hours?

**5.** Explain in your own words what is meant by the term "demand" as applied to an installation or system. Why is the demand averaged over a specified interval of time instead of referring to an instantaneous value?

**6.** Explain clearly what is meant by the term "maximum demand," and illustrate by the use of a load curve.

**7.** Define demand factor, and explain what its numerical value indicates.

**8.** Define diversity factor, and explain for what purpose it is used.

**9.** Define load factor, and explain what its numerical value indicates.

**10.** Define utilization and plant factors and explain what their numerical values indicate.

**11.** How does centralization of power supply affect the load-factor system, and why?

**12.** Suppose that a power plant is to be erected in a city that is without electric service. Outline in tabular form how you would proceed to establish an approximate load graph for the system.

**13.** What are the essential data that must be known from the load curve in order to select properly the sizes of the generating units?

**14.** Outline the method for determining the size and number of generating units for a given plant. How does the nature of the load curve affect the selection?

**15.** Two isolated plants have a capacity of 1,760 kw. each, and each is fully loaded for several hours each day. The diversity factor of the two loads is 1.1. Explain fully the advantages of interconnecting the two plants, giving actual kilowatt reserve thus obtained.

**16.** An office building has an aggregate connected load of 100 kw. of tungsten lamps and a demand factor of 50 per cent. The total output for 1 year was 84,000 kw.-hr. What was the yearly load factor? The maximum daily output was 250 kw.-hr.; find the load factor for that day.

**17.** Is a high load factor more desirable in a hydroelectric station or in a steam-electric plant? Why?

**18.** Connected load, 400 kw.; daily output, 700 kw-hr.; load factor, 25 per cent; demand factor = ?

**19.** Combined load, 1,000 kw.; individual maximum (*a*) 200 kw.; (*b*) 300 kw.; (*c*) 600 kw. Find the diversity factor.

**20.** Motor *A*: rates input, 1,000 kw.; peak, 700 kw.; average load, 300 kw. Motor *B*: rated input, 2,000 kw.; peak, 1,100 kw.; average load 500 kw. A 2,000-kw. generator *C* supplying these motors has a maximum load of 1,200 kw.

*a*. What are the *demand factors* for *A*, *B*, and *C*?

*b*. What are the *load factors* for *A*, *B*, and *C*?

*c*. What is the *diversity factor* for the combined load *A* and *B*?

*d*. What is the *plant factor* for the above installation?

**21.** The yearly output of the New York Edison Company for 1916 was 856,000,000 kw.-hr. On the maximum day, peak load = 255,000 kw.; maximum daily output = 3,000,000 kw.-hr. Determine the daily load factor and the yearly load factor.

**22.** A 125-kw. plant costing $20,000 is used to supply a peak load of 100 kw. Assuming the fixed charges amount to 13 per cent, determine the fixed charge in cents per kilowatt-hour, for yearly load factors of 100, 50, and 25 per cent, respectively.

**23.** Discuss the method of obtaining a modified load graph, and state what advantages it possesses over the standard load graph.

# CHAPTER IV

## GENERATING EQUIPMENT

**15. General Classification.**—A broad classification of generating equipment may include the following types of machines:

- Classification
  - Direct current
    - Two-wire generator
    - Three-wire generator
    - Motor-generator set
    - Rotary converter
    - Mercury-arc rectifier
  - Alternating current
    - Synchronous generator
    - Induction generator
    - Frequency-changer set
    - Phase converter

### DIRECT-CURRENT GENERATORS

**16. Two-wire Direct-current Generators.**—By two-wire generators are meant such generators as have only two line terminals, one known as the positive terminal and the other as the negative terminal. Direct-current generators may be further classified according to:

- Method of excitation
  - Self-excited
    - Shunt
    - Series
    - Compound
      - 1.
        - Short shunt
        - Long shunt
      - 2.
        - Flat compound
        - Overcompound
        - Differentially compound
  - Separately excited
- The number of poles
  1. Bipolar
  2. Multipolar
  3. Homopolar
- The type of armature winding
  1. Multiple or lap
  2. Series, two circuit or wave
  3. Combination of multiple and series
- The method of prime-mover drive
  1. Engine type
  2. Direct connected to steam turbine
  3. Geared to steam turbine
  4. Water turbine

| | |
|---|---|
| The type of service | 1. General power and lighting<br>2. Railway<br>3. Electrolytic and furnace<br>4. Booster<br>5. Exciter<br>6. Balancer |
| Special features of construction | 1. Noncommutating-pole machines<br>2. Commutating-pole machines<br>3. Compensating wound machines<br>4. Diverter-pole machines |

**17. Method of Excitation.**—The excitation of direct-current generators is provided by a stationary electric circuit consisting of one or more field coils of wire placed on each of the field poles. The m.m.f. produced by these coils, when current flows through them, forces the required amount of magnetic flux across the air gap and through the armature of the generator. The sketches given in Fig. 31 illustrate diagrammatically the different methods of connecting the field winding.

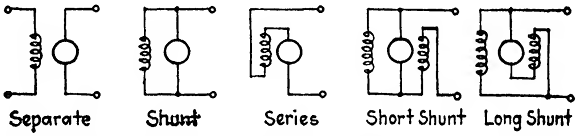


FIG. 31 —Methods of excitation for direct-current machines.

**18. Number of Poles.**—The early types of direct-current generators had only two poles, one north and one south pole. Such machines are known as "bipolar" generators. With the demand for higher capacity generators it was found necessary to use more than two poles; hence, today, practically all direct-current generators have at least four poles. Since the magnetic flux of a generator always forms a closed circuit, there must always be a south pole for every north pole; hence the total number of poles of a "multipolar" generator must always be equal to a multiple of two. The peripheral velocity of the armature is limited by the mechanical strength of the commutator; hence the diameter of the armature varies inversely as the speed of rotation. High-speed generators, therefore, will have smaller diameters and fewer number of poles than low-speed generators.

A modification of the standard type of magnetic field structure has been developed in the so-called "homopolar" generators. Homopolar generators are designed with the armature conductors revolving in a unidirectional field, and thus the e.m.fs. generated in them do not alternate during the revolution of the armature; hence no commutator is needed. Such machines can be used where very large currents at low voltage are required, as, for example, in electrolytic processes.

**19. Types of Armature Windings.**—Neglecting the homopolar machine, which represents a special type of design, direct-current generator armatures can be of the multiple, series, or combination multiple and series windings. The fundamental difference between the multiple and series windings is in the number of parallel paths obtained in the armature. The multiple winding contains as many parallel paths as the generator has main poles. The series winding contains only two parallel paths irrespective of the number of main poles. It also follows that a multiple-wound armature requires as many brush studs as the generator has main poles, while the series-wound armature requires only two brush studs irrespective of the number of main poles. Nevertheless, in the case of large-capacity series-wound machines it is possible to use as many brush studs as there are main poles, thereby decreasing the amount of current that must be collected at each brush stud. It is obvious that the multiple-wound armature is the best suited for medium voltages and high current capacities on account of the larger number of parallel paths through the armature. Series windings, on the other hand, are used in small high-voltage machines, or where it is desirable to use only two brush studs, as, for example, in railway motors.

In multiple-wound machines, if there is any irregularity in the length of the air gap under the poles, the e.m.fs. generated in the different sections of the winding will not be equal, and the unbalanced e.m.f. will tend to cause currents to circulate through the brushes even when the machine is not carrying load. To keep these circulating currents out of the brushes, similar points of the armature winding, which should normally be at the same potential, are joined by low-resistance copper connections called "equalizer rings," and these provide a path that the circulating currents follow in preference to the comparatively high-resistance path through the brushes.

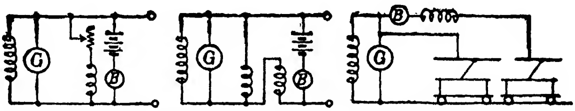
An investigation of the series winding will reveal the fact that equalizer rings are not needed, as each one of the two paths of the winding is made up of conductors under all the main poles of the generator; hence there can be no difference of voltage in the two paths. This property of the series winding is made use of in a combination multiple and series armature winding generally known as a "frog-leg winding." The frog-leg winding consists essentially of a standard multiple winding and a standard series winding placed together in the same armature slots and connected to the same commutator. An investigation of such a winding will reveal the fact that the series elements acts as "equalizer rings" connecting all commutator segments that should normally be at the same potential. In other words, the frog-leg winding has equalizer connections which, in addition to equalizing the e.m.fs. in the armature, supply part of the load current delivered by the generator.

**20. Prime-mover Drive.**—The engine-type generator has its armature mounted on a continuation of the engine crankshaft. Such generators are adaptable to reciprocating steam-engine or internal-combustion-engine drive. Heavy flywheels are generally required with this type of generator, in order to limit the angular velocity pulsations during each revolution normally due to the variable driving torque.

Steam-turbine-driven direct-current generators are often used as spare exciters in steam power plants. The speed of water turbines is, as a general rule, much less than the speed of steam turbines; hence there are no great difficulties encountered in driving direct-current generators by water turbines. The speed of steam and water turbines is very uniform; hence there is practically no generator hunting. A common application of water turbines is found in hydraulic power plants where spare exciter units are direct-connected to water wheels.

**21. Type of Service.**—Generators for power and lighting are generally wound for 125 and 250 volts and are either flat compounded or slightly overcompounded, so that the voltage at the lamps varies but little with change of load. The voltage regulation should not be more than 2 per cent. When power and lighting are supplied together, three-wire systems are often used. The voltage between the two outer wires is generally 250 volts and hence is suitable for power service; the voltage between any outside wire and the neutral is 125 volts and hence is suitable for lighting.

Generators for railway service have compound-wound fields and are designed for 550 or 600 volts for city railway service, 1,200 volts for interurban service, and 3,000 volts for trunk-line electrification. Generators for electrolytic work are usually low-voltage machines of large current capacity. When the terminal voltage is very low, the exciting current will be large if the machine is shunt wound; therefore, such machines are often separately excited from a source of higher voltage. For electric furnace work where the machine is likely to be subjected to short circuits, shunt or differentially compound excitation is desirable, since such generators will not maintain large current on short circuit.



(a) Shunt Booster (b) Compound Booster (c) Series Booster

FIG. 32.—Direct-current boosters.

Boosters are direct-current generators connected in series with the line to raise or lower the voltage. They are generally low-voltage machines of large current capacity and are usually driven at constant speed by shunt motors. Boosters are used extensively to regulate the charge and discharge of storage batteries in parallel with the generators in constant-voltage systems, or to compensate for line drop in distribution systems by adding an equal voltage to the circuit. They may be shunt, series, or compound-wound. In Fig. 32 are shown the simplified diagrams of connections for a shunt, compound, and series booster. Exciters are generally designed for 125 to 250 volts normal. They may be either shunt- or compound-wound. When operated with an automatic voltage regulator, the exciter must be capable of supplying a voltage about 40 per cent more than normal; hence the magnetic circuit should not be highly saturated. The subject of exciters will be covered in detail in Chap. V.

A direct-current balancer consists of two similar direct-current machines directly coupled to each other and connected in series across the outer conductors of a three-wire system of distribution. The purpose of such a set is to maintain the potential of the neutral wire at a point halfway between the potential of the outer wires. Balancers can be either shunt- or compound-wound. Figure 33 shows diagrammatically the application of balancers to a three-wire system. When the loads on the two sides of the three-wire system are balanced, no current flows in the neutral wire; hence the two machines *M* and *G* run light as motors. When the load on one side is increased as shown in Fig. 33*a*, the voltage across machine *G* becomes less than the voltage across machine *M*; hence machine *M* will act as a motor, thereby driving machine *G* as a generator, thus preventing the voltage across *G* from dropping very much below its normal value. By connecting the shunt fields as shown in Fig. 33*b*, the machine *M* will operate at a higher speed, and machine *G* will generate a higher voltage than in Fig. 33*a*, since the shunt field of the motor *M* is connected across the highly loaded side, and the shunt field of generator *G* is connected across the lightly loaded side of the three-wire system. It must be kept in mind that a perfect balance cannot be obtained, because the operation of the balancer set depends on a slight unbalancing of voltages. In Fig. 33*c* is shown a compound balancer. The series fields are so connected that the machine acting as the generator is cumulatively compounded and the machine acting as the motor is differentially compounded. With this arrangement the speed of the motor and the induced voltage of the generator will increase as the amount of unbalancing increases.

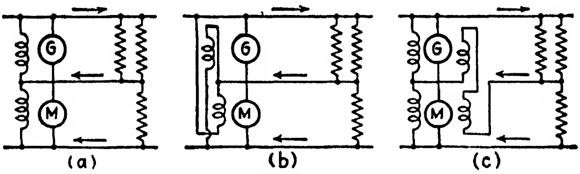


Fig. 33.—Balancer sets.

**22. Special Features of Construction.**—The early types of direct-current machines were built without commutating poles, but it was soon found that more economical machines of much better operating qualities could be produced by the use of commutating poles. For this reason practically all direct-current machines are now built with commutating poles.[1]

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[1] For a detailed treatment of commutating-pole machines, see any of the standard textbooks on direct-current machinery.

The voltage between adjacent commutator segments of a direct-current generator must not exceed the safe insulating value of the insulation between segments. There is induced in every conductor of direct-current generators or motors, which are subjected to rapid changes in load, a voltage that is proportional to the rate of change of the current through the armature. This voltage of self-induction may be considered as superimposed upon the voltage generated in the same conductors due to the rotation of the armature through the main-field flux. The resultant voltage across the insulation between adjacent commutator segments may, therefore, become high enough to start a current flash between adjacent segments. Since this voltage is present between all segments of the commutator, a complete short circuit from positive to negative brush may result. Such a short circuit is generally known as "flashing over." In order to prevent these high voltages between segments, a compensating winding is provided. This winding consists of conductors placed in the pole faces and connected in series with the armature, so that its m.m.f. is just equal and opposite to the armature m.m.f., thereby neutralizing any effect of the armature m.m.f. Since the m.m.f. of the compensating winding varies directly with the load current, there can be no voltage induced in the armature conductors due to the variation of the armature m.m.f.; hence the only voltage present between adjacent commutator segments is that due to the rotation of the armature through the main-field flux. Compensating windings are essential on rolling-mill motors and generators subjected to sudden changes of load, as, for example, in railway service.

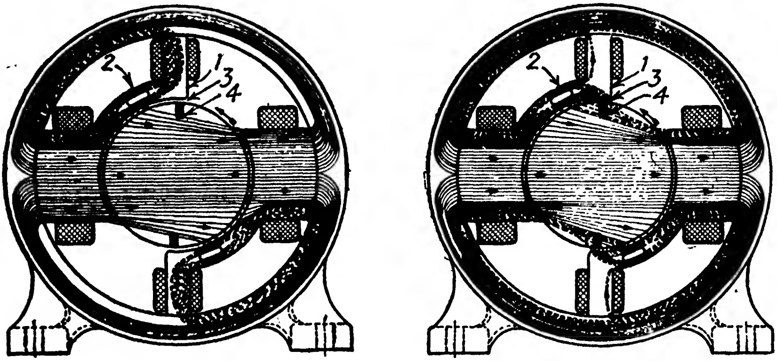
**23. Diverter-pole Generators.**—A diverter-pole generator might be described as a shunt interpole machine, the main pole and interpole being one punching.

At no load, a part of the magnetic flux resulting from the shunt coil on the main pole piece is diverted and does not pass through the armature. As the load increases, the series winding on the diverter pole rediverts this flux to the armature and provides a commutating field.

Figure 34*a* shows diagrammatically the magnetic circuit of a diverter-pole generator at no load, and Fig. 34*b* at full load.

By proper proportioning of the shunt and series windings, the flux in the armature varies with the load so as to compensate fo the I.R. drop in the generator and speed changes of the driving motor.

A flat voltage curve is obtained, since the necessary magnetic changes produced by the series winding take place only in the diverter pole (1), the flux from the main pole remaining constant. The flux densities in the diverter pole (1) are kept low so that the magnetic changes that occur take place on the straight-line portion of the magnetization curve, thus eliminating most of the curvature from the voltage characteristic. By correct adjustment of the diverter-pole winding, a straight flat curve is obtained with only a slight rise on approaching zero load.



a. No Load b. Full Load

FIG. 34*a* and *b*.—Magnetic flux distribution in a diverter-pole generator. Main flux—full lines; leakage flux—dashed lines.

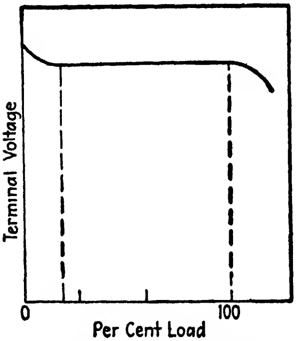


FIG. 34*c*.—Diverter-pole characteristic.

At some value of the load current the ampere turns on the diverter pole will equal those on the main pole and, at this time, the magnetic flux leaking across the bridge to the diverter pole is all rediverted across the air gap. When the load is increased beyond this point, the increased ampere turns on the diverter pole combine with the armature cross-magnetizing force to send magnetic flux in the reverse direction across the leakage bridge, which tends to demagnetize the main pole and reduce the generator voltage.

Good commutation is assured as the diverter pole provides a commutating field of the correct direction for improving commutation, and this field varies with the current output just as in an interpole generator.

This type of generator is particularly well adapted to service in parallel with storage batteries. Owing to its straight flat line characteristic it maintains the bus voltage constant during fluctuations of load and thereby delivers a high percentage of the current required by the load. The general shape of its voltage characteristic is shown in Fig. 34*c*.

**24. The Amplidyne Generator.**[1]—In outward appearance the amplidyne direct-current generator is similar to the conventional direct-current generator. But its ingenious and unique use of a set of extra short-circuited armature brushes and of a specially designed compensating winding creates such precise electrical balance that a very small change of field excitation will readily control very large amounts of armature power.

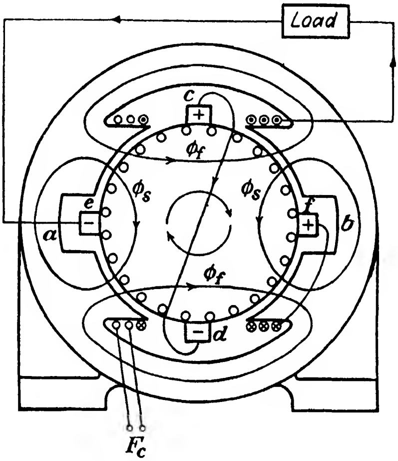


FIG. 35.—Elementary direct-current amplidyne generator.

The general details of the amplidyne generator are shown in Fig. 35. This particular machine has two poles, each pole being split into sections *a* and *b*. The control field is supplied by the exciting winding $F_c$, which sets up the magnetic field $\phi_f$.

This flux $\phi_f$ will generate a voltage in the rotating armature,

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[1] FELIX, FREMONT, What Is the Amplidyne? How Does It Work? *Gen. Elec. Rev.*, August, 1943.

which in turn will cause a relatively large current to circulate through the armature and the short-circuited brushes *c* and *d*. This armature current will set up a strong magnetic field indicated as $\phi_s$.

As the armature rotates, a resultant induced voltage due to flux $\phi_s$ will appear across brushes *e* and *f* which are connected to the load through a compensating winding $W_c$. This winding is designed with exactly the proper number of turns so that it will completely neutralize any armature m.m.f. created by the load current, which would tend to act in opposition to the control flux $\phi_f$, created by the control winding $F_c$.

The operating cycle is therefore as follows: a variation in control winding field current causes a corresponding change in flux $\phi_f$. The variation in $\phi_f$ causes a corresponding percentage change in armature flux $\phi_s$, which in turn will cause a corresponding change in voltage across brushes *e* and *f* and therefore a corresponding change in load current.

If several control field windings independently excited from signal devices are placed on the same pole structure, the amplidyne will respond to their resultant action and amplify it in the same manner as for a single field.

This type of generator has found wide use in applications requiring fast changes in electrical power and controlled by very small signal voltages. It is this amplifier action that is responsible for the name "Amplidyne."

The Westinghouse "Rototrol" and Allis-Chalmers "Regulex" serve about the same purpose as the General Electric "Amplidyne."

**25. Characteristics of Direct-current Generators.** *a. No-load Saturation Curve.*—The no-load saturation curve of a generator shows the relation between the voltage generated at no load and the field current. In the case of shunt or compound generators, the no-load saturation is obtained by running the machine at constant speed and observing the terminal voltage obtained for different values of shunt-field current. Since the shunt-field current is only a small percentage of the total armature current, the armature-resistance drop at no load is neglected and the terminal voltage taken as equal to the generated voltage. In the case of series-field-wound generators it is necessary to excite the field from a separate source in order to obtain the no-load saturation curve. Figure 36 shows a typical no-load saturation curve. Shunt-excited machines are operated at a point slightly above the knee of the curve so that slight changes in speed may not cause large changes in voltage. Compound-excited machines are generally operated lower down on the saturation curve in order that the required increase in voltage may be obtained without the need of too large a series field.

2. *Load Characteristics.*—Consider first a separately excited generator. As load is applied, the terminal voltage will begin to drop on account of the armature-resistance drop and also on account of the decrease in net field flux caused by the armature reaction. A curve showing this variation of terminal voltage with load is given in Fig. 37. It is assumed in the case of the separately excited generator that the voltage across the field remains constant. In a shunt generator the field excitation varies directly with the terminal voltage; hence the terminal voltage will drop faster with increase of load than in the case of the separately excited generator because, in addition to the two causes of voltage drop as obtained in the separately excited generator, there is also a further decrease of terminal voltage on account of the decrease in excitation (see Fig. 37).

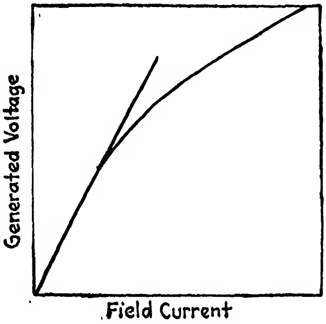


FIG. 36.—No-load saturation curve.

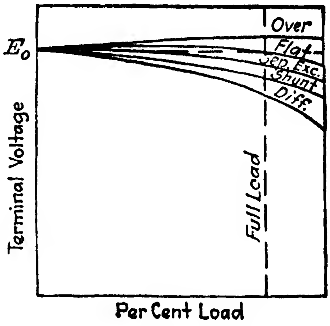


FIG. 37.—Generator voltage characteristics.

A compound generator is said to be flat compounded when the full-load terminal voltage is equal to the no-load voltage, or in other words when the m.m.f. of the series field at full load is just strong enough to overcome the drop in terminal voltage between no load and full load, which would be present in the generator without the series field. If more turns are placed on the series field, the terminal voltage at full load will be higher than the no-load voltage, or in other words the generator will be overcompounded (see Fig. 37). Differentially compounded generators[1] are obtained by reversing the connections of the series field so that its m.m.f. acts in opposition to the m.m.f. of the shunt field. Such generators have been successfully used for vehicle lighting.

**26. Voltage Regulation and Losses.**—Voltage regulation is defined by the following equation:

$$\text{V.R.} = \frac{E_{\text{N.L.}} - E_{\text{F.L.}}}{E_{\text{F.L.}}} \times 100 \text{ per cent} \tag{6}$$

or, voltage regulation is the ratio of the drop in terminal voltage between no load and full load to the terminal voltage at full load expressed as a percentage.

The losses in direct-current machines may be classified as follows:

- Stray losses
  - Mechanical
    - Windage
    - Bearing friction
    - Brush friction
  - Iron
    - Hysteresis loss
    - Eddy-current loss
- Copper losses
  - Shunt-field copper loss
  - Series-field copper loss
  - Armature copper loss
  - Commutating-field copper loss
- Load losses

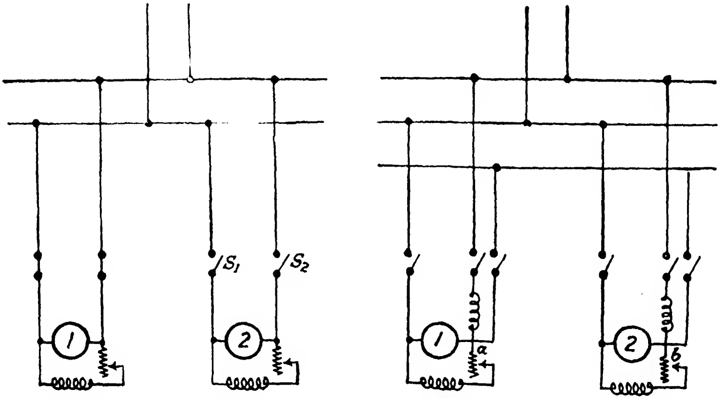
**27. Parallel Operation.** *a. Shunt Generators.*—Figure 38*a* shows two shunt generators, one of which is supplying power to a load and the other ready to be connected to the station busses. Before closing the switches $S_1$ and $S_2$ which connect the second generator to the busses, it is necessary that its polarity be correct and that its terminal voltage be the same as the voltage of the busses. After the switches $S_1$ and $S_2$ have been closed, the second machine can be made to take its share of the load by varying its field resistance. In case generator 1 should suddenly take more than its share of load, its prime mover will tend to slow down in speed, and therefore the terminal voltage of generator 1 will drop. At the same time generator 2 will run faster

---

[1] For a more detailed description of differentially compounded generators, see any standard textbook on direct-current machinery.

and generate a higher voltage on account of the decrease in its load. This increase in voltage of machine 2 will cause it to deliver more load, thereby removing the excess load from machine 1. It follows from the above discussion that shunt generators will automatically adjust themselves to carry the particular percentage of the total load for which they have been adjusted.

*b. Compound Generators.*—In Fig. 38*b* are shown two compound generators operating in parallel. If machine 1 tends to take more than its proper share of the load, the series excitation of machine 1 increases, thereby increasing its voltage, so that it will still take more of the load, so that the operation is unstable. Furthermore, if the prime mover on machine 2 fails for an instant, that machine slows down, its generated voltage falls, and current flows back from the line to operate it as a motor. Under these conditions the shunt excitation remains unchanged, but the current in the series-field winding is reversed, so that the generator will operate as a differentially wound motor, thereby increasing in speed and possibly running away.



(a)-Shunt Generators. (b)-Compound Generators

FIG. 38.—Parallel operation of two-wire direct-current generators.

To prevent instability when compound-wound machines are operated in parallel, a busbar of large cross section and negligible resistance is connected between *a* and *b*, as shown in Fig. 38*b*. Such a busbar is called an "equalizer." The equalizer places the series fields of the two generators in parallel; therefore any increase of voltage of one machine will cause an increase of current through both series fields, the actual values of series-field current being inversely proportional to the resistance of each coil. In this manner compound-wound generators can be operated in parallel with just as much success as shunt-wound machines.

**28. Three-wire Direct-current Generators.**—The great disadvantage of direct current for general power purposes lies in the fact that its voltage cannot readily be changed, except by the use of rotating machinery, which in most cases is too expensive. In some cases the advantages obtained from the use of direct current are great enough to overbalance its disadvantages. In order to obtain at least two values of voltage the so-called three-wire direct-current system was developed.

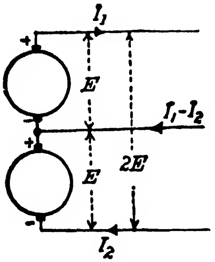
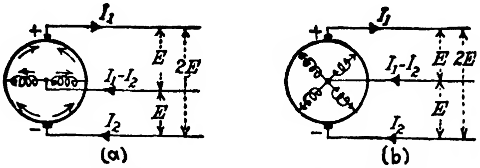


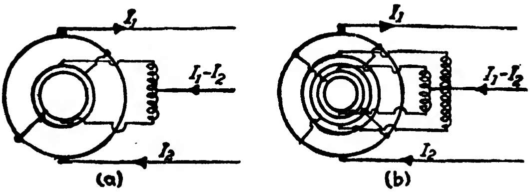
FIG. 39.—Three-wire system using two generators.



(a) (b)

FIG. 40.—Elementary three-wire direct-current generators.

The early three-wire systems were operated with two similar generator units connected in series, the neutral of the system being obtained from the common point between the two generators, as shown in Fig. 39. Because of the excess cost of such a system on account of the necessity of two generators, the three-wire generator was developed. Such a generator is illustrated in Fig. 40. It consists of a standard two-wire machine with one or two coils of high reactance and low resistance, connected permanently to diametrically opposite points of the armature wind-



(a) (b)

FIG. 41.—Three-wire direct-current generators with external compensators.

ing. In some cases these coils are connected directly to the armature windings and rotate with the generator, their neutral points being connected together, the connection to the neutral wire of the system being made through one slip ring. It is found advisable in some cases to place the coils or compensators, as they are sometimes called, apart from the generator. Examples of such machines are shown in Fig. 41. It can readily be seen that the voltage between terminals of the compensators is alternating, but, owing to the high reactance of the coils, very small values of alternating current will flow through the compensators. If the loads applied to each side of a three-wire system are balanced, there will be no current flowing over the neutral of the system, and hence there will be no direct current flowing through the compensators. Under these conditions the potential of the neutral line will be exactly halfway between the potentials of the two outer wires. When a three-wire system is unbalanced, there will be a current flowing over the neutral line, and hence the current in the compensators will be the resultant of an alternating and direct current. Under these conditions the potential of the neutral will no longer be midway between the two outside terminals of the generator. For this reason it is not good practice to operate a three-wire system with more than 25 per cent unbalanced load. Machines can be built to give a regulation of 2 per cent or less with an unbalanced load of 25 per cent.

**29. Compound-wound Three-wire Generators.**—From a study of Fig. 39, it is obvious that in order properly to compound a three-wire generator the series field must be divided into two sections, the two sections being connected in the two outer lines of the generator, respectively. In this manner proper compounding is obtained which is independent of the amount of unbalancing of the loads. In general all the series coils on the north poles are placed on one side of the circuit and all series coils on the south poles placed on the other side of the circuit.

**30. Parallel Operation of Three-wire Generators.**—When two or more three-wire generators are operated in parallel, it becomes necessary to install two equalizer busses on account of the two sections of the series-field winding being in the two outer lines of the system. A simplified diagram of connections is given in Fig. 42. In order properly to protect each generator, it is necessary to place circuit breakers in the armature circuit of each generator instead of in the line circuits. This complicates the switchboard wiring very much, as indicated in Fig. 42.

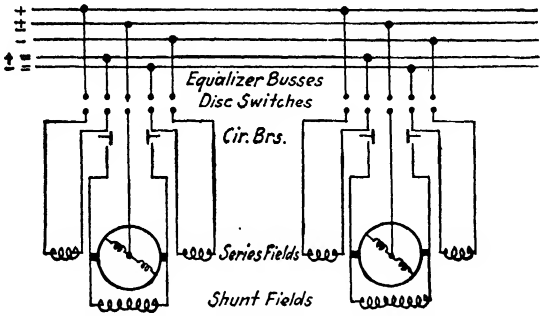


FIG. 42.—Parallel operation of three-wire direct-current generators.

## ALTERNATING-CURRENT GENERATORS

**31. Synchronous Alternating-current Generators.**—Synchronous alternating-current generators may be classified according to:

- Frequency
- Number of phases
  - Single
  - Two
  - Three
    - Y connected
    - Delta connected
- Relative motion
  - Revolving armature
  - Revolving field
  - Engine type
- Type of prime mover
  - Water-wheel type
    - Vertical
    - Horizontal
  - Steam-turbine type

**32. Frequency.**—There are two frequencies, namely, 25 and 60 cycles per sec., which are considered as standard in the United States, with some 50 cycles per sec. used in some sections. There are a few installations still in operation at other frequencies, but these are being rapidly displaced in favor of one of the above frequencies. Generally, it can be said that the weight per kilowatt capacity of all electrical equipment increases as the frequency is decreased; hence it is to be expected that the cost per kilowatt capacity of electrical equipment should increase as the frequency is decreased.

For general lighting service higher frequencies are better on account of the absence of flicker in the light given out by lamps.

There is naturally a great advantage derived from one standard frequency in that different companies can then interconnect their systems, which is becoming more and more important as the demands for electric power increase. There is, therefore, a general tendency to make 60 cycles per sec. the one standard of the country, but there are still a few demands that are important enough so that 25 cycles per sec. is still used to a considerable extent. The most important requirement for 25 cycles per sec. is for railway service. Probably the reason 25 cycles per sec. was adopted in some railway electrifications was owing to the fact that the early synchronous converters did not operate satisfactorily on frequencies above 40 cycles per sec. It should be kept in mind that a good many electric railways operate with direct current obtained from alternating-current systems through synchronous converters.

**33. Number of Phases.**—Practically all modern alternating-current generators are wound three phase, but there are a few single-phase and two-phase generators used in systems that were originally developed as single- or two-phase systems. The reason why practically all generators are three phase is that more capacity can be obtained out of a given armature when wound three phase than when wound either single or two phase. Furthermore, it is more economical to transmit power over a three-wire three-phase circuit than over a four-wire two-phase circuit. To prove this statement, take a machine with six slots per pole. Let $e$ equal the effective value of the e.m.f. induced in each coil of the winding and $I$ the current per conductor, which will be the same for any of the windings for the same temperature rise.

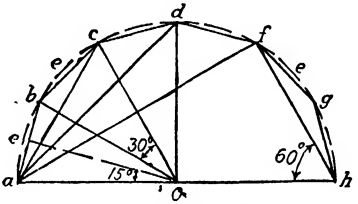


FIG. 43.—Induced voltages in alternators.

When wound single-phase using all the slots, the terminal voltage obtained is $ah$ (Fig. 43) where $ah$ is made up of the vector summation of six voltages, each being equal to $e$. The single-phase voltage obtained in this case is equal to

$$ah = \frac{e}{\sin 15 \text{ deg.}} = \frac{e}{0.2588} \qquad (7)$$

Therefore the output is

$$P_1 = \frac{e}{0.2588} I \cos \phi = 3.86eI \cos \phi \qquad (8)$$

where $\phi$ is the power-factor angle.

When wound single-phase using only four slots per pole, the terminal voltage will then be equal to

$$af = 0.866ah = \frac{0.866e}{0.2588} = 3.32e \qquad (9)$$

Therefore the output is

$$P_1 = 3.32eI \cos \phi \qquad (10)$$

When wound two-phase with three slots per phase per pole, the terminal voltage per phase will be equal to

$$ad = 0.707ah = \frac{0.707e}{0.2588} = 2.74e \qquad (11)$$

Therefore the output is

$$P_2 = 2 \times 2.74eI \cos \phi = 5.48eI \cos \phi \qquad (12)$$

When wound three-phase with two slots per phase per pole, the terminal voltage per phase will be equal to

$$ac = \frac{ah}{2} = \frac{0.5e}{0.2588} = 1.93e \qquad (13)$$

Therefore the power output is

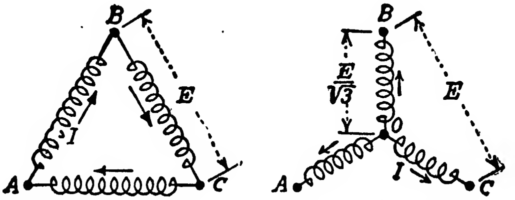
$$P_1 = 3 \times 1.93eI \cos \phi = 5.79eI \cos \phi \qquad (14)$$

Taking the three-phase rating as 100 per cent, the comparative ratings are as given below:

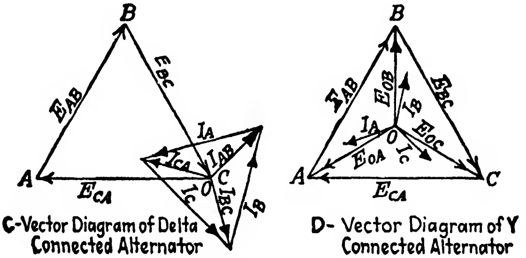
| Number of Phases | Rating, Per Cent |
|---|---|
| Three phase | 100.0 |
| Two phase | 95.0 |
| Single phase, using all slots | 67.0 |
| Single phase, using only four slots per hole | 57.7 |

**34. Armature Connections.**—As indicated in Art. 33 nearly all modern alternating-current generators are wound for three-phase service. Three-phase generators may be connected either of two ways, namely, in delta or Y. The two methods are illustrated in *A* and *B* of Fig. 44. In each case the terminal e.m.fs. are 120 electrical degrees apart, as indicated by the complete three-phase vector diagrams shown in *C* and *D* of Fig. 44 which are drawn for a power factor of 80 per cent lagging current. Of these two methods, the Y-connected generator is preferable, the main advantages being:

1. A neutral point of the winding is available. Such a neutral point is often useful, as will be seen later.



A- Delta-Connection B-Y-Connection



C-Vector Diagram of Delta Connected Alternator D- Vector Diagram of Y Connected Alternator

Fig. 44.

2. Approximately 58 per cent less conductors are needed in the Y-connected generator to produce the same delta voltage.

3. It is impossible for third harmonic currents to circulate in the generator windings.

In large-capacity generators it is not practical to use a single circuit per phase on account of the large section of copper that would be necessary; hence two or more parallel circuits per phase are often used in order to avoid large sections of conductors, which would be hard to handle and form into coils.

**35. Grounding of Generator Neutral.**—As was indicated in Art. 34, three-phase generators are generally connected in *Y*, thereby making available a common point to all three phases, known as the neutral. It is also common practice to connect this neutral point to ground, the main reasons being as follows:

1. The neutral of the three-phase system is stabilized.
2. It offers a low-resistance path to ground, thereby preventing the accumulation of electrostatic charges.
3. It makes possible the protection of generators against internal grounds as well as short circuits from phase to phase by means of the differential protection generally given to alternators (see Chap. XVII).

The neutral may be grounded directly or through a resistance, the particular method adopted being dependent on particular conditions. In the case of power plants directly supplying a large number of comparatively low-voltage feeders and particularly underground cables, a ground on any part of the circuit will mean a dead short circuit on the particular generator phase. Such plants generally connect a large enough resistance in the neutral to limit such short-circuit currents to a safe value. One of the most common causes of interruption of this nature is due to arcing grounds, which in some cases may set up transient voltages of very large magnitudes. If a resistance is used instead of a reactance, the transient high-frequency oscillations produced by an arcing ground will be damped out to a considerable extent, so that very high voltages will not occur. Also owing to the presence of the resistance in the neutral, the current flowing to ground will be more in phase with the voltage, and more definite selective action of the relays in the system is obtained.

In the case of power plants supplying only high-voltage transmission lines, it is common practice to connect the generator neutral direct to the ground. In such cases there is generally enough reactance in the circuits, so that the currents that will flow in case of grounds are not dangerously high. In power plants involving a number of units that have different characteristics or different wave shapes of voltage, a harmonic current will circulate between the machines if all are grounded; hence often only one or two generators are grounded. In case all machines are alike, there is no reason why all may not be safely grounded.

**36. Relative Motion.**—Practically all alternators now in use are of the revolving-field type, the revolving-armature type of generator being confined to direct-current units, in which case the necessity of a commutator practically demands that the armature be the revolving member. The revolving field has entirely superseded the revolving-armature type of construction in the case of alternators owing to the following main reasons:

1. The armature end windings can be more satisfactorily braced in the case of a stationary armature.
2. With the terminal voltages obtained from present-day alternators, it is entirely out of the question to use rubbing contacts to collect the current from the armature.
3. Cheaper construction.

Revolving-field alternators are divided into two classes: (1) salient-pole machines and (2) nonsalient-pole machines. The nonsalient-pole generators are practically confined to high-speed turbogenerators, in which case the rotors must be made of relatively small diameters and, in order to provide ample strength, are made cylindrical with the field windings placed in slots around the surface of the rotor.

**37. Type of Prime Mover.**—The type and speed of the prime movers will necessarily determine to a great extent the general type of alternator used. Alternating-current generators can, therefore, be classed as engine type, water-wheel type, or steam-turbine type.

*a. Engine-type Alternators.*—This type of generator is designed for operation with reciprocating steam engines and internal-combustion engines, which may be either gas or oil engines. The application of these different types of prime movers is discussed in Art. 5. Since the angular velocity of any type of reciprocating engine is not uniform, it is necessary that such generators be operated with a large flywheel mounted on the same shaft with the generator and engine. In some cases the rotor of the alternator can be designed to incorporate the necessary flywheel effect. In Figs 45 and 46 are shown the armature and rotor of a typical engine-type alternator.

For higher capacity alternators of moderate speeds it has been found best to use the type of construction shown in Fig. 47. The pole pieces, instead of being bolted on to the speed ring as shown in Fig. 46, are secured by means of dovetails and tapered keys, two tapered keys being used, these being driven in from opposite ends.

*b. Water-wheel-type Alternators.*—As the name indicates, such units are driven by water turbines, which may be of the impulse,

FIG. 45.—Stationary armature of engine-type alternator for diesel-engine drive. (*Westinghouse Electric Corporation.*)

FIG. 46.—Rotating field for engine-type alternator of Fig. 45. (*Westinghouse Electric Corporation.*)

reaction, or propeller type. The range of operating conditions for this type of unit, as found in practice, is very great. The Keokuk 9,000-kva. generators operate at a speed of 58 r.p.m., while water-wheel-driven generators operating at 300 r.p.m. are very common, and in some cases a speed as high as 750 r.p.m. has been used. Such demands as these call for varied types of construction. The demands of the prime movers, namely, impulse, reaction, and propeller wheels, also have a great influence on the type of construction used for the generators. Impulse water-wheel generators are generally of the horizontal type, as shown in Fig. 11; reaction water-wheel generators of the horizontal and also of the vertical types have been built, but the hydraulic details of the turbine discharge or draft tube are better worked out in the case of vertical units; hence there is a general tendency in present-day design to adopt the vertical type of construction for the reaction-wheel generator units. A typical vertical reaction water-wheel unit is shown in Fig. 12, and a

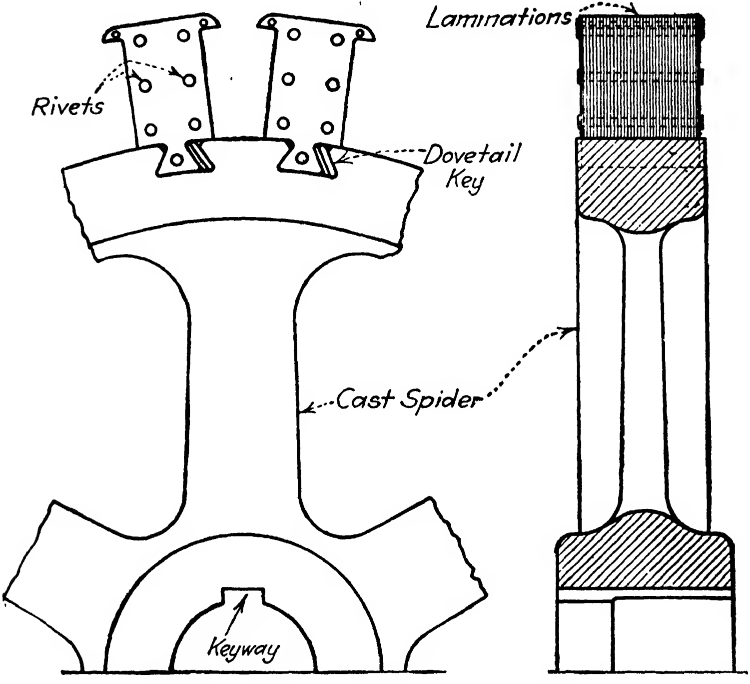


Fig. 47.—Rotor of moderate-speed alternator.

noteworthy installation of vertical reaction water-wheel-driven generators is shown in Fig. 52. The propeller type of water wheel has very much of the same general characteristics as the reaction wheel; hence it is to be expected that the vertical type of construction is the most suited for such installations.

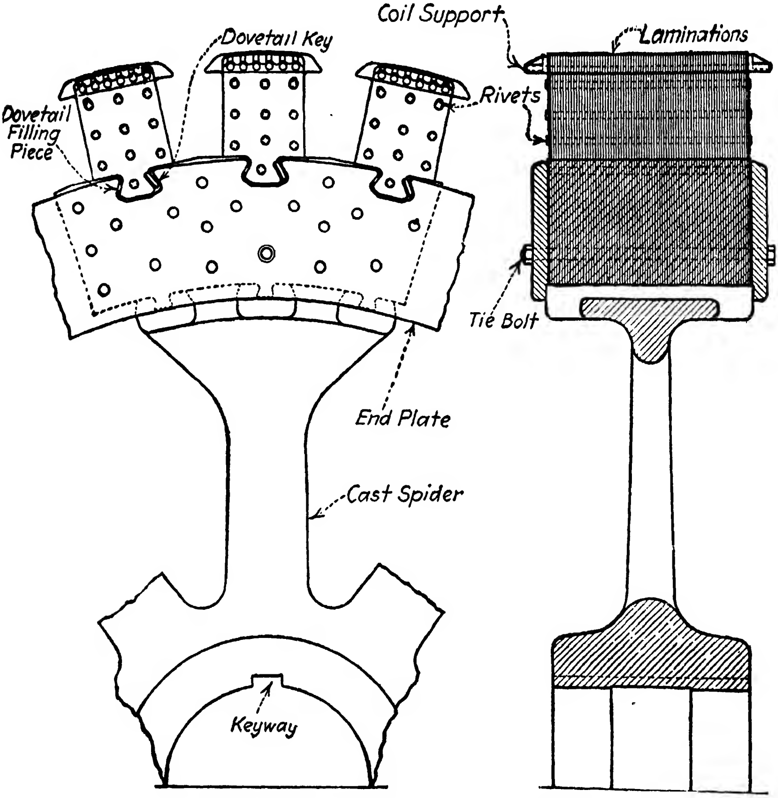


Fig. 48.—Rotor of medium-speed alternator.

Slow-speed horizontal generators are, in general appearance, very similar to engine-type alternators, as shown in Fig. 47. For high speeds and moderate capacities, the field spider is sometimes made up of sheet-steel punchings (Fig. 48), and for higher capacities rolled-steel plates are used (Fig. 49). These punchings or plates are held together by means of rivets or bolts, the complete rotor being provided with dovetailed grooves into which are fastened the field poles (see Figs. 50 and 51). Vertical units, as a

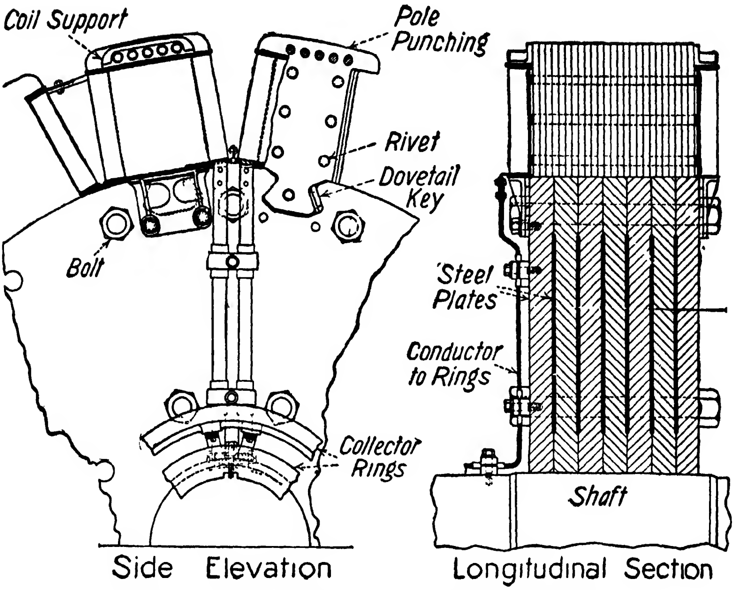


FIG. 49.—Rotor of high-speed salient-pole alternator.

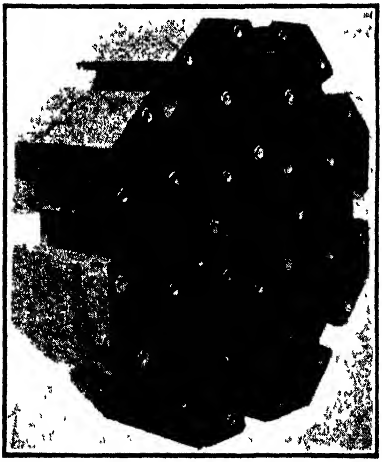


FIG. 50.—Rotor for high-speed salient-pole alternator.

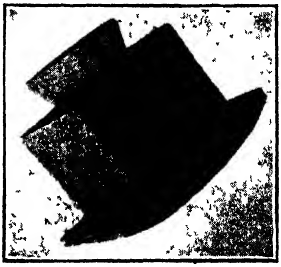


FIG. 51.—Laminated pole for rotor shown in Fig. 50.

general rule, operate at moderate speeds and hence have fairly large diameters. The rotors of such units resemble flywheels, with the field poles bolted to the outside circumference. An example of a rotor for a fairly large generator is shown in Fig. 54, the stator for the same unit being shown in Fig. 53. For very large capacities it becomes necessary to build up the spider of separate parts, which are in themselves complete flywheels as indicated in Fig. 12. In order to obtain good speed regulation of water-wheel units, it is necessary that they be designed with a large flywheel effect. This is generally obtained by designing the generator rotor with sufficient weight.

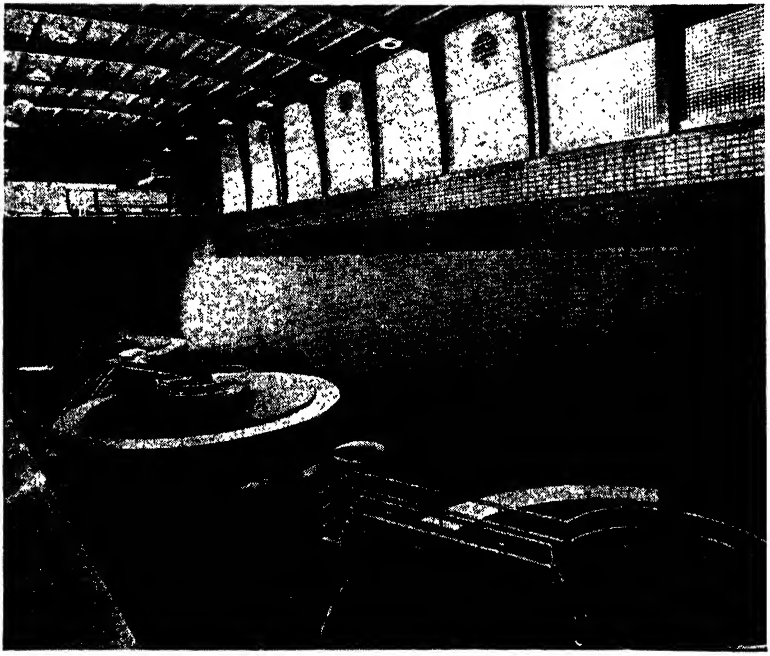


Fig. 52.—Interior view of generator room of Chickamauga powerhouse, of the Tennessee Valley Authority. (*Allis-Chalmers Manufacturing Company.*)

Of late years welding has been used more and more in the manufacture of electrical equipment. Rotors and stator frames are built up of standard structural steel members which are then welded together. This procedure means a considerable saving in labor and time of manufacture and also produces a stronger machine.

A recent development, which is finding considerable favor, is the umbrella type of construction for vertical water-wheel generators. In this type of machine the thrust bearing is placed below the rotor. In place of two guide bearings as used in the conventional design, only one guide bearing is used in the new design, this bearing being incorporated with the thrust bearing. The umbrella type of generator is specially adapted to low- and medium-head plants where the generator proportions involve a comparatively large rotor diameter to a short length. This makes it possible to locate the one guide bearing very close to the center line of the rotor. Furthermore, since the thrust bearing is below the rotor, the entire weight of the unit is transmitted through the lower frame bracket direct to the foundation.

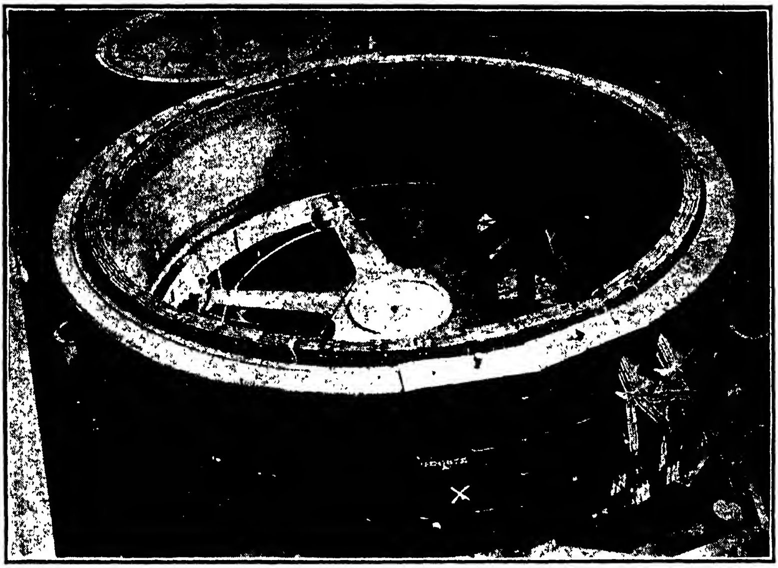


Fig. 53.—Yoke of 18,750-kva., 6,600-volt, 60-cycle, three-phase, 112½-r.p.m. vertical water-wheel generator for Southern Power Company. (*Allis-Chalmers Manufacturing Company.*)

The problem of supporting the revolving element of vertical units is one requiring careful consideration. All vertical units have the entire weight of the generator rotor and water wheel carried by a thrust bearing located at the top of the generator. There are two generally accepted types of thrust bearings that are used in practice, namely, the Kingsbury thrust bearing and the spring thrust bearing. The Kingsbury bearing consists of a stationary and a revolving plate submerged in a bath of oil. The lower plate, which is stationary, is made up of segments that are free to move in a shoe so that proper alignment of the individual segments is automatic. In the case of the spring bearing the stationary plate is supported by a large number of short helical springs which allow proper alignment of the two halves of the bearing.

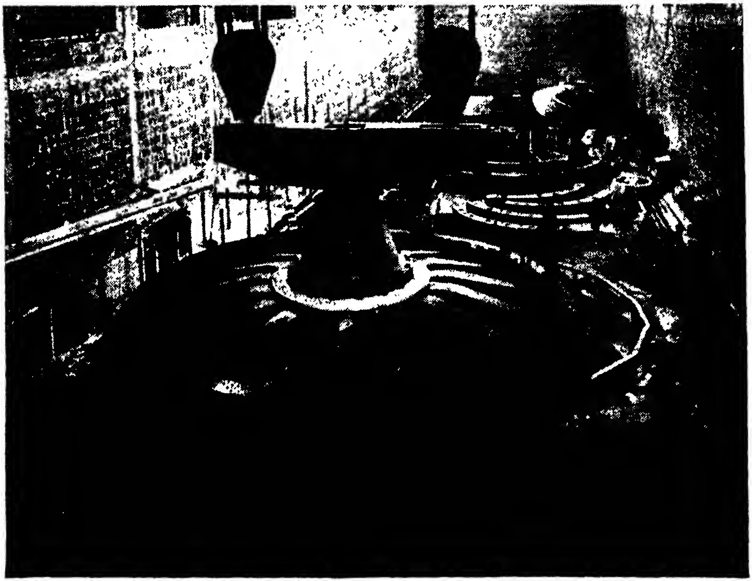


Fig. 54.—Rotor of 30,000-kva., 75-r.p.m., vertical water-wheel generator. Diameter of rotor, 31 ft. 7⅛ in. Outside diameter of complete unit, 46 ft. 3 in. Total rotor weight plus hydraulic water-wheel thrust, 2,050,000 lb. (*Allis-Chalmers Manufacturing Company.*)

*c. Steam-turbine Type.*—As the name implies, such generators are designed for operation with steam turbines. The standard speeds of such units are as follows: 1,500 r.p.m. for two pole 25 cycles per sec. units; 1,200, 1,800, and 3,600 r.p.m. for 60 cycles per sec. units of six, four, and two poles, respectively. Of the 60 cycles per sec. units the most common is probably the four-pole generator running at 1,800 r.p.m. In the early development of such units vertical mounting was considered feasible, and accordingly a number of such vertical units were built, but it was soon realized that the horizontal method of mounting was superior in many details; hence, today turbogenerators are entirely of the horizontal type. The high speed at which these generators run necessarily makes their relation of length to diameter much greater than in the definite-pole engine-type machines; also since a high-speed machine is so much smaller for the same capacity than a slow-speed one, the amount of heat liberated will be much greater in proportion to the size of the machine. This necessitates forced ventilation, and in order properly to place the ventilating air at the points where it will do the most good, turbogenerators are totally enclosed, with definite air passages through the machine. Methods of ventilating such machines will be covered later. A brief description of the most important features of turboalternators is given below.

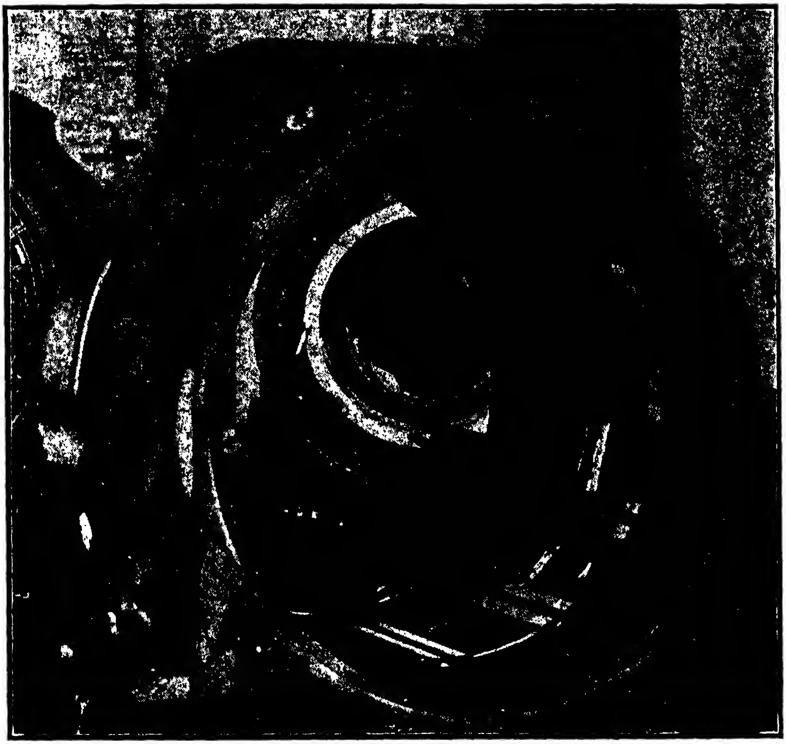


Fig. 55.—Turbostator yoke and punchings; showing the method of inserting the punchings. (*Allis-Chalmers Manufacturing Company.*)

(1) Armature Yoke.—The armature yoke of a typical machine

is shown in Fig. 55. It is cast in one piece except in the large-size machines, in which case it is made up in sections. The armature laminations are fastened to the yoke by means of dovetailed grooves as shown in Fig. 55, a section of lamination being shown in place.

(2) Armature Core.—The armature core forms the part of the magnetic circuit in the stator. It is built up of sheet punchings of high permeability and low hysteresis loss. These are thoroughly japanned on both sides in order to reduce eddy currents in the iron to a minimum and are stacked in sections separated by spacers, thereby providing radial ducts throughout the length of the armature core and ensuring proper circulation of cooling air through the machine.

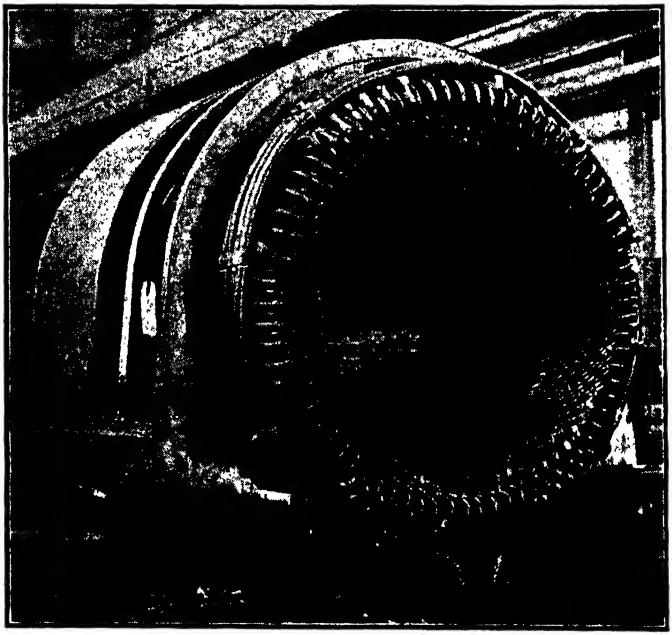


FIG. 56.—Stator of turbogenerator, 12,500 kva., 2,300 volt, 1,800 r.p.m., three phase, 60 cycle. (*Allis-Chalmers Manufacturing Company.*)

(3) Armature-coil Supports.—It is essential that the free ends of the armature coils be rigidly supported to withstand the large stresses produced under bad short-circuit conditions. Under short circuits the end connections of the coils may be dis-

placed laterally and radially; hence they must be firmly supported to the frame as shown in Fig. 56.

(4) Rotor.—There are two common types of rotor construction that have been found satisfactory. In Fig. 57 is shown a solid type of rotor, in which case the rotor and shaft are forged in one solid piece. Figure 58 shows a complete rotor made up of rolled-steel plates about 2 in. thick. In this type of construction the shaft is a forging ending in a flange of the same diameter as the rolled-steel disks. The shaft flanges and the rolled-steel disks are held together by means of large through bolts. In both types, the slots that carry the field winding are milled out, as shown in Fig. 59. The advantage of the rolled-steel-plate method of

FIG. 57.—Rotor of 12,500-kva., 11,000-volt, 60-cycle, three-phase, 1,800-r.p.m. turboalternator built for City of Cleveland. (*Allis-Chalmers Manufacturing Company.*)

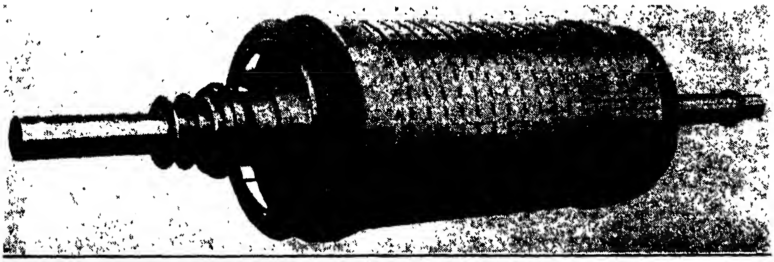


FIG. 58.—Rotor for 7,500-kva., 1,800-r.p.m., four-pole turbogenerator. (*Allis-Chalmers Manufacturing Company.*)

construction is that a more uniform grade of steel can be obtained than is possible with the solid forging.

(5) Field Winding.—The field winding is generally composed of strap copper laid flatwise in the rotor slots. This brings the pressure due to centrifugal force on the flat side of the copper; hence there is no possibility of the insulation between turns becoming chafed or cut. Figure 59 shows a rotor in the process of being wound. The insulation between turns is generally composed of mica in order to withstand without injury the high temperatures to which turboalternators are subjected. In some of the larger machines it has been found necessary to use something mechanically stronger than mica and the standard insulating tapes for the slot insulation. The intermittent heating and cooling of the rotor cause the field copper to expand and contract, thus producing a rubbing action between coils and slots.

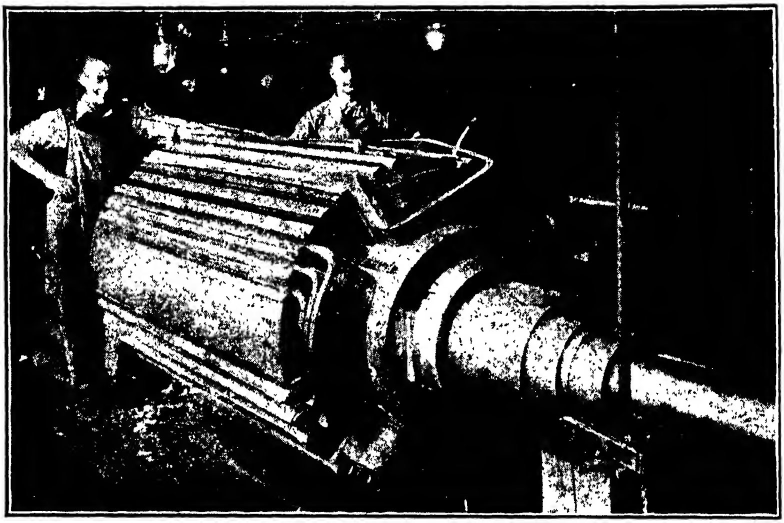


FIG. 59.—Rotor of 12,500-kva., 1,800-r.p.m., 60-cycle turboalternator in process of winding. (*Allis-Chalmers Manufacturing Company.*)

**38. Leakage Reactance and Armature Reaction.**—Figure 60 shows a two-pole three-phase alternator, the size of the dots and crosses indicating the relative values and directions of the currents in the three phases. Diagram *A* indicates the conditions existing between the armature and the field when the armature current is in phase with the generated voltage. Diagram *B* indicates conditions when the current in the armature lags the generated voltage by 90 electrical degrees, and diagram *C* when the current in the armature leads the generated voltage by 90 electrical degrees. There are two distinctly *different* results produced in an alternator due to the armature windings carrying current, namely, *leakage reactance* and *armature reaction.*

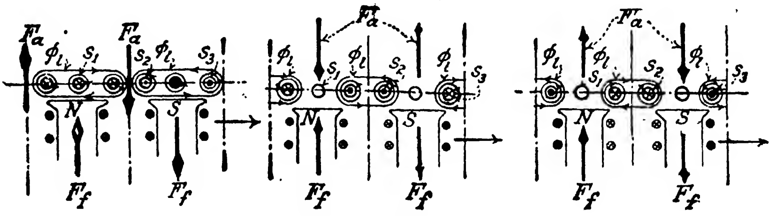


Fig. 60.—Armature reaction.

**39. Leakage Reactance.**—The alternating current in the armature windings will set up a certain magnetic flux $\phi_l$, which will encircle each conductor or group of conductors, as shown in Fig. 60. This flux is generally called the armature-leakage flux to distinguish it from the flux that crosses the air gap and is available as useful flux to generate the alternator voltage. The effect of the armature-leakage flux in an alternator is identical with the effect of the flux produced in a choke coil, or any other alternating-current circuit. In all cases a voltage of self-induction is induced in the particular circuit. This voltage of self-induction is proportional to the rate of change of current producing the magnetic flux or, expressed mathematically,

$$e_{s.i.} = -L\left(\frac{di}{dt}\right) \qquad (15)$$

where *L* is the inductance of the circuit. It should be realized that as long as the circuit is not magnetically saturated or its physical dimensions and qualities are not changed, the inductance is as much a constant of the circuit as is its electrical resistance. It follows, therefore, that an alternator has inductance and hence reactance, which is generally spoken of as the *leakage reactance,* because it is produced by the armature-leakage flux.

The leakage reactance of salient-pole alternators varies with power factor, being a maximum when the current is in phase with the generated voltage and a minimum when the current is out of phase with that voltage by 90 electrical degrees. This is due to the difference in the magnetic reluctance of the path of the leakage flux at unity and zero per cent power factor. The actual difference is not great, and for all general purposes the leakage reactance of a given alternator may be assumed constant. In the case of nonsalient-pole machines the leakage reactance does not vary with power factor, since the reluctance of the air gap is uniform around the entire circumference of the rotor.

**40. Armature Reaction.**[1]—The resultant m.m.f. produced by a three-phase alternator armature when carrying current is of practically constant magnitude but revolves at synchronous speed; hence it is fixed in position relative to the field m.m.f. When the armature current is in phase with the generated voltage, the armature m.m.f. is cross-magnetizing; at zero per cent power-factor leading current the armature m.m.f. is magnetizing, and at zero per cent power-factor lagging current the armature m.m.f. is demagnetizing in its effect upon the field m.m.f. These three conditions have been shown in diagrams *A*, *B*, and *C* (Fig. 60). In all the cases considered, the *magnetic flux* that will cross the air gap will be due to the *net* m.m.f. obtained from the interaction of the *armature* and *field* m.m.fs.

To simplify the discussion that follows, an alternator is assumed to have a constant field m.m.f. It will be further assumed that it supplies a resistance load; hence the alternator power factor may be taken as unity. At this power factor the armature m.m.f. is cross-magnetizing, and therefore the magnetic flux crossing the air gap is practically the same in magnitude at full load as at no load. Suppose a complete three-phase short circuit occurred at the terminals of the generator. Since the resistance of the alternator is small compared with its leakage reactance, the initial rush of current flowing into the short circuit will be

$$I_i = \frac{E_g}{(\sqrt{3}\,X_l)}\,* \tag{16}$$

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[1] For a detailed treatment of armature reaction of alternators, see any standard textbook on alternating-current machinery.

* This equation assumes that the current transient of the alternator is symmetrical about its horizontal axis. For a more detailed treatment of the transient period of an alternator under short circuit, see Chap. XIII.

where $I_i$ = initial current, amperes

$E_g$ = the generated voltage per line, or normal no-load voltage

$X_t$ = transient reactance in ohms, approximately equal to the leakage reactance

Immediately after the short circuit has occurred, the power factor begins to drop, the final value being practically zero per cent lagging current. At this power factor the armature m.m.f. is demagnetizing; hence the net m.m.f. acting across the air gap will be

$$\text{M.m.f.}_{\text{net}} = \text{m.m.f.}_f - \text{m.m.f.}_d \qquad (17)$$

where $\text{m.m.f.}_d$ is that portion of the total armature m.m.f. which is effective in demagnetizing the field poles. In the case of nonsalient-pole machines that have distributed field windings as well as distributed armature winding, the entire armature m.m.f. is effective in demagnetizing the field.

Still assuming that the field m.m.f. is constant, it is clear that the net m.m.f. will be small on account of the high value of the armature-demagnetizing m.m.f. due to the high armature current. The magnetic flux crossing the air gap will vary practically in direct proportion to the net m.m.f., because the magnetic circuit of the alternator will not be saturated under these conditions. It is evident, therefore, that the generated voltage will begin to drop immediately after the short circuit has occurred, the particular value of the voltage at any instant being determined by the value of the flux crossing the air gap at the same instant. The current flowing into the short circuit at any instant can still be obtained as before, namely,

$$I_x = \frac{E_x}{(\sqrt{3}\,X_t)} \qquad (18)$$

where $I_x$ = current flowing into the short circuit, at $x$ sec. after the short circuit has been produced

$E_x$ = generated voltage at $x$ sec. after the short circuit has occurred

$X_t$ = transient reactance of the alternator

The current flowing into the short circuit will become steady at a value that will produce sufficient armature-demagnetizing m.m.f. to limit the flux crossing the air gap to a value just large enough to generate the necessary voltage to send this current through the armature-leakage reactance.

In the actual case of an alternator equipped with a voltage regulator, the field m.m.f. does not remain constant, but increases after the short circuit has occurred, because all voltage regulators try to maintain constant voltage. In computing short-circuit currents in a large network, it is convenient to use a *fictitious* quantity called *synchronous reactance*, which is equal to the no-load voltage of the alternator divided by the *sustained short-circuit current* which the alternator will deliver to a short circuit at its terminals or, expressed mathematically,

$$X_s = \frac{E_g}{(\sqrt{3}\, I_s)} \qquad (19)$$

where $E_g$ = no-load voltage
$I_s$ = sustained short-circuit current
$X_s$ = synchronous reactance, ohms

The reason that this *fictitious* quantity is spoken of as a reactance is due to the fact that the effect of armature reaction in reducing the generated voltage and hence the short-circuit current is the same as if the *generated voltage* actually *remained constant* and an additional reactance were introduced in the alternator, the value of the total reactance that would be necessary in order to limit the short-circuit current to the sustained value being called the *synchronous reactance* to distinguish it from the *leakage reactance*, which is the actual reactance in the alternator and therefore determining the instantaneous value of short-circuit current. The quantity synchronous reactance is used so extensively that often the student takes for granted that such a quantity actually exists, the result being that the actual operation of a generator under short-circuit conditions is not understood.

**41. Magnetic-flux Distribution in the Air Gap of Alternators at Full Load.** *a. Nonsalient-pole Machines.*—The common type of construction of turboalternator field windings is shown in Fig. 59. A cylindrical rotor is used, the field winding being distributed around the circumference of the rotor. The field m.m.f. produced by such a winding is, therefore, also distributed along the air gap of the machine. Similarly, the m.m.f. produced by the armature current of a three-phase alternator is distributed around the circumference of the armature. The actual distribution of these two m.m.fs. along the air gap of the machine is accurately represented by two stepped waves[1] that move at synchronous speeds; hence they are fixed in space with respect to each other. Modern turboalternators are designed with a fairly large number of slots per pole, on both the armature and field; hence these two stepped waves of m.m.fs. approach rather closely the shape of sine waves.

If the field and armature m.m.fs. are distributed in space according to the sine law, they can be represented by two vectors,

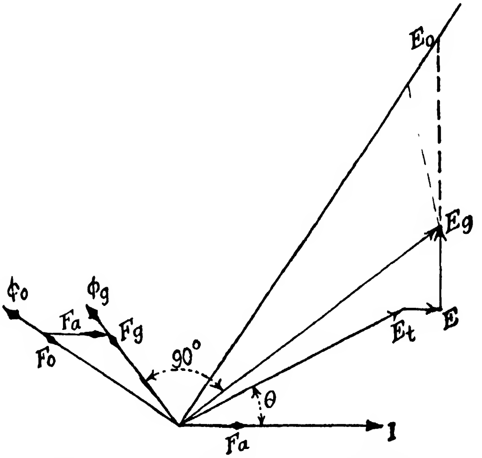

FIG. 61.—Time and space vector diagram of an alternator. Current lagging voltage by small angle.

the angle between these vectors indicating the displacement in electrical degrees between the two m.m.f. waves. The resultant obtained from the addition or subtraction of two sine waves is another sine wave; hence the net m.m.f. acting across the air gap of turboalternators is distributed according to the sine law, which indicates that the magnetic-flux density along the air gap of all nonsalient-pole machines also follows a sine law, since the magnetic reluctance is uniform around the entire circumference of the rotor.

*b. Salient-pole Machines.*—In such machines the armature m.m.f. can also be considered as distributed according to the sine

[1] See footnote to Art. 40.

law, but the field m.m.f. takes on a rectangular shape due to the fact that the field windings are confined to the external surface of the salient poles. The resultant m.m.f. that will be available in sending magnetic flux across the air gap will be composed of a rectangular wave and a sine wave of m.m.f. In addition to the unsymmetrical wave of net m.m.f., the magnetic reluctance around the air gap is not uniform in the case of salient-pole machines; therefore the flux crossing the air gap when the generator is delivering current cannot be of sine-wave shape.

**42. Alternator Vector Diagram at Full Load.** *a. Nonsalient-pole Machines.*—Assume an alternator supplying a load whose power factor is practically 80 per cent lagging current. In Fig. 61 is shown the vector diagram for one phase of such a generator. The current $I$ lags the terminal voltage $E_t$ by the angle $\theta$. In order that a terminal voltage $E_t$ be maintained, it is necessary that the generated voltage be higher by the amount of the resistance drop $IR$, and the leakage reactance drop $IX_l$. On the diagram, $E_tE = IR$ and $EE_g = IX_l$. In order to generate a voltage $E_g$, a 90 deg. leading magnetic flux $\phi_g$ is needed. This much of the vector diagram of Fig. 61 represents the relations as to time among current, voltage, and flux.

In order to establish a magnetic flux, there is needed an m.m.f. $F_g$, which is the resultant of the field m.m.f. $F_0$, and the armature m.m.f. $F_a$. The relation between the flux $\phi_g$ and the m.m.f.s $F_g$, $F_a$, and $F_0$ represents the space diagram of the alternator. These quantities do not change with time but have certain relative positions in space as indicated by the diagram of Fig. 61. As was indicated in Art. 41, the m.m.fs. acting across the air gap of a nonsalient-pole machine are distributed approximately as the sine law; hence they can be represented as vectors, and for convenience these vectors are plotted together with the time diagram. If the load is thrown off, the armature m.m.f. becomes equal to zero, and the m.m.f. acting across the air gap is that due to the field alone, or $F_0$ (Fig. 61), and a magnetic flux $\phi_0$ will be produced. If the magnetic circuit of the alternator is not saturated, the ratio $\phi_0/\phi_g$ will be equal to the ratio $F_0/F_g$ and also equal to the ratio $E_0/E_g$, where $E_0$ is the no-load voltage of the alternator for the same field current corresponding to the value of $E_g$. If, however, the magnetic circuit is saturated, the following will be true:

$E_0/E_g = \phi_0/\phi_g$ which will be less than $F_0/F_g$, but $E_0$ will still fall on the same line as indicated in Fig. 61.

The vector connecting $E_0$ and $E$ is seen to be made up of two components, namely, $EE_g$, which is the leakage reactance drop through the armature, and $E_0E_g$, which is the vector difference between the voltages generated at no load and full load. This vector $E_0E$ is the *synchronous-reactance* drop, and similarly the vector $E_0E_t$ is known as the *synchronous-impedance* drop of the alternator. An inspection of Fig. 61 will reveal the fact that the length $E_0E$ may be variable for a given fixed-load current, depending on the particular saturation point of the magnetic circuit; hence it follows that the values synchronous reactance and synchronous impedance decrease with increasing saturation of the magnetic circuit. In Fig. 62 is shown a time and space vector diagram of an alternator operating at zero per cent power-factor lagging current.

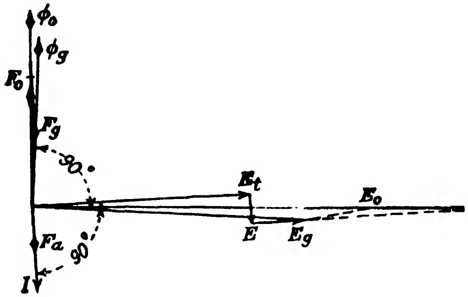

FIG. 62.—Time and space vector diagram of an alternator. Current lagging voltage by 90 deg.

*b. Salient-pole Machines.*—As stated in Art. 41 it is not correct to represent the field or the net m.m.f. acting across the air gap at full load by vectors in the case of salient-pole machines; hence a salient-pole machine cannot have a space vector diagram of m.m.fs. and flux. Nevertheless, what has been shown to be true by means of the space diagram in the case of nonsalient-pole machines is also true for the salient-pole machines, even though it is impossible correctly to represent the various components by means of vectors.

**43. Alternator Characteristic Curve.** *a. No-load Saturation Curve.*—A curve showing the variation of $E_0$ (Figs. 61 and 62) for different values of field exciting current is known as the no-load saturation curve. Such a curve is shown by curve 1 (Fig. 63). This curve rises as a straight line until the iron part of the magnetic circuit becomes saturated, from which point the curve bends over rapidly, a larger and larger rise of field current being necessary for successive jumps in voltage. The straight line drawn tangent to such a curve represents that portion of the field current or field m.m.f. consumed across the air gap of the machine.

*b. Full-load Saturation Curve.*—A similar curve showing the variation at full load of $E_t$ at zero per cent power-factor lagging current (Fig. 62) for different values of field current can be drawn as indicated by curve 2 (Fig. 63). At zero per cent power-factor lagging current, the armature reaction is demagnetizing, and if the resistance of the armature is neglected, the terminal voltage can be obtained as the arithmetical difference of the no-load voltage and the synchronous-reactance drop (Fig. 62). Since the reactance drop of modern alternators is of the order of ten to twenty times the resistance drop, it is perfectly permissible to make the above assumption. Therefore, the difference in the ordinates of curves 1 and 2 (Fig. 63) represents the synchronous-reactance drop between terminals of the generator and approximately the synchronous-impedance drop between terminals, or $\sqrt{3}IZ_s$, where $I$ is the alternator current per phase and $Z_s$ is the synchronous impedance per phase. Similar curves can be obtained for full load at any desired power factor, such as curves 3 and 4 (Fig. 63), by an application of the vector diagram of Fig. 61.[1]

It is obvious that the point of intersection of curve 2 (Fig. 63) with the horizontal axis represents full-load current delivered by the generator at zero per cent power-factor lagging current at zero terminal voltage, which can be obtained only when the generator terminals are short-circuited; hence a short-circuit current line can be drawn through the origin and a point equal to full-load current plotted directly above the point $S$, as shown by curve 5 (Fig. 63). An inspection of Fig. 63 will reveal the fact that full-load short-circuit current is delivered at a value of field current corresponding to normal no-load voltage. Hence for this particular value of field current,

$$\sqrt{3}\,E_0 = \sqrt{3}\,IZ_s \tag{20}$$

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[1] For a complete discussion of predetermining alternator characteristics, see any modern textbook on alternating-current machinery.

and

$$\frac{IZ_s}{E_0} = 1, \text{ or } 100 \text{ per cent} \tag{21}$$

Such a generator is said to have a synchronous per cent impedance of 100 per cent. The leakage-reactance drop $IX_l = EE_g$ (Fig. 61), of a typical large alternator, is approximately 25 per cent of the normal no-load voltage; hence the generated voltage under full-load short-circuit current conditions has a magnitude of 25 per cent the corresponding normal no-load voltages (neglecting the resistance drop).

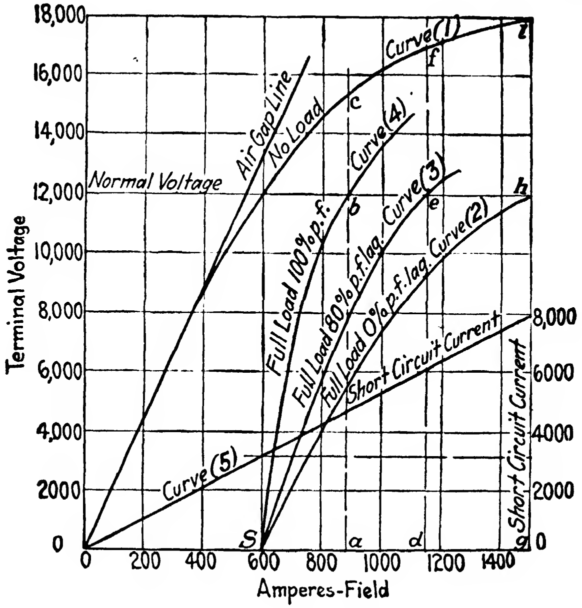

FIG. 63.—Characteristic curves of a large alternator.

**44. Voltage Regulation.**—The voltage regulation of alternators is found in the same manner as for direct-current generators (as given in Art. 25). In the case of alternators, however, the voltage regulation is different for different values of power factor. The voltage regulation at full load for the alternator whose characteristic curves are given in Fig. 63 is as follows:

At 100 per cent power-factor lagging current,

$$\text{V.R.} = \frac{bc}{ab} = 28.4 \text{ per cent}$$

At 80 per cent power-factor lagging current,

$$\text{V.R.} = \frac{ef}{de} = 41.6 \text{ per cent}$$

At 0 per cent power-factor lagging current,

$$\text{V.R.} = \frac{hl}{gh} = 50 \text{ per cent}$$

**45. Low Short-circuit Current versus Good Regulation.**—In Art 24 it was stated that direct-current generators used for lighting should not have a voltage regulation higher than 2 per cent. In contrast to such a value the regulation of an alternator at 80 per cent power factor may be as high as 42 per cent (see Art. 44). Good voltage regulation of alternators means very low synchronous reactance and, hence, very high values of current under short circuits. It is more important to the operating engineer that generators be able to stand without injury a complete short circuit than to have generators of good voltage regulation. The amount of money invested in modern large units is too much to warrant taking any chances with the damage that a short circuit may cause. Furthermore, by the use of voltage regulators, which will be described in a later chapter, the voltage of alternators may be controlled so that good operating conditions are maintained.

**46. Parallel Operation of Alternators.**—Before an alternator can be connected in parallel with another machine that is supplying a load, it is necessary that the incoming machine have the same voltage and frequency, and also be in phase with the operating machine; and before the switches are closed, it is necessary that the polarities and phase sequence of the machines be identical. The proper time to close the switch on the incoming machine can be indicated by synchronizing lamps or better by some form of synchroscope, which is described in Chap. XII. If two alternators are operating at the same frequency and are in phase but are not adjusted to give the same terminal voltage, there will be available the difference of the two alternator voltages, which will cause a current to circulate between the two machines. Since the resistance of alternators is very small compared with their reactance, the circulating current will be

$$I' = \frac{E'}{A_A + X_B} \tag{22}$$

where $I'$ = the circulating current, amperes
$E'$ = resultant voltage, causing current $I'$ to flow
$X_A$ and $X_B$ = synchronous reactances of the alternators

It is obvious, therefore, that the circulating current will lag one alternator voltage and lead the other alternator voltage by 90 electrical degrees. Therefore, this current will demagnetize the field of the alternator of higher voltage, thereby making the terminal voltages of the two machines equal.

Often one of two alternators, when operating in parallel, may slow down or increase its speed because of some cause or other, in which case the frequencies of the two machines will momentarily be different. Assuming that both alternators still maintain the same value of terminal voltage, there will be a resultant voltage due to the displacement of the two alternator terminal voltages, which will cause a current to circulate between the two machines. This current, however, is a power current, being practically in phase with the bus voltage. With respect to the alternator of higher speed it is a generator current, and with respect to the alternator of lower speed it is a motor current, the result being that the two alternators will automatically return to the same speed and therefore to the same frequency.

If two machines that are operating in parallel have the same effective value of voltage, but one is a true sine wave and the other possesses a third harmonic, there will be present a resultant third harmonic voltage acting between the machines, and, if the alternators are Y-connected with their neutrals grounded, a third harmonic current will flow between the two generators.

**47. Losses in Alternating-current Generators.**—The losses of alternating-current generators are essentially of the same nature as those for direct-current generators given in Art. 26. The relative importance of these losses is, however, different in most cases. Windage becomes very high in the case of turboalternators, while it is very low for direct-current generators. Brush friction in the case of alternators is merely due to the friction on the field slip rings and is, therefore, rather small. The iron losses are slightly higher in the case of alternating-current generators than for direct-current machines. The main reason for this is that higher frequencies of rotation are used for alternating-current machines. The copper losses are confined to the armature and field, there being no series- or commutating-pole field in the case of alternators. There are, however, rather high eddy-current losses in the armature conductors when alternators are delivering current, these losses being due to the main flux and also the leakage armature flux set up by the armature current.[1] In order to limit these losses to a reasonably small value, the conductors of alternator armatures are generally laminated.

**48. Ventilation of Alternators.**—The rating of any piece of equipment is dependent upon the temperature rise of the different parts of the equipment and, hence, upon the rate at which the losses, which appear as heat, can be radiated from the different surfaces of the equipment. It follows, therefore, that the rating of equipment can be increased by two methods, namely, increasing the radiating surface or increasing the amount of ventilation. The amount of radiating surface of generators depends on the particular type of machine. In the case of engine-type generators the amount of radiating surface obtained combined with the natural fanning action of the rotor is sufficient to carry away the heat produced in the machine; hence there are no complications present in properly ventilating such generators.

In the case of water-wheel-driven generators of the horizontal type and of medium capacities, the rotor is equipped with fans at both ends by which air is forced into the air gap of the machine, than radially outward through the vent ducts in the stator, and then expelled into the room through the openings in the stator frame. In large horizontal generators it becomes necessary to pipe the discharge air to the outside of the power house and, in some cases, also to pipe the cooling air from outside. In such cases the generators must be completely enclosed. The same general method is utilized in ventilating vertical water-wheel units. The air enters the machine from the water-wheel pit, or jointly from the water-wheel pit and above the generator, and passes through the air gap and radially outward through the vent ducts to the back of the stator core, whence it is conducted through ducts to the outside of the power house. In some cases it is necessary to use independent motor-driven fans to produce the required air circulation, the rotor fans not being capable of maintaining a large enough quantity of air flowing through the machine.

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[1] For a more detailed solution of these eddy currents, see any modern text-book on alternating-current machinery.

The problem of ventilation for turboalternators becomes very complicated on account of the relatively small radiation surface and the large axial length. The first method used for such generators is known as the simple radial system, as shown in Fig. 64. This method is the same as is used for water-wheel units, except that, on account of the much larger volume of air needed, independent motor-driven fans are always supplied to maintain

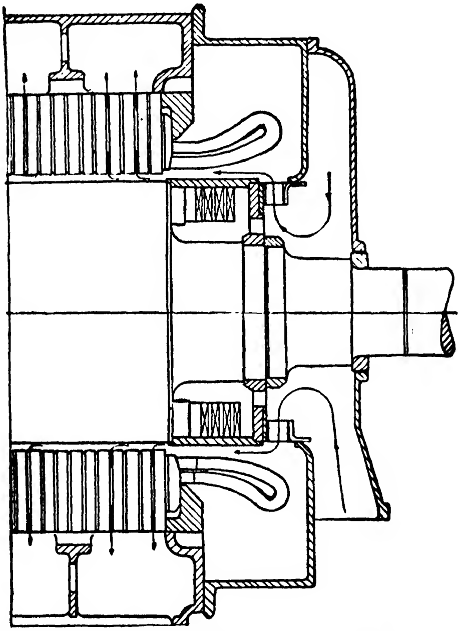

FIG. 64.—Simple radial ventilation with air entering at the ends of the air gap only.

a higher air velocity through the machine. With this construction, it becomes impossible to cool properly the center portion of the machine; hence the so-called multiple radial system was developed. This system is shown in Fig. 65. It differs from the simple radial system in that air from the end bells is carried axially across the back of the core in passages provided in the frame, passes radially into the frame through radial vent ducts in parts of the core, and travels axially through the gap and out to the back of the core through radial vent ducts in other sections of the core. Air from the end bells is also forced into the gap at the ends of the rotor. All the air is finally discharged at the bottom of the generator. Another method used in turboalternator ventilation is shown in Fig. 66. This method is known as the circumferential system. Air is delivered by the fans between and around the stator coils into a chamber formed by the end housings. The sections *AA* and *BB* form an inner annular belt just back of the stator core. The adjacent sections *AA* open directly to the incoming air, and the adjacent sections *BB* directly to the outer annular belt *D*, from which the air is discharged at the top or bottom of the generator, or at both places at the same time.

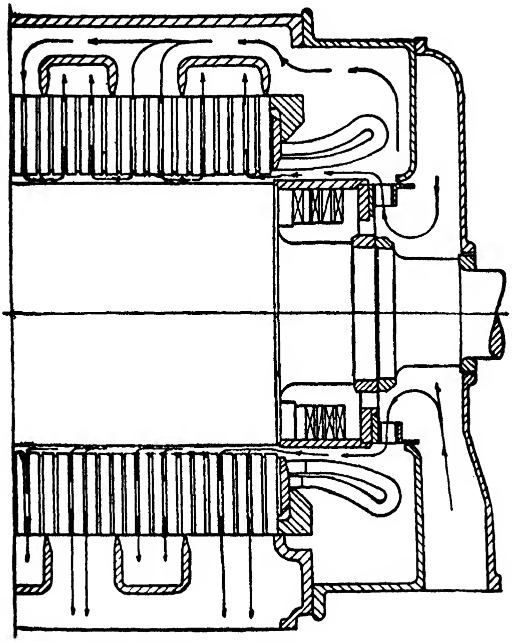

FIG. 65.—Turbogenerator with multiple-path ventilation.

It is very important that the air which is used for ventilating purposes, especially in the case of turboalternators, be perfectly clean. To secure clean air it is often necessary to pass the air through a washer before forcing it through the machine. A washer serves also as a cooler, which helps materially in the cooling of the machine. In some cases the ventilating system is made completely closed, the same air being used over and over. The air that is discharged from the generator is conducted through proper ducts to a cooler or washer and thence back to the intake of the generator. An air washer is nothing more than a large tank through which the air is passed. In this tank are mounted a large number of nozzles, which supply a continuous spray of cool, clean water.

**49. Hydrogen Cooling.**—The use of hydrogen as the cooling medium for electrical machinery has been introduced by manufacturers in the last few years, and it has so far met with considerable favor in the operation of certain types of machines. Some of the advantages of hydrogen over air are:[1] The density of hydrogen is about one-fourteenth that of air; the heat conductivity through loose types of insulation is about 25 per cent better with hydrogen; the heat conductivity across iron laminations is about three times as good with hydrogen. One disadvantage is that hydrogen and air when mixed in proper proportions will form an explosive gas; however, if the hydrogen content is above 70 per cent, there seems to be little danger of an explosion.

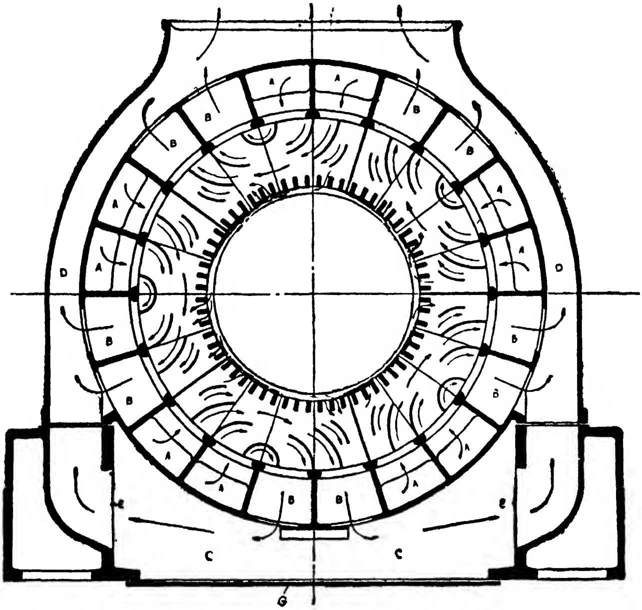

FIG. 66.—Circumferential method of ventilating turbogenerators. (*Courtesy Allis-Chalmers Manufacturing Company.*)

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[1] FECHHEIMER, C. J., Development of Hydrogen-cooled Condensers, *Elec. Jour.*, p. 165, March, 1931.

Hydrogen-cooled synchronous condensers can readily be built, since the whole unit is completely enclosed without any difficulty. In the case of alternators there is introduced a serious design problem at the point where the alternator shaft extends through the generator housing. Special pressure seals around the shaft extension must be designed in order to prevent a passage of air into the alternator case. Such an alternator is shown in Fig. 67. The machines must be made perfectly airtight, maintaining the internal pressure of hydrogen slightly above the pressure of the outside atmosphere.

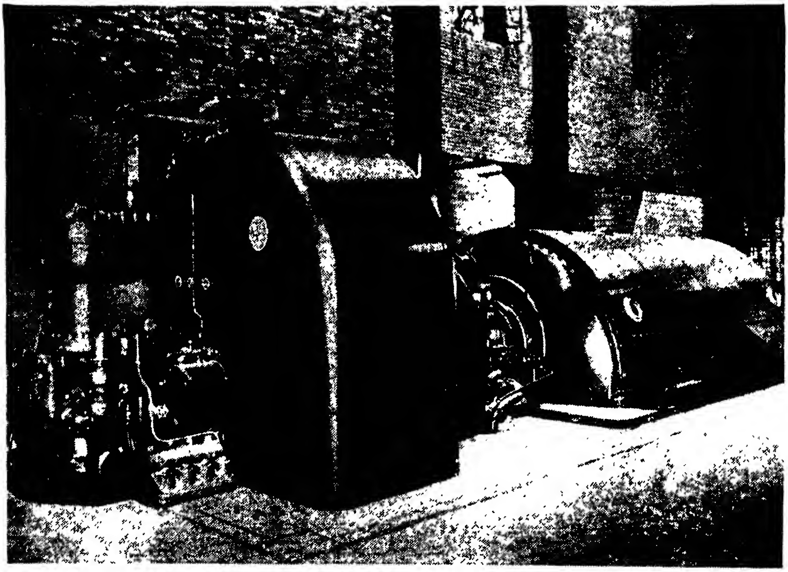


FIG. 67.—A 50,000-kw., 3,6000-r.p.m., 60-cycle, 11,500-volt, three-phase, hydrogen-cooled generator. (*Westinghouse Electric Corporation.*)

**50. Induction Generator.** *a. Theory.*—The torque produced by an induction motor depends on the magnetic flux that crosses the air gap, the current, and the power factor of the rotor. The magnetic flux produced in a three-phase motor is practically constant in magnitude and rotates at synchronous speed. The rotor current, however, is not constant but varies with the voltage induced in the rotor conductors and the impedance of the rotor winding. The rotor-induced voltage depends on the rate at which the rotor conductors cut the magnetic flux crossing the air gap, or, in other words, on the slip. As the load on an induction motor is decreased, the slip decreases so that there is less cutting of magnetic flux by the rotor conductors and, hence, less rotor-induced voltage, less rotor current, and hence less torque. At no load, the slip is practically zero; hence the rotor revolves at synchronous speed, and there can be no rotor current and no torque. If the motor is driven at a speed above synchronous speed, the slip becomes negative, and the rotor-induced voltage is therefore reversed in direction; hence the rotor current and the torque are reversed. Such a condition will therefore correspond to a generator, the reversed current in the rotor setting up a reversed current in the stator which, with respect to the motor, is a leading current.

To summarize, an induction generator is obtained by driving an induction motor at a speed above synchronous speed, in which case the machine can be considered as receiving from the line the necessary exciting current and supplying to the line the power or energy current. It follows from the above that the output of an induction generator depends on the slip and hence on the speed. The power factor of the output is fixed, not by the load, but by the constants of the machine itself. Since the exciting current must be supplied to the induction generator from some outside source, it is absolutely essential that other synchronous equipment be operated in connection with induction generators. The frequency and voltage must be controlled by the other synchronous generators that are connected to the same system, since the induction generator is dependent on the voltage and frequency for its operation.

## ✓ MISCELLANEOUS GENERATING EQUIPMENT

**51. Motor-generator Sets.** *General Classification.*—Motor-generator sets may be used to transform electrical energy from one form into another, as follows:

1. Transforming from direct current to direct current at different voltage.

2. Transforming from alternating current to direct current, or vice versa.

✓ 3. Transforming from alternating current to alternating current at different frequency.

Motor-generator sets of class 1 comprise direct-current balancers and boosters, which have been discussed in Art. 21. Motor-generator sets of class 2 may be further divided into the two classes, namely, induction motor generators and synchronous motor generators.

**52. Induction Motor-generator Sets.** *a. Construction.*—An inductor motor-generator set consists of an induction motor direct-connected to a direct-current generator. The motor is generally of the squirrel-cage type on account of its simplicity and also because constant speed is desired, since the motor acts the part of a prime mover, and a decrease in speed with load would mean a change in direct-current voltage. The generator is no different from a generator designed for any other prime-mover drive.

*b. Applications.*—Induction motor generators are used to supply direct current for lighting and general power up to medium capacities. Small storage-battery charging sets are often of the induction-motor type. The great advantage of the induction-motor drive lies in the fact that induction motors are not so susceptible to changes in voltage as synchronous motors. For intermittent operation the induction motor is probably preferable on account of its ease in starting up. Induction-motor-driven exciters are very common, owing to their reliability, ease of starting, and their tendency not to "pull out" because of voltage variations.

**53. Synchronous Motor-generator Sets.** *a. Construction.*—As the name implies, such a motor-generator set comprises a synchronous motor connected to the same shaft of a direct-current generator. Figure 68 shows the rotating element of a 2,000-kv. synchronous motor-generator set.

*b. Advantages and Disadvantages.*—The main advantage of the synchronous motor-generator set is the power-factor corrective effect which can be accomplished by properly adjusting the field current of the synchronous motor. The fact that they run at synchronous speed is sometimes of importance. Synchronous motors are not self-starting unless equipped with auxiliary squirrel-cage windings on the rotor. The synchronous as well as the induction motor-generator set afford free control of the direct-current voltage at all loads, independent of the alternating-current voltage. The synchronous motor requires direct current for the excitation of its field, which can be obtained from the generator it drives, provided the direct-current voltage is not much above 250 volts. Otherwise, a separate exciter may be desirable, as, for example, in the case of motor-generator sets supplying 600 volts or above, for railway service.

c. *Applications.*—The general applications of synchronous motor-generator sets may be tabulated as follows:

1. Lighting service.
2. Industrial service.
3. Electrochemical service.
4. Railway service.
5. Storage-battery charging.

For lighting service the generator may be designed for two- or three-wire service. The demand for direct current for lighting service has practically disappeared, alternating current with a frequency of 60 cycles per sec. being just as efficient for this type of service. There are a good many industrial loads requiring variable-speed operation, for which the direct-current motor is very well adapted. For such service it is often economical to transform the alternating-current supply into direct current. If the generators are designed for a three-wire system, a large range of motor-speed variation can be obtained at rather high efficiencies throughout the entire range of speed variation. Direct current is absolutely essential in some chemical processes, as, for example, in electrolytic service. The direct-current voltage for this service will vary for different requirements, but seldom exceeds 250 volts. For city railway service, there is probably no question as to the superiority of direct current. The intermittent variable-speed duty imposed by such service makes direct current necessary. The two standard voltages for such service are 550 and 600 volts. For interurban and main-trunk-line electrification, alternating as well as direct current is used. For direct-current service the standard voltages are 1,200, 1,500, 2,400, and 3,000 volts. Storage-battery charging sets of large capacities are sometimes of the synchronous-motor type. In general, it may be said that synchronous-motor drive for direct-current generators is economical for the larger capacity units, where continuous operation is needed and where power-factor correction can be economically employed. For small intermittent-duty units, the induction motor set is superior.

*d. Starting of Synchronous Motor-generator Sets.*—The most common method used in starting such units is from low-voltage taps on transformers or autotransformers, by means of the torque produced by squirrel-cage windings which are placed in the pole shoes (Fig. 68). After the unit has come up to speed, full voltage may be applied to the stator. Another method not often used in this country is to have a small induction motor connected to the same shaft. This motor brings the unit up to speed, after which the synchronous motor will fall into step and take its load. In some cases, such units can be started from the direct-current side, operating the direct-current generator as a motor.

Fig. 68.—Armature and rotor from motor-generator set consisting of 2,000-kw., 275-volt, 300-r.p.m., direct-current generator driven by 12,000-volt, three-phase, 60-cycle, synchronous motor. (*Allis-Chalmers Manufacturing Company.*)

√ **54. Frequency Changers.** *a. Construction.*—Frequency changers consist of an alternating-current generator direct-connected to the shaft of an alternating-current motor. A synchronous motor is generally used, but in some cases an induction motor may be found advisable. The rotating element of a 1,200-kva. 300-r.p.m. frequency-change set is shown in Fig. 69. In this case a synchronous motor is used, and in order that the unit may be made self-starting, squirrel-cage windings are placed in the pole faces. Since the speed of alternating-current motors and generators is definitely fixed with respect to the frequency, it follows that the number of poles on the generator and motor must be so chosen that the desired frequencies are obtained for a common speed. In the case of a 60- to 25-cycle set, the highest possible speed is 300 r.p.m., in which case the 60-cycle machine must have 24 poles and the 25-cycle machine 10 poles. In the case of a 50- to 60-cycle set, as shown in Fig. 70, the highest possible speed is 600

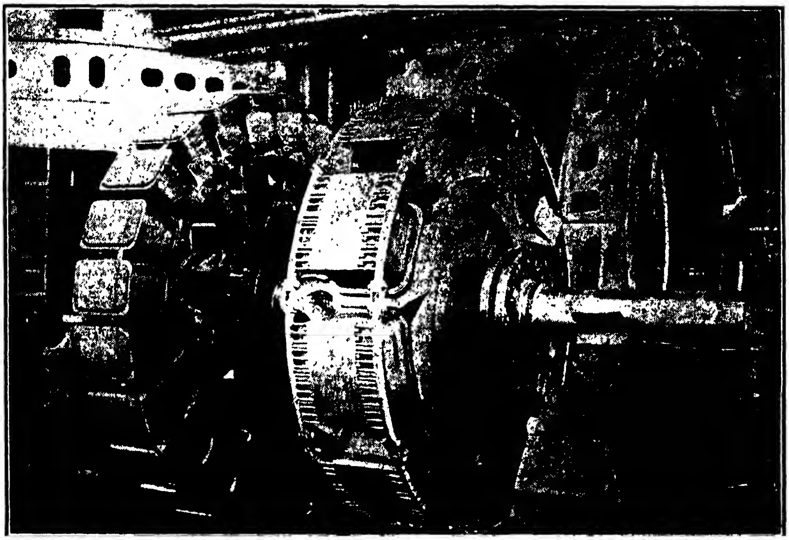


Fig. 69.—Rotor of 1,200-kva. frequency-changer set, 300 r.p.m., 25 to 60 cycles. (*Allis-Chalmers Manufacturing Company.*)

Fig. 70.—A 15,000-kva., 50- to 60-cycle, frequency-changer set, Southern California Edison Company. (*Westinghouse Electric Corporation.*)

r.p.m., in which case the 60-cycle unit must have 12 poles and the 50-cycle unit 10 poles.

*b. Application.*—Frequency changers may be used for two distinct purposes, namely:

1. As a means of interchanging energy between two systems of different frequencies.
2. To supply certain types of loads at a frequency different from the frequency of the system. When supplying a load at different frequency, as, for example, a railway load from a system of 60 cycles per sec., it is possible to use a synchronous set having rotors of 10 and 4 poles which will supply 24 cycles per sec. at 720 r.p.m. A frequency of 24 cycles per sec. would probably meet the railway demands as well as one of 25 cycles per sec. Such a set if driven from a 25 cycle per sec. supply would run at 750 r.p.m. and generate 62.5 cycles per sec. In case an induction motor of about 4 per cent slip were used on the 25 cycle per sec. side, the generator would deliver practically 60 cycles per sec. at 720 r.p.m. A synchronous-motor frequency-changer set has the advantage that it may be used for power-factor correction in the same way as a synchronous motor-generator set.

*c. Parallel Operation.*—In order to illustrate the problems involved in parallel operation, two sets operating at 720 r.p.m. will be chosen. These sets are used to supply 24 cycles per sec. from a 60-cycle-per-sec. supply. In Fig. 71 the two sets are illustrated. Set I is running, while set II is to be started and synchronized to the line. The large letters *N* and *S* represent the poles of the 60 cycle per sec. motors; the small letters *n* and *s* represent the poles of the 24 cycle per sec. generators. It is necessary not only that any set of north poles on the two motors have the same relative angular position, but also that the generator poles have the same relative angular position. A study of Fig. 71 will soon reveal the fact that there is only one possible point at which the generators can be synchronized to five points at which the motors can be synchronized. If the motors have been synchronized at the wrong points, it is necessary that one motor be made to slip one or more poles. This can be accomplished in two ways: (1) by means of a double-throw switch in the field circuit with which the polarity of the poles may be reversed one or more times, thus causing the rotor to fall back a corresponding number of pole pitches; or (2) by opening and closing the main line switch, thus momentarily allowing the rotor to slow down. This should not be done with full line voltage applied to the motor.

*d. Electronic Frequency Changers.*[1]—Heavy-power electronic frequency changers may soon replace the rotating type changers.

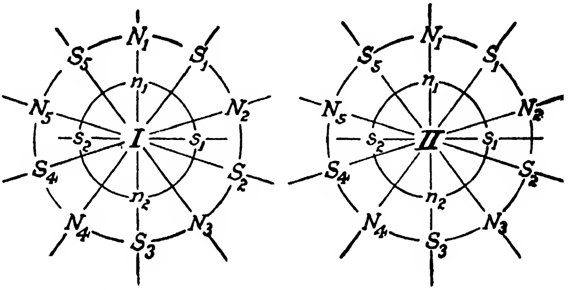
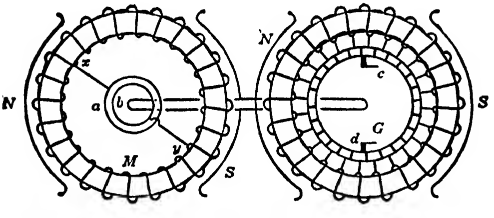


FIG. 71.—Correct angular relation of two frequency changers for parallel operation.

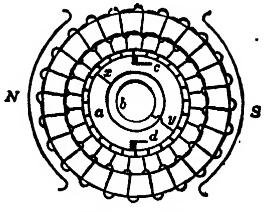
Alternating-current power of any frequency is first converted to direct-current power through a typical rectifier circuit and then converted back to alternating-current power of any second frequency through an inverted rectifier circuit or "inverter."

**55. Rotary Converters.** *a. General.*—In Fig. 72 is shown a two-pole single-phase synchronous motor *M*, direct-connected



Synchronous Motor Direct-current Generator

FIG. 72.



Rotary Converter

FIG. 73.—A rotary converter.

to a two-pole direct-current generator *G*. The synchronous motor in this case is of the revolving-armature type instead of the revolving-field type as described in Art. 54. It will be noticed that the armatures of both machines are alike; hence the motor and generator can be combined to form one machine as shown

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[1] Typical electronic frequency changers are discussed in J. G. Tarboux, "Alternating Current Machinery," International Textbook Company.

in Fig. 73. If an alternating voltage is applied to the slip rings *ab*, the machine will operate as a synchronous motor, and direct current will be supplied from the commutator brushes *cd*. The current flowing in the armature conductors of a rotary converter is equal to the difference between the instantaneous values of the alternating and the direct currents that tend to flow in the same conductors. The overlapping of the motor and generator currents in a rotary converter is its most interesting property. As these currents partly neutralize each other, the current actually flowing in the armature conductors is much less than would be the case otherwise, and the copper losses are thus correspondingly reduced. The actual magnitude of this resultant current is dependent upon the power factor, as will be shown later. The number of poles of a rotary converter is dependent upon the frequency of the alternating-current supply and the safe speed of the rotating armature and commutator. The direct-current voltage generally used is 275 volts for power and lighting, and 500, 600, 1,200, or 1,500 volts for railway service. Either single-, two-, three-, or six-phase converters can be built, but six-phase converters are more common, owing to their higher efficiency and better operating characteristics.

*b. Connections.*—The armature winding is an ordinary direct-current winding, which may be either series or multiple (see Art. 20). In the case of a multiple winding, equalizer connections must be used in order to equalize the effect of the magnetic flux under all poles. Taps are brought out from equidistant points in the armature and connected to the slip rings. There are a large number of possible ways that are used to connect the transformer terminals, supplying converters, to the slip rings. A detailed description of these connections, is given in Chap. VIII. In order to obtain satisfactory commutation, commutating poles must be used in the same manner as in the case of direct-current generators.

*c. Voltage Ratios.*—The theoretical voltage ratios of rotary converters are definitely fixed by the number of phases and the method by which the transformer terminals are connected to the slip rings. In a two-ring or single-phase converter, the two collector rings are connected to armature points that are 180 electrical degrees apart. The commutator brushes are also located at points 180 electrical degrees apart, connection being made with conductors that are midway between poles (Fig. 74). The direct-current voltage $E$ is therefore equal to the maximum value of the alternating-current voltage or $\sqrt{2}\,E_1$ for a sine-wave voltage between slip rings, or

$$E_1 = \frac{E}{\sqrt{2}} = 0.707E \qquad (23)$$

where $E$ equals the direct-current voltage and $E_1$ equals the effective value of the single-phase voltage between slip rings that are connected to the armature winding at points 180 electrical degrees apart. As shown in Art. 33, the voltages generated by a distributed winding can be represented by a polygon enclosed by a semicircle as shown in Fig. 43. The same general diagram can be applied to the voltage relations that will exist in a converter. In Fig. 74 if the diameter of the circle $OD$ is equal to the single-phase voltage $E_1$ applied to a two-ring converter, then $OA$, $OB$, and $OC$ are the voltages between collector rings that are connected to the armature winding at points 120, 90, and 60 electrical degrees apart.

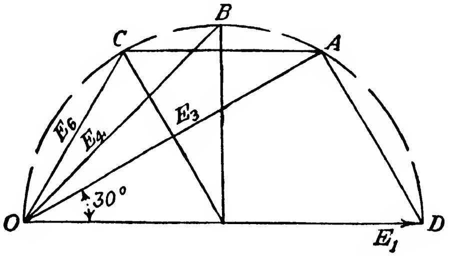


FIG. 74.—Voltage relations of synchronous converters.

Therefore,

$$E_3 = OA = 0.866E_1 = \frac{0.866E}{\sqrt{2}} = 0.612E \qquad (24)$$

$$E_4 = OB = \frac{\sqrt{2}\,E_1}{2} = \frac{\sqrt{2}\,E}{2\sqrt{2}} = 0.5E \qquad (25)$$

$$E_6 = OC = \frac{E_1}{2} = \frac{E}{2\sqrt{2}} = 0.354E \qquad (26)$$

The effective voltage $E_0$, between any collector ring and the neutral point, is equal to the radius of the circle in Fig. 74, or

$$E_0 = \frac{E_1}{2} = \frac{E}{2\sqrt{2}} \qquad (27)$$

The theoretical voltage ratios for the most common types of synchronous-converter connections can therefore be obtained from the above figures. These ratios are shown in Table VII.

TABLE VII.—THEORETICAL VOLTAGE RATIOS FOR ROTARY CONVERTERS

| | Theoretical Ratio, Alternating Current to Direct Current |
|---|---|
| Single phase, two collector rings | 0.707 |
| Three phase, three collector rings | 0.612 |
| Two phase, four collector rings | 0.707 |
| Six phase, six collector rings (diametrical) | 0.707 |
| Six phase, six collector rings (double delta) | 0.612 |

The conditions that affect the theoretical ratios obtained above are:

1. The wave form of the converter e.m.f., which depends upon the shape of the poles, particularly on the percentage of the armature circumference covered by the pole face.

2. The wave form of the impressed voltage. Variations due to this are small and can generally be neglected.

3. The resistance of the windings of the converter, of its brushes, of its commutator, and the brush-contact resistance. The drop in these resistances varies with load and affects the voltage ratio.

4. Operating conditions such as brush position, shunt-field and series-field excitation and whether the machine is converting from alternating current to direct current, or vice versa.

As an approximation, the ratios at full load can be increased over the theoretical values by about 2¼ per cent in order to take into account the above conditions which affect the theoretical ratios.

*d. Current Ratios.*—The current ratios of a converter are not so definitely fixed as the voltage ratios, but are different for different power factors. The ratios are also modified on account of the losses in the converter. A rather close approximation, however, can be obtained by neglecting the internal losses. The alternating-current input must equal, therefore, the direct-current output, and if unity power factor be assumed, the following relations may be deduced:

1. Single-phase two-collector rings:

$$E_1I_1 = EI$$

But

$$E_1 = \frac{E}{\sqrt{2}}.$$

Therefore

$$I_1 = \sqrt{2}\,I = 1.414I \tag{28}$$

where $E_1$ = effective alternating single-phase line voltage
$E$ = direct voltage
$I_1$ = effective alternating line current
$I$ = direct current

2. Three-phase three-collector rings:

$$3E_0I_1 = EI$$

But

$$E_0 = \frac{E_1}{2} \qquad \text{and} \qquad E_1 = \frac{E}{\sqrt{2}}$$

Therefore

$$I_1 = \frac{2\sqrt{2}}{3}I = 0.943I \tag{29}$$

where $E_0$ = effective alternating voltage to neutral.

3. Two-phase four-collector rings:

$$2E_1I_1 = EI$$

But

$$E_1 = \frac{E}{\sqrt{2}}$$

Therefore

$$I_1 = \frac{I}{\sqrt{2}} = 0.707I \tag{30}$$

4. Six-phase six-collector rings:

$$6E_0I_1 = EI$$

But

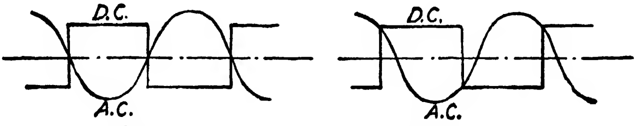
$$E_0 = \frac{E_1}{2} \qquad \text{and} \qquad E_1 = \frac{E}{\sqrt{2}}$$

Therefore

$$I_1 = \frac{\sqrt{2}}{3}I = 0.472I \tag{31}$$

The ratios at any other power factor than unity can be determined by dividing the above results by the power factor.

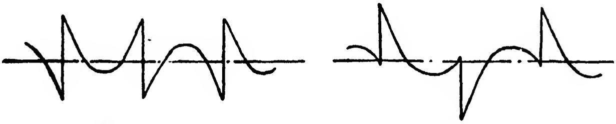
*e. Heating and Capacity.*—As has been indicated, the effective current in each part of a converter-armature winding is the difference between the instantaneous values of alternating-current input and direct-current output. Figure 75*a* shows the curves of the direct and of the alternating current that tend to flow in certain armature conductors at unity power factor. Figure 76*a* shows the difference between the two currents, which is the curve of current that actually flows in the particular conductor. The effective current in a converter armature is a minimum when the alternating-current input to the machine is at unity power factor. At this power factor the relative positions of the waves of alternating and direct current are such that their difference (Figs. 75 and 76) is a minimum. At power factors different from unity, with a given energy output the effective current is greater than at 100 per cent power factor.



a. Unity p.f. b. 86.6 per cent p.f.

FIG. 75.—Currents tending to flow in converter-armature conductor

For a given output from a converter, the alternating current flowing into the armature at each collector ring decreases as the number of collector rings is increased. It follows, therefore, that the actual current flowing in the armature conductors of a converter for a given output becomes less and less as the number of collector rings is increased; hence for a given armature copper loss the converter capacity increases as the number of collector rings is increased. The relative ratings of a given armature are given in Table VIII, the rating as a direct-current generator being taken as 100 per cent.



a. Unity p.f. b. 86.6 per cent p.f.

FIG. 76.—Current flowing in converter-armature conductor.

TABLE VIII.—COMPARATIVE CAPACITIES OF ROTARY CONVERTERS FOR SAME AVERAGE HEATING AND AT UNITY POWER FACTOR

| | |
|---|---|
| Deep-current generator | 100 |
| Single-phase converter | 85 |
| Two-phase converter | 164 |
| Three-phase converter | 134 |
| Six-phase converter | 196 |
| Twelve-phase converter | 224 |

Owing to the high capacity obtainable from a six-phase converter and the fact that six phases can be easily obtained from a bank of three-phase transformers having double secondaries, practically all converters are of the six-collector-ring type. The complications in wiring and the expense involved do not warrant the application of a 12-phase machine. The capacity of a given converter cannot, however, be determined on the basis of the average heating, but will depend on the temperature at the hottest part of the machine. In a synchronous converter the coils that lie in the most direct path between the alternating-current and the direct-current sides of the armature (namely, the tap coils or the coils adjacent to the alternating-current taps) have the greatest $I^2R$ loss. Furthermore, this $I^2R$ loss increases as the power factor of the alternating-current input is decreased. The approximate values of the loss in the tap coils as compared with the average are given in Table IX for the same armature operated as different machines.

TABLE IX.—COMPARISON OF LOSSES IN THE SAME ARMATURE COIL WHEN OPERATED AS SEVERAL MACHINES AT UNITY POWER FACTOR

| When operated as | Loss in | Relative loss |
|---|---|---|
| Direct-current generator | any coil | 1.00 |
| Three-phase converter | tap coil | 1.25 |
| | average of all coils | 0.59 |
| Six-phase converter | tap coil | 0.43 |
| | average of all coils | 0.27 |

In a converter the alternating-current and the direct-current armature reactions neutralize each other to a great extent, and there is not the same tendency for distortion and shifting of the magnetic field with changes of load as obtained in direct-current generators. Hence considerably larger currents can usually be commutated by a given size of machine designed as a converter than when designed as a direct-current generator.

*f. Voltage Variation.*—It is evident that the ratio between the alternating- and direct-current voltages of an elementary converter is a nearly fixed quantity and remains constant within a very few per cent from no load to full load. Some additions to the ordinary converter or some auxiliary apparatus is necessary to obtain a variable direct-current voltage. The important commercial methods of obtaining a variable direct-current voltage are:

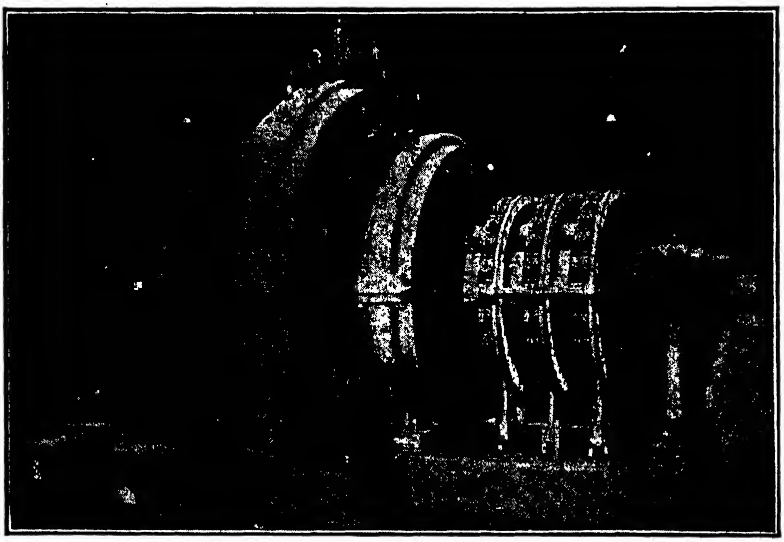


Fig. 77.—A 2,000-kw., 270-volt, six-phase, 60-cycle booster converter, 450 r.p.m. (*Westinghouse Electric Corporation.*)

1. With an alternating-current synchronous booster.
2. With an alternating-current potential regulator or regulating transformer.
3. With a direct-current booster.
4. By automatic compounding.

(1) Synchronous-booster Converter.—A synchronous-booster converter is a rotary converter with a mechanically connected alternating-current generator, the armature winding of which is connected in series relation with the armature winding of the rotary converter so that the voltage generated in it, whenever

its field is excited, either adds to or subtracts from the voltage supplied to the converter and affects the direct-current voltage accordingly. A six-phase synchronous converter is shown in Fig. 77. The complete rotating element of this converter, composing the converter armature, alternating-current booster armature, commutator, and collector rings, is shown in Fig. 78. The booster, necessarily, has the same number of poles as the converter. It may obviously be excited in either direction, so that, for a given variation of direct-current voltage required, the voltage of the booster necessary is only one-half the corresponding alternating-current voltage.

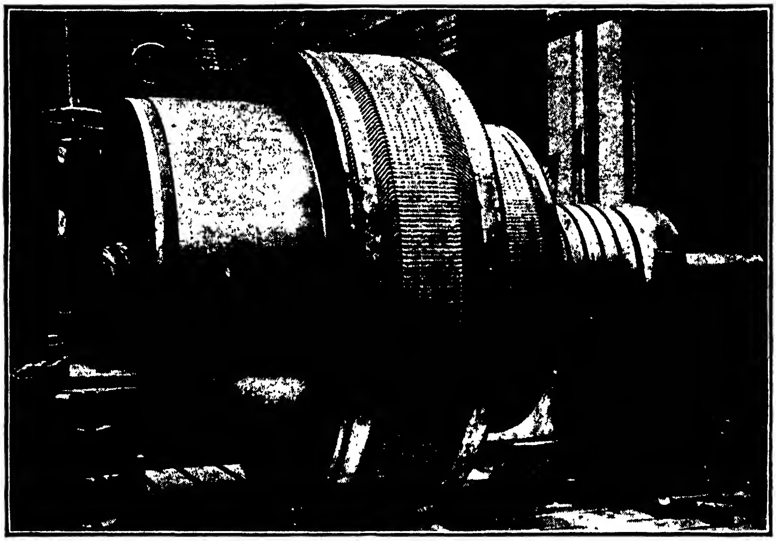


FIG. 78.—Armature of 2,000-kw. booster converter, shown in Fig. 77. (*Westinghouse Electric Corporation.*)

(2) Regulating Transformer or Potential Regulator.—A regulating transformer consists of a transformer secondary with a large number of taps and some switching device to change the converter connections from one tap to the other. The transformers and switching devices are large, heavy, and expensive, and the method has the objection that the voltage cannot be varied so as to follow a smooth curve unless the transformer is supplied with an excessive number of taps. The regulating-transformer method is, therefore, not used very often, the induction or potential regulator having superseded it.

A potential or induction regulator[1] is essentially a transformer, the primary of which can rotate inside of the stationary secondary. The secondary induced voltage will depend on the relative position of the primary with respect to the secondary and, hence, can be varied from a maximum positive value to a maximum negative value. By connecting the secondary windings of such transformers in series with the alternating-current supply lines, it is possible to vary the supplied voltage of the converter and, hence, also vary the direct-current voltage output.

(3) Direct-current Booster.[2]—A direct-current generator can be connected in series with the direct-current side of the converter, and by varying the field of this generator the direct-current voltage can be varied. The speed of the booster, if direct-connected, is determined by the speed of the converter, which may prevent economical design. The weight, space, and cost for this combination are generally greater than for the synchronous-booster converter. A serious objection to the direct-current booster arrangement is that there are two commutators to operate and maintain.

(4) Automatic Compounding.—With this method of voltage variation it is necessary that there be a certain amount of reactance in the supply lines to the converter, which may be in reactance coils or embodied in the supplying transformers. Since the voltage applied to the primaries of the supplying transformers is constant, it follows that the voltage available at the collector rings will depend on the resistance and reactance introduced in the transformer or reactance coils and the power factor of the converter. The power factor of the converter may be varied between rather wide limits by properly varying the field current; hence the current taken from the alternating-current supply may be made either to lead or to lag the voltage at the collector rings. In Fig. 79 is shown how the voltage $E_c$ applied to the collector rings will vary for different power factors from lagging to leading current for a constant primary transformer voltage $E_s$. This principle is made use of by supplying converter fields with a series winding as well as a shunt winding, so that as the direct-current load increases the field excitation is increased, thereby causing the converter to take a leading current, the effect of

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[1] For a more detailed discussion of induction regulators see Chap. VII.

[2] See Art. 21.

which is to raise the voltage applied to the collector rings and, hence, counterbalance the drop in direct-current terminal voltage due to the increase of load. In other words, by introducing reactance in the alternating-current supply lines, the direct-current voltage may be maintained practically constant at all loads by the increased excitation produced by the series-field winding. The objection to this scheme lies in the fact that the converter does not operate at 100 per cent power factor.

*g. Three-wire Synchronous Converters.*[1]—In Art. 28 it was shown that, by connecting a high-reactance and low-resistance coil between diametrically opposite points of a direct-current generator armature, a neutral line could be obtained by bringing out a tap from the middle point of the reactance coil, thereby obtaining a three-wire generator. The secondary windings of the transformers supplying a converter are essentially high-reactance coils connected to the armature, and if the neutral of such transformer secondaries is available, a line can be brought out which, in conjunction with the two direct-current lines, will form a three-wire direct-current system. The necessary arrangements for operating three-wire converters in parallel are essentially the same as required for the operation of three-wire direct-current generators (see Arts. 29 and 30).

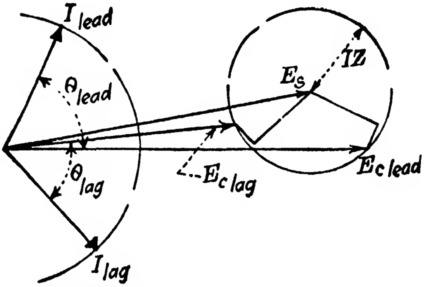

FIG. 79.—Effect of converter power factor on voltage applied to collector rings.

*h. Parallel Operation.*—As in the case of direct-current generators (see Arts. 27 and 30), converters can be operated in parallel, the division of load being determined by the induced voltage of the individual machines. With converters having no reactance in the supply lines, it is impossible to vary the direct-current

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[1] For a detailed discussion of the transformer connections necessary, see Chap. VII.

voltage; hence two converters of different voltage ratios cannot be satisfactorily operated in parallel. Small differences in the ratios of converters can, however, be corrected, in the case of converters having a certain amount of reactance in the supply lines, by properly adjusting the field current. It is not good practice to supply more than one converter from the same transformers, as such a connection would introduce a closed circuit of low impedance through the several armatures, allowing heavy currents to circulate in case of rather small differences in the characteristics of the several machines thus operating.

*i. Hunting.*—Hunting of synchronous converters may be caused by the periodic variation of the supply frequency, by sudden changes of load, or by excessive line drop. A variation of frequency is generally caused by the hunting of the prime movers driving the alternators supplying the system. In modern power plants there is very little variation in frequency, since steam-turbine units are not subject to variations in speed, and engine-type as well as water-wheel-type alternators are designed with sufficient flywheel effects practically to overcome this tendency. The main cause of converter hunting is due to variations in the alternating-current supply voltage with changes of load, as caused by the drops in the line due to relatively high resistance and reactance. A variation in applied voltage will be followed by a change in armature reaction and power factor, which in turn will cause a variation in the magnetic flux.

During hunting, the rotor is alternately ahead and behind its true synchronous position. In forging ahead energy is expended in the converter, while when dropping back energy is given up by the converter. The machine operates alternately as a motor and generator. Probably the most serious result caused by hunting is the shifting of the magnetic flux across the pole faces, resulting in a shifting in the magnetic neutral of the machine. In the case of noncommutating pole converters, this naturally causes sparking at the brushes. Hunting can be practically eliminated by placing damper windings in the pole faces. This winding is essentially a squirrel-cage winding as used for starting synchronous motors (see Fig. 68). The shifting of the flux across the pole faces will set up currents in these windings which will oppose any such change, thus damping out the oscillations in speed as soon as they begin.

*j. Starting of Synchronous Converters.*—There are three methods by which synchronous converters may be started, namely, alternating-current self-starting, alternating-current motor-starting, and direct-current self-starting methods.

(1) Alternating-current Self-starting Method.—By means of a squirrel-cage winding embedded in the slots in the pole faces, the converter can be started by the direct application of alternating currents (at reduced voltage) to the collector rings. The starting voltage is usually about one-third of the running voltage. For small- and medium-capacity machines only one starting transformer tap is used, while for larger units it is customary to employ two taps. In the case of commutating-pole converters, it is necessary to raise the direct-current brushes from the commutator, when the converter is started from the alternating-current side, in order to prevent sparking at the brushes. It is necessary, however, to have a source of excitation, as well as a means of indicating the polarity of the direct-current side of the converter as synchronism is approached. Consequently, two brushes, one of each polarity, are left on the commutator at all times. The width of these brushes should be such that not more than one armature coil is short-circuited, in order that they will not spark to any considerable extent.

When starting converters, voltages will be induced in the field windings, owing to transformer action, the magnitude of which will depend on the ratio of armature and field turns. To prevent a dangerously high induced voltage in the shunt-field winding, the field circuit may be opened in several places during the starting period by means of a multipoint field "break-up" switch. Another method of preventing this high induced voltage in the shunt field is to short-circuit the winding. The current set up in the short-circuited winding will prevent the magnetic flux produced by the armature current, and therefore the induced voltage in the field circuit, from reaching a dangerous value. The series-field circuit should also be closed on itself during the starting period, but on account of its low resistance it is generally necessary to short-circuit this winding through an external resistance.

After the converter has been brought up to speed and connected to the alternating-current lines, the direct-current polarity may be wrong; hence it is necessary that the converter be made to slip a pole. In the case of small units this can be accomplished by merely opening and closing the main switch in the alternating-current lines. A more general method is to reverse the current through the shunt-field circuit, while the converter is connected to the starting transformer taps. To do this, the field break-up switch must be of the double-throw type. After the direct-current voltmeter indicates the correct polarity, the shunt-field switch must be again reversed to its original position.

(2) Alternating-current Motor-starting Method.—This method utilizes an induction motor direct-connected to the converter. The motor has a fewer number of poles than the converter in order that the unit may be brought up to synchronous speed. Synchronizing is accomplished by the same methods as are used for two alternators when being paralleled.

(3) Direct-current Self-starting Method.—In some cases, where another source of direct current is available, converters may be started from the direct-current side, by operating the unit as a shunt motor. The armature current at starting is limited by an adjustable resistance that is controlled by a starting switch. If there is no switch between the transformers and the collector rings, the transformer windings are in parallel with the converter-armature winding; hence the starting current will also depend on the resistance of the transformer secondaries, the collector rings and the alternating-current brushes, the booster winding, if there is one, and the leads between the transformers and collector rings.

**56. Converters versus Motor-generator Sets.**—The choice of a motor-generator set or a converter for a given service is determined by the nature of the service and the characteristics of the system supplying the energy to the transforming equipment. Some of the factors that should be considered when making such a choice are as follows.

1. Reliability.
2. Voltage regulation.
3. Power-factor corrective effect.
4. Efficiency.
5. Cost.
6. Parallel operation.
7. Starting.

The design of synchronous converters has been improved to such an extent that their disadvantages are few as compared with their advantages; hence they are being used more and more for the transformation of alternating current to direct current. There are, however, a few cases where the motor-generator set seems to be more desirable or necessary. In general these cases may be as follows:

1. At the end of a long transmission line with excessive ohmic resistance.

2. On a system with very poor regulation where the direct-current service may require close independent regulation.

3. Where a large low power-factor corrective effect is desired. By using a synchronous motor of sufficient capacity operating with leading current, the effect of lagging current on the system can be neutralized. In many cases, however, it is preferable and more economical to use converters and synchronous condensers.

4. Where frequency and regulation are so poor as to prohibit the use of synchronous apparatus, in which case an induction motor generator is applicable.

**57. Mercury-arc Rectifiers.**[1] *a. Glass-bulb Rectifiers.*—A single-phase glass-bulb rectifier is illustrated in Fig. 80. It consists of a highly exhausted bulb *B* where the mercury vapor condenses, a mercury cathode *K*, an auxiliary anode *a*, and two projecting anode tubes *A*. The operation of a mercury-arc rectifier depends on the fact that the mercury arc when operating in high vacuums has the peculiar property of permitting the passage of current in one direction only. The best explanation for this valve action is based upon the electron theory. Briefly, this theory is as follows: electrons that are emitted from the cathode spot strike neutral vapor molecules. The collision of an electron and a neutral molecule ionizes the molecule by the removal of an electron. The new electron joins the old one in conducting the current. The remainder of the molecule has a net positive charge and is a positive ion. It is, therefore, attracted to the cathode. As the positive ions approach the cathode, they produce a high space-charge potential gradient, which causes a further emission of electrons from the mercury surface. At the same time the positive ions striking the mercury surface heat it up to a temperature of about 600°C., thereby causing a violent evolution of

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[1] For more details, see Marti and Winograd, "Mercury Arc Rectifiers," McGraw-Hill Book Company, Inc., New York, 1930.

mercury vapor. This causes a considerable rise in the vapor pressure immediately surrounding the cathode spot, which enables the electrons to strike the molecules after a very short travel. The vapor pressure has been estimated to be of the order of 2.58 atm., under which conditions the average gradient over one "mean free path" is about 2,500,000 volts per cm. Once free of the cathode, the vapor expands to a low pressure, in which space the current-carrying electrons travel in the general direction of the anodes. The rectifying action of the rectifier is therefore due to the ability of the cathode spot to give

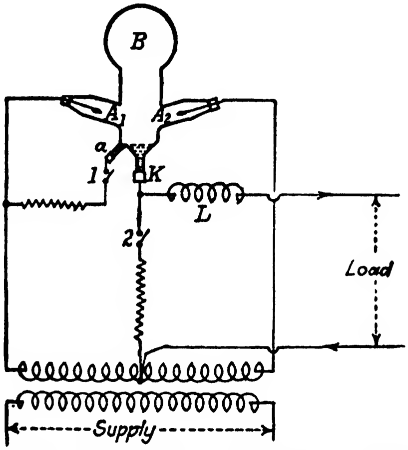

Fig. 80.—Single-phase mercury-arc rectifier.

off electrons that are attracted to any positively charged anodes. As long as the anodes are unable to give off electrons, conductivity in the other direction is normally nil. This rectifying action is not a peculiar property of mercury; mercury is used because its vapor can be easily condensed and led back to the cathode without loss.

The elementary electrical connections of a two-anode single phase rectifier are shown in Fig. 80, in which both alternations of the alternating-current supply may be utilized. The direct-current system is obtained from the mid-point of the supply-transformer secondary and from the cathode $K$, the cathode terminal being the positive side of the direct-current system. During one alternation of the impressed voltage, the anode $A_1$ is at a higher potential than the cathode $K$, while the other anode $A_2$ is at a lower potential than the cathode $K$. During the next alternation, $A_2$ will be at a higher potential and $A_1$ at a lower potential than the cathode $K$; hence the mercury arc will flow between $A_1$ and $A_2$ to $K$, one end of the arc changing between the anodes as the polarity of the impressed voltage is varied. The resultant voltage available between the cathode and the mid-point of the transformer secondary is shown in Fig. 81*a*. As it requires only a cessation of the current for a small fraction of a second to cool the cathode spot sufficiently to extinguish the arc, a reactance $L$ should be inserted in the rectified circuit, thus prolonging the current wave and preventing it from dropping to zero. The reactance also damps out, to a great extent, the undulations in the resultant current wave, thereby producing a unidirectional current which is suitable for most direct-current demands. To start the arc the arrangement is tilted so that the mercury runs from the cathode to the ignition anode $a$. With switches 1 and 2 closed (Fig. 80), current will immediately flow between these two points, and on the vessel being tilted back an arc is started at the point of rupture. This starts the main arc between the anode tubes and the cathode. Glass-tube rectifiers are built for outputs up to about 50 kw. They are used extensively for charging storage batteries and operating direct-current street arc lights. For the successful operation of the rectifier high vacuums are essential, the normal working range being 0.01 to 0.001 mm. Hg.

*b. Polyphase Rectifiers.*—It has been shown that in order to maintain a single-phase arc it is necessary to introduce a reactance in the circuit of the rectified current. In the case of polyphase rectifiers a reactance is not necessary owing to overlapping of the voltage waves, as shown in Figs. 81*b*, *c*, and *d* for a three-, six-, and twelve-phase rectifier, respectively. It will also be noticed that the voltage wave between the cathode and transformer neutral becomes more uniform as the number of phases is increased. Glass-bulb rectifiers are generally of the single-phase or three-phase type, while power rectifiers are generally of the six-phase type.

*c. Power Rectifiers.*—A power rectifier is shown in Fig. 82. The major portion is the large welded-steel cylinder $K$ in which the arc operates and above it the narrower condensing cylinder $C$. These two cylinders are connected by the heavy anode plate $D$, while the lower portion of the arc chamber is closed in by the plate *M*, in the center of which the cathode is located. The condensing cylinder is closed at its top by a plate carrying the ignition coil *B*. The rectifier, as a whole, is mounted on the

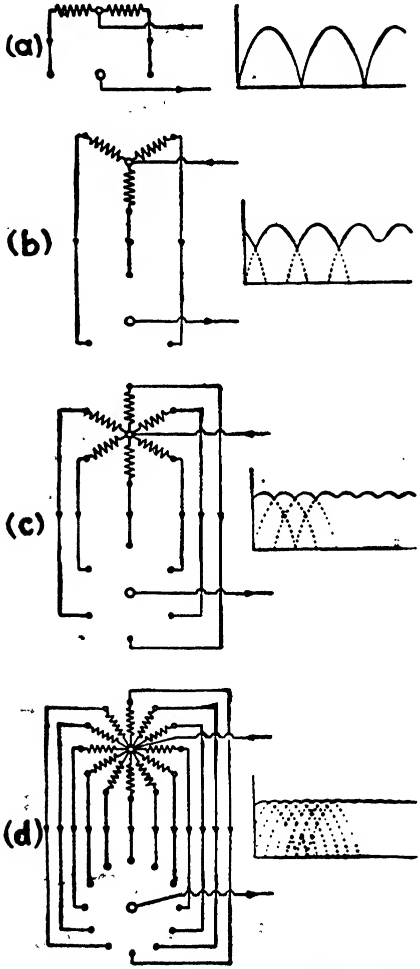

FIG. 81.—Polyphase mercury-arc rectifiers. (*Allis-Chalmers Manufacturing Company.*)

insulators *P*, these in their turn being carried on the foundation ring *Q*. There are six main anodes *E* and two auxiliary anodes *G* placed in a circle around the anode plate. The auxiliary anodes serve to maintain the arc when the load drops to a very low level (about 40 amp.). These auxiliary anodes constitute a single-

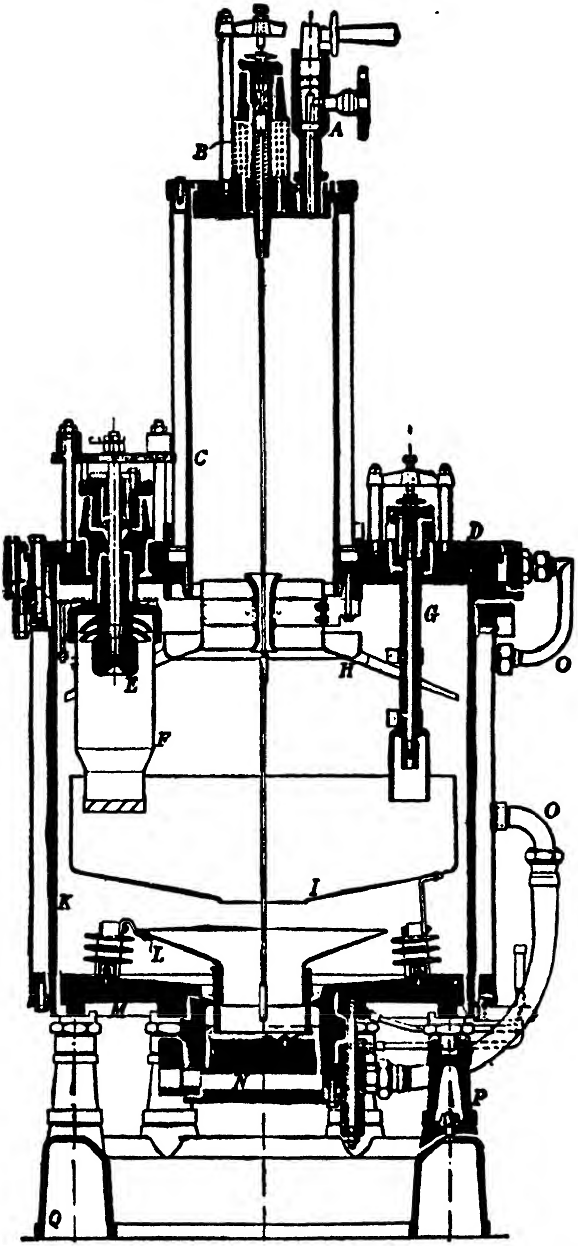

FIG. 82.—Section through a power mercury-arc rectifier. (*Allis-Chalmers Manufacturing Company.*)

phase rectifier, providing about 0.5 kva. which keeps up the temperature of the cathode spot. The mid-point of the exciting transformer is brought out as in the case of the main transformer and connected through a resistance and small reactance to the cathode; the former limits the current consumed, while the latter ensures that the auxiliary arc will not drop to zero at each half period.

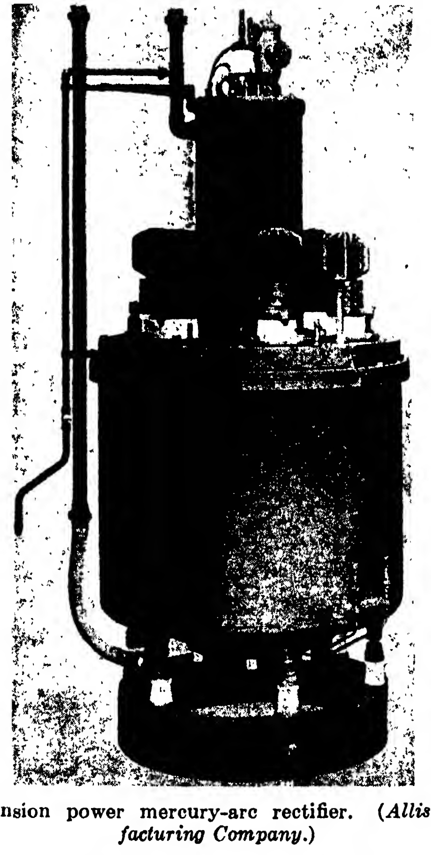

FIG. 83.—High-tension power mercury-arc rectifier. (*Allis-Chalmers Manufacturing Company.*)

The main anodes are screwed to the anode bolts that convey the current to them; the transformer connections are brought to lugs fitted to the upper part of these bolts. Specially designed insulators separate the anodes from the anode plate. The arc guides *F* are fixed to the main insulators and at their open ends terminate in the large collecting funnel *I*. Immediately above the cathode there is a smaller funnel *L*. The arc works between the main anodes *E* and the cathode; it has a well-defined path, which diminishes the risk of flashing over. At the point of contact of the arc with the mercury, a dense cloud of vapor is given off. The un-ionized portion of this vapor rises between the anodes and finds its way into the condensing cylinder where a reduction in temperature takes place owing to the water jacketing, and it is recondensed and in the form of drops falls back into the collector *H*. From here it runs down the sloping troughs to the sides of the arc chamber and thence back to the cathode, so that there is no loss and the mercury need never be replenished.

For cooling purposes a small quantity of fairly good water is necessary, that usually obtainable from the town mains being suitable. It first passes through the cathode base *N*, from there to the jacketing round the large cylinder and the anode plate by the connections *O*, after which it passes to the jackets surrounding the condensing cylinder and then out to waste or a separate recooling system.

The diagram of Fig. 84 shows the ignition and excitation circuit. When the main transformer is energized, the primary switch of the excitation transformer *Tex* closes, thereby completing the circuit of the ignition coil *IC*. This brings down the ignition anode until it touches the mercury bath of the rectifier. Coil *IC* is now short-circuited, owing to the current passing down the rod to the ignition anode, which causes the right-hand contacts of relay *R* to open. The ignition anode is now drawn up by the spring acting in opposition to coil *IC*, and at the point of rupture with the mercury an arc is started. As the two excitation anodes *Ex* are already under pressure, an arc now starts between them and the cathode. The excitation-current strength being greater than that of the ignition current, the second part of relay *R* operates and its contacts are opened, thereby extinguishing the ignition arc and leaving the rectifier ready to be loaded as required.

The direct-current load current can be controlled by the use of properly constructed grids. These grids are placed directly below or surrounding each anode and biased with either direct-current or alternating-current voltage. The biasing potential is connected between the grids and the cathode. In the case of alternating-current grid control, the biasing potential must be

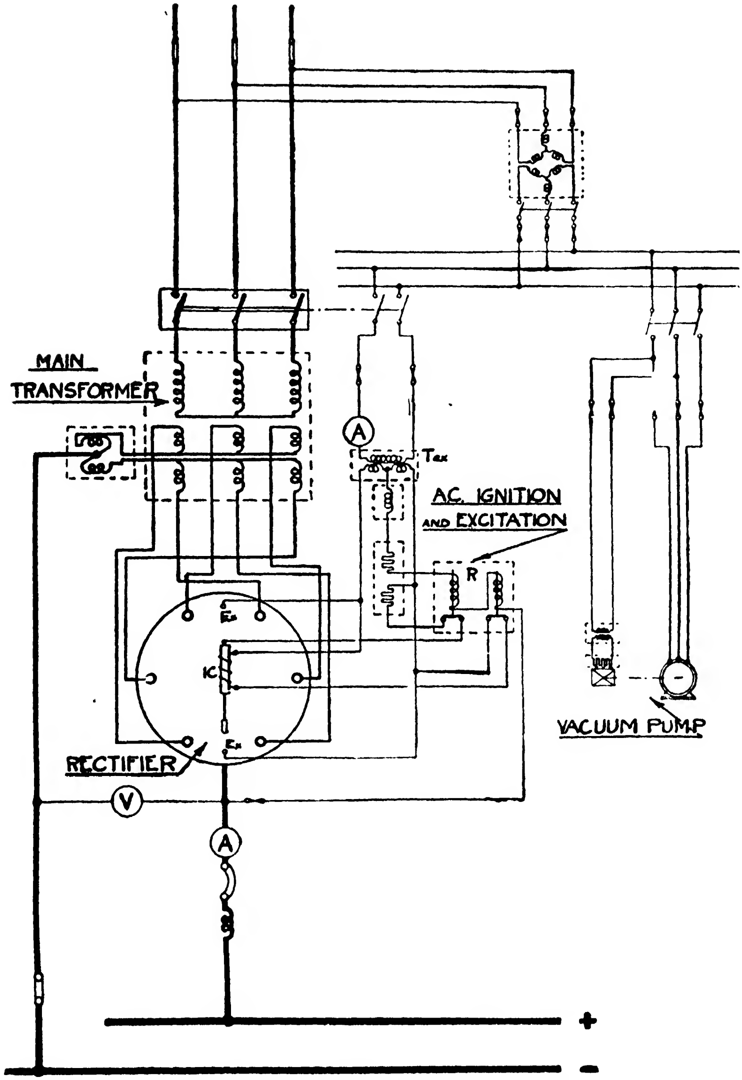

Fig. 84.—Typical diagram of connections for rectifier equipment.

supplied from a polyphase source of the same number of phases as used in the main power circuit. The action of the grids is to control the instant at which firing of each anode will start. A sufficiently negative potential on the grids will prevent the arc from starting.

High-power rectifiers are made in various sizes with ratings from about 150 to 2,000 kw. at pressures up to about 1,800 volts. For higher pressures up to 6,000 volts in one unit, the current ratings are somewhat reduced. A typical high-tension rectifier is shown in Fig. 83. For larger amounts of power, rectifiers may be connected in parallel; and for higher voltages, rectifiers may be connected in series. With a rectifier equipment in its simplest form, there is only one important auxiliary provided, namely, the vacuum-pump set. From what has been said, it will be appreciated that a high vacuum is absolutely essential to the satisfactory operation of the plant. Stated briefly, the following are the main advantages obtained by the use of this class of plant:

1. Efficiency high over the whole working range.
2. Simple operation and attention a minimum.
3. No synchronizing.
4. High momentary overload capacity and insensibility to short circuits.
5. Negligible maintenance.
6. Low weight. No special foundations.
7. Noiseless and vibrationless operation; consequently rectifier substations can be erected in densely populated localities.
8. New substations need only be of light construction.

It has been found that occasionally a cathode spot will spontaneously appear on an anode when it is bearing negative voltage. When this happens, a reverse current will flow. This phenomenom is known as "arc-back." Once formed, a cathode spot on the anode will maintain itself as long as current is conducted to it and the rupturing of this current requires the opening of protective circuit breakers.

In the multianode tank rectifier in which the arc is maintained in the chamber continuously, it is necessary to use grids, shields, and baffles to guard against arc-back. Considerable separation of the anode and cathode is required for this, as well as for mechanical reasons. The shields, grids, and electrode separation increase arc drop, ranging from about 20 to 30 volts for cathode currents of 1,000 to 4,000 amp.

The latest development in power rectifiers involves the use of single anode tanks, known as ignitrons or excitrons. A typical unit of this type is shown in Fig. 84*a*. In such a tank the arc is allowed to extinguish itself at the end of each conducting period.

To ignite the arc, the ignitor is subjected to synchronously timed impulses, which will create the cathode spot and put the tank into operation. The direct-current output can be controlled by changing the time of the ignitor impulses.

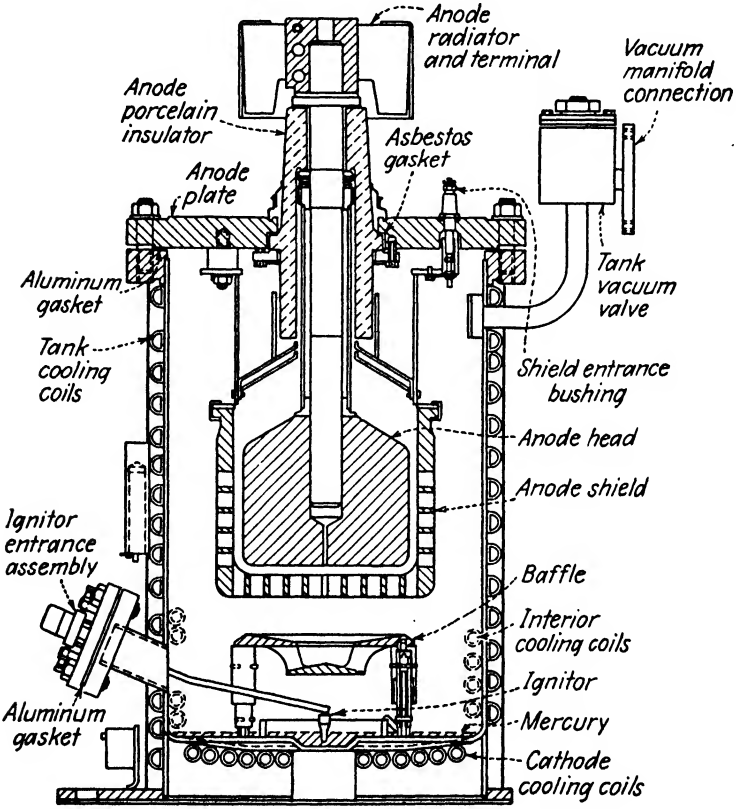

FIG. 84*a*.—Cross section of the ignition showing construction.

The ignitor impulses are obtained from a polyphase power source, each phase containing a circuit so designed as to give one pulse of current in each cycle through the ignitor rod to the cathode. The impulsing transformer is phased out with respect to the rectifier transformer so that the excitation impulses have the correct phase relationship with respect to the voltage applied to the main anodes. The impulse circuit is in reality a form of half-wave rectifier with special iron-cored reactors to give the impulse current a sharp rise, which ensures accurate and reliable ignition. With the compact construction of the single-tank type of rectifier, arc-voltage drops as low as 15 to 20 volts are obtainable with cathode currents of 1,000 to 4,000 amp.

The general circuit arrangement of such units in multiphase groups is fundamentally the same as used in the multianode tank type.

**58. Phase Converters.**—In Art. 54 was given a discussion of equipment for the transformation of alternating current of one frequency to another frequency. It is often also desirable to transform alternating-current energy of a single-phase system to a polyphase system. This cannot be done by stationary equipment, since the power supply of a single-phase circuit is pulsating. Rotating equipment must therefore be used which will store up this pulsating energy and deliver it as constant polyphase energy. Such a machine is known as a phase converter, the connections of which are illustrated in Fig. 85. Such a machine is well adapted to railway service. The difficulties involved in collecting energy from overhead trolley wires or third-rail circuits and the complications involved in switching are so great that practically all alternating-current railway electrifications have been confined to single-phase systems. By means of a phase converter mounted in the electric locomotive, single-phase energy may be supplied to the trolley wire or third

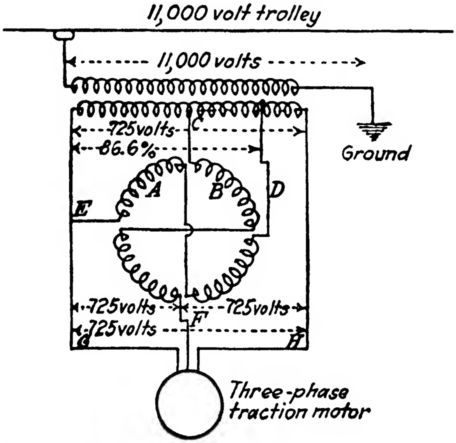

Fig. 85.—Single-phase to three-phase converter.

rail while three-phase energy may be delivered to the driving motors.

In Fig. 85 single-phase energy is delivered at 11,000 volts to the primary of a single-phase transformer. The secondary to this transformer supplies what amounts to a two-phase squirrel-cage induction motor. Phase *A* of this induction motor is connected across 86.8 per cent of the secondary voltage. After the rotor has been brought up to speed, phase *A* will produce a revolving magnetic field which will cut the conductors of phase *B* and therefore induce a voltage in quadrature to the single-phase e.m.f., having a value approximately equal to 86.6 per cent of the secondary-transformer voltage. The actual voltages obtained are better shown in Fig. 86. It is apparent from Fig. 86 that the actual three-phase voltages are obtained by two phases connected in *T*, in the same manner as a three-phase system is obtained from a two-phase transformer bank. In other words, the phase converter may be considered as obtaining a two-phase system from a single-phase supply, the transformation to three-phase being obtained by properly connecting the individual circuits of the two-phase system thus obtained. In Fig. 85 is shown a three-phase motor connected at *FGH*. The function of the phase converter is reversible, and when the motors are running above synchronous speed, as will be the case when a train is running downgrade, they become induction generators supplying three-phase power to the converter, which in turn supplies single-phase power back to the system, thereby giving a large and uniform braking effect.

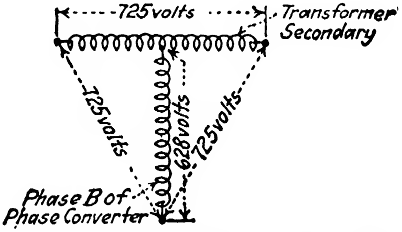

FIG. 86.—Voltage diagram of single- to three-phase converter.

### Questions for Class Discussion

#### DIRECT-CURRENT MACHINES

1. Name a few types of loads that either require or operate more satisfactorily with direct current. Give reason.

**2.** State briefly the applications for the following types of direct-current generators: (*a*) shunt, (*b*) flat compounded, (*c*) overcompounded, (*d*) differentially compounded, and (*e*) separately excited.

**3.** Explain briefly the general arrangements of armature windings for direct-current machines.

**4.** State the purpose of interpoles and of compensating windings on direct-current machines.

**5.** Sketch typical load-characteristic curves for (*a*) overcompounded, (*b*) flat-compounded, (*c*) separately excited, (*d*) shunt, and (*e*) differentially compounded direct-current generators. Explain these curves.

**6.** Define voltage regulation of a generator.

**7.** Tabulate and explain the losses in direct-current machines.

**8.** Explain how shunt and compound direct-current generators operate when connected in parallel.

**9.** Explain briefly the general details of a three-wire direct-current generator.

**10.** What are the advantages of the Edison three-wire system as compared with the ordinary two-wire system?

**11.** Make a diagrammatic sketch of connections for two compound-wound three-wire direct-current generators operating in parallel. Show the necessary switches and circuit breakers for proper operation and protection.

**12.** What is the highest voltage for which direct-current generators and motors are built at the present time?

**13.** What standard direct-current voltages are used for lighting? For lighting and power? For railway service?

**14.** Explain the fundamental principle of the diverter-pole generator. Give its voltage characteristic, and state its field of application.

### SYNCHRONOUS ALTERNATING-CURRENT GENERATORS

**15.** Why is alternating current in general preferable to direct current for transmission and distribution? Why is alternating current not universally used?

**16.** What two frequencies have become standard in this country? Tabulate the advantages and disadvantages of each, and explain why most large central stations generate at the higher frequency.

**17.** Do most alternating-current stations generate single-phase or polyphase, and why? For what purpose might a large single-phase load be used.

**18.** Why are most alternating-current stations three-phase rather than two-phase?

**19.** Name the two standard methods of connecting a synchronous three-phase generator. Why is a resistance sometimes connected in the grounding circuits?

**20.** Discuss briefly the general mechanical details of the following types of synchronous generators: (*a*) engine type, (*b*) water-wheel type, and (*c*) steam-turbine type.

**21.** How is the required strength of rotor obtained in the case of a high-speed salient-pole alternator?

**22.** Describe how the field of a nonsalient-pole steam-turbine type of generator is wound.

**23.** Explain what happens in the magnetic and electric circuits of an alternator between the instant of short circuit and the time when conditions have become stable.

**24.** What is the general shape of the wave of magnetic-flux distribution in the air gap of a salient- and nonsalient-pole machine: (*a*) At no-load? (*b*) At full load?

**25.** Explain clearly what is meant by the terms "leakage reactance," "synchronous reactance," and "synchronous impedance."

**26.** Does power factor have any effect upon the regulation of an alternator? Explain.

**27.** Is it desirable to build alternating-current generators with inherently good regulation? Give reasons. How does good regulation affect the short-circuit current of an alternating-current generator?

**28.** Considering the fact that alternating-current generators are usually built with inherently poor regulation, is it as necessary to provide automatic oil switches in the generator circuits for protection against short circuits as is the case with direct-current generators?

**29.** Are synchronous generators suitable to parallel operations? Explain. What effect will the following have upon the operation of alternators in parallel: (*a*) Unequal induced voltages? (*b*) Sudden decrease or increase in speed of one unit? (*c*) Different wave shapes of induced voltage?

**30.** What methods of ventilation are used for turboalternators? Why is the problem of proper ventilation of these units extremely important?

**31.** A customer has a load of 70 per cent lagging power factor. Does the reactive power represent "so much coal"? Why, then, charge the customer for this reactive power?

**32.** The A.I.E.E. standardization rules specify given temperature limits for certain insulating materials. Why is it undesirable to operate machinery above these limits? Is it permissible to do so in cases of emergency, and what is the consequence?

**33.** To what extent is welding being used in the manufacture of electrical machinery? Discuss its advantages.

**34.** Discuss the general features of design of the umbrella type of waterwheel generator.

**35.** State the advantages of hydrogen cooling for large units, and discuss the limitations involved.

## INDUCTION GENERATORS

**36.** An induction generator is obtained when an induction motor is driven above synchronous speed. Could an induction motor be used for regenerative braking in electric-train control? In this type of application would some scheme have to be devised to obtain low synchronous speeds while braking? Would induction-motor drive, therefore, be suitable for passenger service?

**37.** The more an induction generator is speeded up, the more power it delivers to the line. What happens to the frequency of the system to which power is being supplied? Do these features make it a desirable type of generator for a system consisting of isolated hydroelectric plants? Is synchronous apparatus necessary on the line to furnish excitation?[1]

**38.** What are the advantages and disadvantages of the induction generator as compared with the synchronous generator?

### Motor-generator Sets

**39.** What are the relative merits of induction-motor generator sets and synchronous-motor generator sets?

**40.** What are the general methods used for starting a synchronous-motor generator set?

### Frequency Changers

**41.** Determine the highest r.p.m. at which a 60 to 25 cycle per sec. frequency changer can operate? What must be the number of poles for each machine?

**42.** From the results of Question 41, what do you consider some of the difficulties in the design of frequency changers?

**43.** Explain the difficulties encountered in synchronizing two 60 to 25 cycle per sec. 300-r.p.m. frequency changers.

**44.** What two methods are used to cause one motor-generator frequency changer to slip a pole? Explain.

### Rotary Converters

**45.** Describe the general construction of a rotary converter.

**46.** Determine the theoretical voltage ratios of a two-, three-, four-, and six-collector-ring rotary converter.

**47.** Name a few factors that affect the theoretical voltage ratios as obtained in Question 46.

**48.** How does the efficiency of a converter compare with direct-current generators of the same capacity? Why?

**49.** What is the general nature of the current that flows in the armature conductors of a rotary converter when delivering full load?

**50.** Is the capacity of a converter determined by the average heating in the armature conductors or by the maximum heating in the tap coils? Explain.

**51.** How can voltage adjustment be obtained on a rotary converter? Explain each method.

**52.** Explain the principle of a booster converter.

**53.** Is it best to run a converter off of six-phase, three-phase, or single-phase alternating-current supply? Why?

**54.** What result is obtained by changing the field excitation of a converter? Explain.

**55.** What is the objection to operating a converter at low power factor?

**56.** What are some of the methods that are employed in starting converters?

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[1] For descriptions of a number of hydroelectric induction-generator plants, see *Gen. Elec. Rev.*, November, 1919.

**57.** Contrast the advantages and disadvantages between motor-generator sets and synchronous coverters.

### MERCURY-ARC RECTIFIERS

**58.** Describe the operation of a single-phase glass-bulb rectifier. Is the current obtained from such a device direct or pulsating? What is the object of the inductance coil in the load circuit?

**59.** Give a brief description of a power-arc rectifier.

**60.** Is there any advantage gained by increasing the number of phases of a rectifier? Explain.

**61.** State briefly some of the advantages of a power-arc-rectifier substation as compared with a synchronous-converter substation.

### PHASE CONVERTER

**62.** How can single-phase energy be converted into polyphase energy? To what application is such a process desirable? Explain.

# CHAPTER V

# SYNCHRONOUS GENERATOR EXCITATION

**59. Exciter Capacity and Voltage.** *a. Capacity.*—There is no definite method that can be given by which the exciter capacity can be determined for a given alternator. This can be explained in the following manner: The induced voltage of an alternator is proportional to the product of the number of conductors in series upon the armature, the speed of rotation of the field, the number of field poles, and the magnetic flux per field pole. If all the above factors except the field flux be assumed, for preliminary discussion, as being constants, it can be stated that the induced voltage will be directly proportional to the magnitude of the field magnetic flux. The magnitude of the magnetic flux per pole varies with the ampere turns upon each field pole, but not directly, the law of variation being determined by the magnetic characteristics of the particular grade of iron used in the field construction. For a particular grade of iron and constant value of field ampere turns, it can be further stated that the magnetic flux will be dependent upon the physical dimensions of the magnetic circuit.

From the above discussion it is clear that two alternators requiring the same total field flux may nevertheless have very different values of total field ampere turns, the difference of ampere turns being entirely dependent on the particular number of field poles of each alternator, and also on the physical dimensions of the field circuits of each of the two machines. It is also important to note that a given number of field ampere turns may be produced by an infinite number of combinations of field current and number of field turns. It can be seen, therefore, that two alternators requiring the same total field magnetic flux may have very different values of field current, even though both exciters are for the same voltage.

From the above discussion the following general conclusions are evident: The excitation required varies considerably for different machines, depending upon the size, the number of poles, the speed, and the regulation desired. For alternators of different capacities but otherwise similar, the relative excitation naturally decreases as the size of alternator increases. High-speed machines generally require less excitation than slow-speed ones, owing to the smaller number of poles. In general, it may be said that small-capacity machines with many poles require a proportionally large excitation, and large-capacity machines with a few poles a proportionally small excitation. A small alternator of many poles may require as much as 3 to 5 per cent exciter capacity, while a large machine of a few poles may require only as much as 0.3 per cent exciter capacity.

*b. Voltage.*—Exciters are built for either 125 or 250 volts, these two values being found best suited for all the exciter demands. In the case of very large alternators it is desirable to use 250-volt exciters in order to decrease the current, and thereby use small copper sections in the entire field windings, in both the exciter armature and alternator field, as well as in the connecting circuits. For exciters of the same capacity and speed, the 250-volt machine would require a commutator of only one-half the length, which is of exceeding importance in the case of high peripheral velocities.

**60. Systems of Excitation.**—The most common and simplest system of excitation used in general practice involves a self-excited direct-current shunt generator. The alternator field current is controlled by varying the exciter voltage by means of a regulating rheostat in the shunt field of the exciter.

In some cases the field excitation may be obtained from a separate constant-potential direct-current source. In this case the regulating rheostat must be placed in the alternator field circuit.

For the larger machines it is desirable to use a separately excited direct-current generator as the source of alternator excitation, the power supply for the field of the main exciter being supplied by a pilot exciter. As before, the alternator field current is varied by rheostatic control of the main exciter field current.

Some excitation systems employ rectifiers such as ignitrons with some sort of battery supply for starting conditions.

**61. Exciter Characteristics.** *a. Pilot Exciters.*—Pilot exciters are normally designed to operate at constant voltage independent of load, therefore they are compound-wound direct-current machines with practically flat load-voltage characteristics.

*b. Separately Excited Main Exciters.*—The main advantage of a separately excited direct-current generator, over the standard self-excited type, is the better voltage stability of the former. Any voltage may be obtained over any range, depending on the degree of excitation. It is this feature which makes the separately excited exciter particularly desirable for large alternators.

The field circuit should be designed with low inductance in order that the changes in excitation may take place quickly.

*c. Self-excited Main Exciters.*—Consider the case of a shunt generator designed for power purposes. The no-load saturation curve rises first as a straight line, known as the air-gap line; then as the iron part of the magnetic circuit becomes saturated, it bends over rapidly. The normal point of operation of such a direct-current generator would be on the knee of the curve. A straight line drawn through the operating point of the generator and the origin of the curve would represent the shunt-field characteristic of the machine. Changing the resistance in the shunt-field circuit will correspond to changing the slope of the field-characteristic line, the intersection of the field line and the no-load saturation curve being the operating point of the generator with the new setting of resistance.

Suppose the resistance were changed just the right amount so that the air-gap line and the field line became coincident; then their intersection would be anywhere along the extent of the air-gap line (assuming no residual magnetism of the field) and the generator would be unstable. In the actual machine there is some residual flux present in the magnetic circuit, and this gives to the generator, when operating with the field circuit open, a small residual voltage. This, then, changes the slope of the air-gap line, and the field line no longer coincides with the air-gap line but intersects it with a small angle. This angle is so small that the intersection of these two lines is not at a definite point, but occurs over a considerable range of the lines, thus causing the generator to be unstable when worked on this part of the saturation curve. The above trouble is not present in power generators because they are not called upon to operate at a large range of voltage change.

It is possible to increase the degree of stability of an exciter by increasing the reluctance of the magnetic circuit, thereby necessitating a large field m.m.f., but such a method has the disadvantage that it introduces a strong field which accumulates a large amount of stored energy, thereby decreasing the sensitiveness of the exciter to the changes of alternator voltage.

From the above discussion it follows that the exact characteristic of an exciter should lie between a characteristic that has a long straight line as the air-gap line and then bends over rapidly, and a characteristic that starts bending over at a very low voltage.

**62. Methods of Driving Exciters.**—The general trend is to have the main exciter and pilot exciter, if used, direct-connected to the alternator. This type of installation gives a self-contained power unit. It has some advantages and disadvantages. It is cheaper and more economical of space. It does not require special prime movers for the exciters alone. On the other hand, the design of high-speed and also low-speed direct-current generators is somewhat complicated, the high-speed unit being subjected to large centrifugal forces which are difficult to handle, particularly on the commutator. The physical dimensions of a direct-current generator are inversely proportional to its speed, making the exciters for low-speed units very large. For high speeds and also low speeds it may, therefore, become economical to use separate prime-mover drives for exciters. Another advantage of the separatively driven exciter may be that in case of exciter trouble the main alternator can remain in operation, receiving its excitation from a spare exciter.

In the case of a steam plant the prime mover may be a steam turbine. As a general rule, however, a steam turbine has too high a speed in the small sizes that are required for exciter drive; hence it is not used very widely except as a spare which may operate as an emergency. In a hydraulic plant, the hydraulic design is generally too complicated and the cost too high to consider water-wheel-driven exciters; hence in such plants motor drive is generally used except for those plants using the direct-connected system. The induction motor is the best type of exciter drive obtainable if there is absolute assurance of a continuous alternating-current supply to operate the motors. The low-slip induction motor has practically constant speed and will not drop out of step very easily. It can be started at a moment's notice, a feature that is of great importance.

In a number of plants, both hydraulic and steam, the alternating-current supply for driving the exciters and all other station auxiliaries is supplied by a set of station alternators that are driven by independent prime movers. This system is entirely independent from the main power system, hence avoiding the danger of interruption of the exciter supply in case of any interruption of the main power system.

In most cases of motor-driven exciters the alternating-current supply is obtained from the main busbars, in which case extreme care should be taken to obtain a system of plant layout in which there is very little chance of the alternating-current supply to the exciter motors failing.

**63. Automatic Voltage Regulation.**—Good voltage regulation of power networks is probably the most important element in the normal process of delivering good service to the customer. With the trend toward larger and larger interconnected systems it has been necessary to improve methods of voltage regulation. During system faults or normal switching operations, it is absolutely necessary that all voltage fluctuations be kept down to a minimum in order that the system retain its stability.

Modern automatic voltage regulation of alternators is based upon one fundamental objective, namely, to maintain constant voltage as nearly as possible. To do this the excitation systems are designed to possess the maximum speed of response. Older methods, which were used to limit the action of regulators in case of short-circuit conditions, are now considered unwise. Suitable protective relaying of faulty circuits has improved to the extent that only one demand is placed on the voltage regulator, namely, to regulate for constant voltage regardless of what may occur outside the power plant.

Voltage regulators may be classified as follows:

1. Vibrating type.
2. Rheostatic type.

The vibrating-type regulator is one of the older types and is still found in use, but it no longer holds first place. There seems to be a definite trend away from it toward the rheostatic type. The rheostatic type may be further classified as "direct acting" or "indirect acting."

**64. Vibrating-type Regulator.**—The alternating voltage is regulated indirectly by rapidly opening and closing a shunt circuit across the exciter rheostat, thus varying the exciter voltage in order to maintain the desired alternating voltage.

The regulator (Fig. 87) consists mainly of two parts, a direct-current control system and an alternating-current control system. The former is simply a direct-current regulator having a main control magnet and relay magnet connected across the exciter mains, the contacts of the relay being arranged to shunt the exciter-field rheostat. This operation maintains not a constant but a varying exciter voltage, the value varying in accordance with the demands of the alternating-current control magnet which is connected to the alternating-current bus, the latter magnet being considered as the alternating-current portion of the regulator. This magnet is of the ordinary solenoid type, having a laminated iron core which is attracted upward by the magnetizing force.

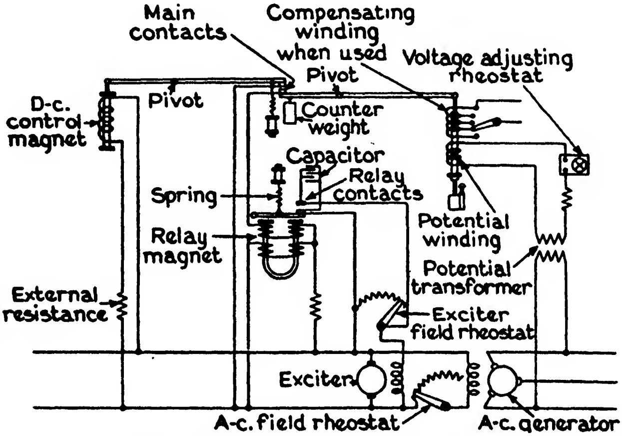

FIG. 87.—Elementary diagram of connections for vibrating-type regulator.

The core is attached to a pivoted lever, at the opposite end of which a counterweight is supported to assist in bringing the lever and core to a point of equilibrium. On the same end of this lever is shown the lower main contact which, in combination with the upper main contact, constitutes what are known as the floating main contacts.

It will be seen from the foregoing that the exciter voltage is controlled by the rapid opening and closing of the relay contacts. The value of the voltage depends upon the position of the alternating current magnet core and lever arm, which is in turn dependent upon the value of the alternating voltage being held.

**65. Rheostatic Direct-acting Regulators.** *a. Westinghouse Silverstat.*—A general schematic diagram of this regulator together with the connections to an alternator and exciter are shown in Fig. 88. Fluctuations in alternating-current voltage are detected by the potential transformer. This voltage is rectified through a rectox rectifier unit. The rectified current operates the main control unit, which is merely a direct-current coil with an internal moving iron armature. The motion of this armature controls the amount of regulating resistance that is inserted in the field circuit of the exciter.

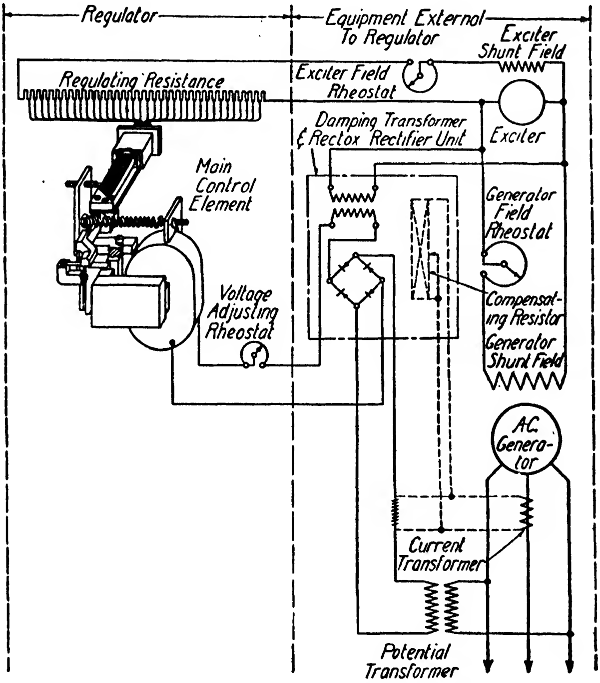

FIG. 88.—Pictograph schematic wiring diagram of typical Westinghouse Silverstat voltage regulator applied to a three-phase generator.

The regulating resistance is entirely stationary. This resistance is tapped at suitable intervals, each tap being connected to one end of a leaf spring. All leaf springs are assembled in a group and clamped together at one end, with proper insulation between springs. The opposite ends of these springs are equipped with small silver buttons, which under the normal rest position of the regulator are all separated by a small distance.

A drop in voltage decreases the magnetizing effect of the regulator coil and reduces the flux in the air gap of its magnetic circuit. This, in turn, decreases the magnetic pull on the iron armature attached to the moving arm and allows the coil spring to move it in a direction to begin closing in sequence more of the silver buttons. This action shorts out in small steps additional portions of the regulating resistance, which being connected in the field circuit, causes the field current to be increased and the voltage raised back to its normal value. When the voltage is restored to its normal value, the moving arm of the regulator is again in a balanced state.

For a rise in voltage the sequence of operation is reversed until a new balanced state is obtained.

The maximum travel of the moving arm being only a fraction of an inch permits the regulator resistance to be quickly varied from maximum to practically zero when operating conditions require such control.

For larger exciters requiring higher field currents, two or more regulating resistances are used, connected in parallel. The main control unit is of the same general design as described above. The operating iron armature now controls one or more driving bars, which in turn control the several silver-button spring assemblies.

To stabilize the regulated voltage and prevent excessive swinging under various conditions of excitation change, a damping effect is introduced into the regulator coil circuit by means of the damping transformer.

The regulating resistor unit in the smallest regulator is composed of carbon disks, while in the larger regulators conventional embedded resistance wire is used.

*b. General Electric Diactor.*—A perspective drawing and diagram of connections for this type of regular is shown in Fig. 89*a*. The circuit is similar to that used in the Westinghouse Silverstat regulator, the main difference being in the regulating resistor unit. The regulating unit is composed of two or more stacks of special nonmetallic resistance material shown at the upper left-hand corner of Fig. 89*a*.

The stacks are formed as shown in Fig. 89*b* from three main parts: (1) resistance plates, (2) metal contact plates, (3) insulating spacers. Each resistance plate has a silver-button insert passing through the plate near the front end. The button is slightly thicker than the resistance plate itself. Insulating spacers separate the individual resistance plates at the rear of the stack. The metal contact plates located at the center are thicker than either the protruding portion of the silver buttons or the insulating spacers, and thereby act as fulcrums on which the resistance plates may be tilted. Small fins, protruding from the top and bottom of the metal contact plates, fit into slots cut in the edges of the resistance plates, locking them in position. The metal contact plates also form the electric contacts between the resistance plates, making a resistance path for the current to flow through at the center of the stacks when the rheostat is in the

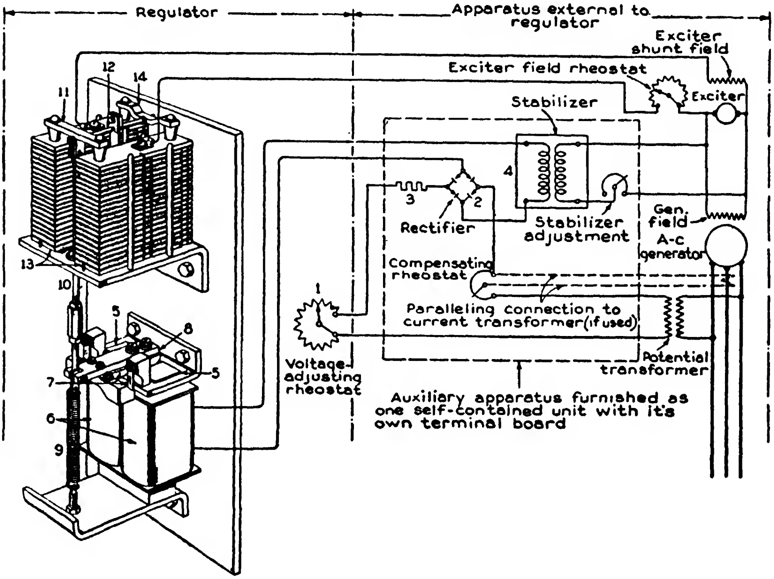

FIG. 89a.—Perspective drawing and connection diagram of a two-stack Diactor generator-voltage regulator, type GDA. (*General Electric Company.*)

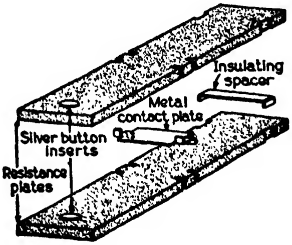

FIG. 89b.—Parts of rheostatic stacks showing their construction and position.

maximum resistance position. It should be noted that there is no electric contact between these metal contact plates themselves, since they are separated by the resistance plates.

The top plate of each stack is made of metal to act as a contact plate for the complete stack. The bottom resistance plate of each stack rests on a copper bracket, which serves as a contact plate and forms a circuit to the adjacent stack. All stacks are connected in series.

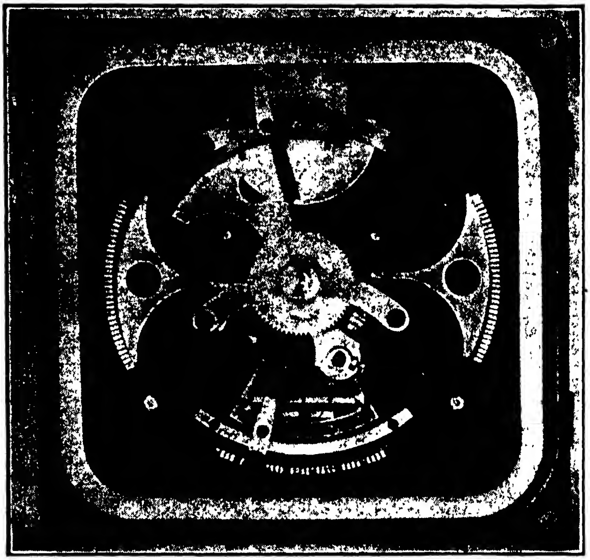

FIG. 90*a*.—Two-sector direct-acting automatic regulator. (*Allis-Chalmers Manufacturing Company.*)

Changes in machine voltage will cause a change in position of the operating rod (10) (See Fig. 89*a*). Since the resistor elements are pivoted at their mid-point, an upward motion of the operating rod (10) will cause the back of the stack to be compressed while the front ends of the resistor plates are separated.

When the stacks are tilted back so that the front ends of the plates are separated, the rheostat is in the maximum-resistance position.

If the stack is gradually tilted forward, its resistance is gradually reduced. This change is caused by a decrease in contact resistance between the resistance and metal plates at the center of the stacks as they tilt forward, combined with the gradual short-circuiting of the plates by the silver inserts (at the front end of the plates) as they come together.

If the tilting action is continued, the resistance is gradually decreased until in the extreme low-resistance position the silver inserts form a continuous silver path, or column, through the stacks, reducing the resistance to a negligible value.

*c. Allis-Chalmers Rocking Contact.*—An assembled view of such a regulator is shown in Fig. 90*a*. The design of the different

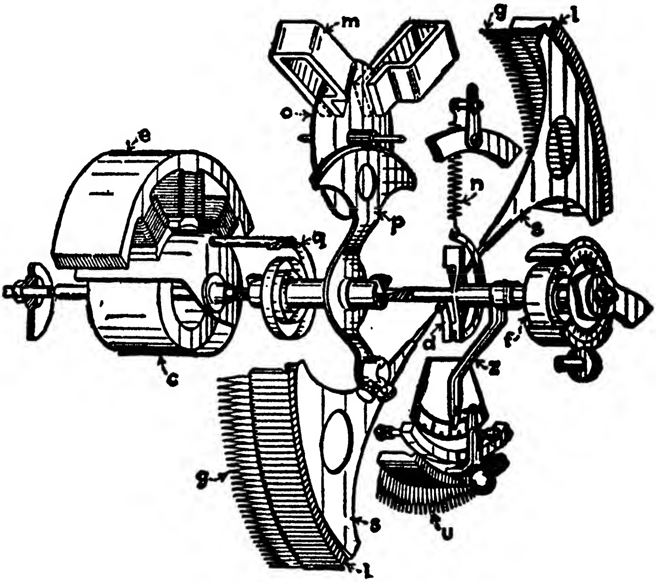

Fig. 90*b*.—Motive system and mechanism of direct-acting regulator.

parts and their general arrangement can best be explained by referring to Fig. 90*b*. The control device is built on the principle of the induction motor. The stator laminations *e* are circular and carry a split-phase winding. Concentric with the stator pole faces is a cylindrical soft-iron core, which completes the path of the field lines leaving only a small air gap. In the field in this air gap is placed a thin hollow drum of aluminum, *c*, carried by a steel spindle, the latter being supported at both ends by jewel bearings. The electric torque produced by the current in the split-phase winding is counterbalanced by a combination of two springs, which produce a constant torque whatever the position of the drum.

The field rheostat with contact device is an integral part of the regulator. The stationary contacts *l* to which the resistance coils *g* are connected are arranged concentrically with the rotor spindle in two or four rows, depending upon the size of the regulator. The inner side of these contacts, facing the spindle, is provided with a V-shaped groove that serves as a guide for the moving contacts. The latter have the shape of a sector, with a curved strip of silver or carbon as contact surface and a steel needle as pivot. The latter rests in a jewel cup, which is carried by a leaf spring supported from the rotor spindle. The rotor can be turned through an angle of 60 deg. and in doing so carries the two needle points over the corresponding arc of a circle. This causes the sectors to roll in the grooves of the stationary contacts, putting in or cutting out resistance. The latter in the case of a generator voltage regulator is connected in series with the shunt field of the exciter, as shown in Fig. 90*c*.

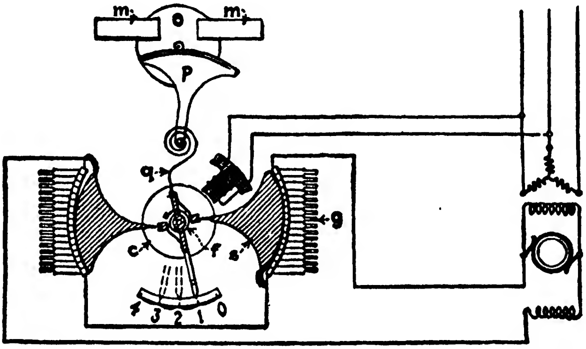

FIG. 90*c*.—Connections for regulating a single alternator.

The regulator is made stable by a suitable damping mechanism which consists of an aluminum disk *o* rotating between two permanent magnets *m*. The disk is geared to the rack of an aluminum sector *p*, which can turn concentrically with the rotor spindle and is fastened to the aluminum drum *c* by means of a flexible spiral spring *q*, acting as a recall spring. If a change in voltage occurs, the eddy currents induced in the disk *o* tend to resist quick response of the moving system. Owing to the flexible coupling, however, the drum, which directly controls the contact sectors *s*, will immediately take up a position in which the torque of the various springs and the electrical torque are again balanced.

An elementary diagram of connections for the voltage regulation of alternators is shown in Fig. 90*c*. The split-phase winding is connected across the terminals of the alternator, and the rheostat *g* is in series with the field winding of the exciter. The cycle of operation is as follows: Assuming the generator fully loaded, the contact segments will then take up a position similar to the one shown in Fig. 90*c*, in which a great part of the resistance is short-circuited. A drop in load tends to raise the voltage, but the smallest increase is immediately followed by an increase of the electrical torque so that the system becomes unbalanced. As a result the sectors are displaced to the left till the mechanical torque, now increased by the torque of the recall spring *q*, again equals the electrical torque.

**66. Indirect Rheostatic-type Regulators.**—Several manufacturers have designs along this line, the basic principle being common to all, with special differences as to details. The heart of this regulator is in the main control unit.

This control unit is composed of a three-phase torque motor with the movable contact arm rigidly coupled to its shaft. The torque of this motor is proportional to the average of the three-phase voltages. Its torque is counterbalanced by a suitable spring. The Westinghouse Company uses a single direct-current solenoid in its main control unit in place of the torque motor. This solenoid is energized from the three-phase alternating-current generator terminals through suitable potential transformers and a special arrangement of rectox rectifiers.

Two pairs of moving contacts are mounted on the main contact arm located between two pairs of stationary contacts mounted on and insulated from the base. The two voltage-lowering contacts are on the right; the raising contacts are on the left.

The stationary top contacts make contact a short interval before the lower contacts close. Thus on a slight voltage change, a top contact will close and on a severe voltage change both contacts on one side will close.

An air dashpot or magnetic damping device is provided to prevent the regulator from acting during a momentary change in voltage not requiring a change in excitation.

Notice that the main control element (Fig. 91*a*) operates four sets of contacts, two for "voltage lowering and two for voltage raising," see contacts $L1$, $L2$, $R1$, and $R2$ (Fig. 91*b*). One of the "raising" and one of the "lowering" contacts control some form of motor-operated exciter field regulating rheostat. These contacts are known as the "notching" or "inching" contacts, since their operation will change the field regulating rheostat in typical small steps similar to any ordinary faceplate rheostat.

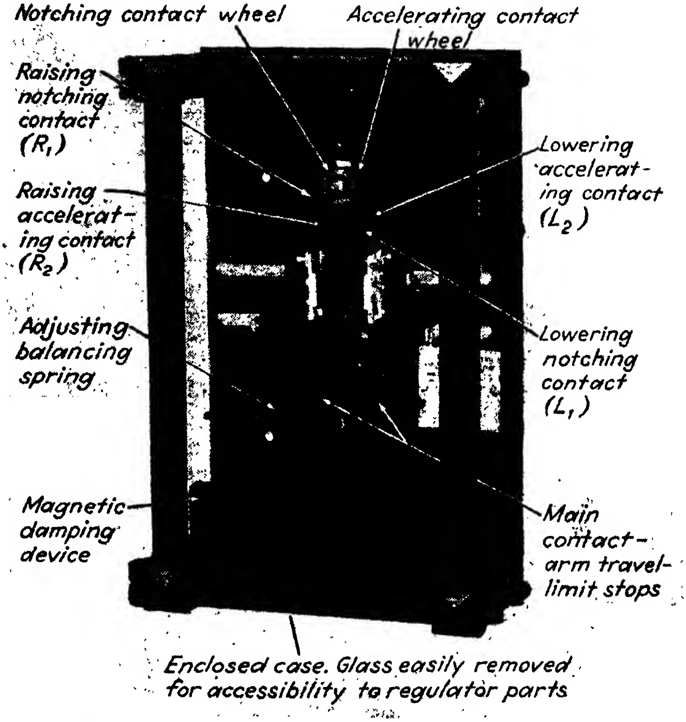

FIG. 91*a*.—Main control element of voltage regulator. (*General Electric Company.*)

The other pair of contacts (one "raising" and one "lowering") control high-speed contactor relays, which either short-circuit or introduce a fixed amount of resistance in the exciter field circuit. This is illustrated by contacts $A$ and $B$ in Fig. 91*b*. These last two main control unit contacts are known as the "accelerating" or "field-forcing" contacts. They operate only on a sudden large change in alternating-current machine voltage and cause a correspondingly fast adjustment of exciter-field current.

Several types of motor-operated exciter field rheostats may be used with the above main control unit. The simplest is a carbon-pile rheostat in which the amount of resistance is controlled by the pressure exerted on the column of carbon disks. Some units have a typical wire-wound series type of motor-operated face-plate rheostat, shown schematically in Fig. 91*b*. The Allis-Chalmers Manufacturing Company adapts the rocking sector of its self-contained "direct-acting" regulator to a field regulating rheostat as shown in Fig. 92.

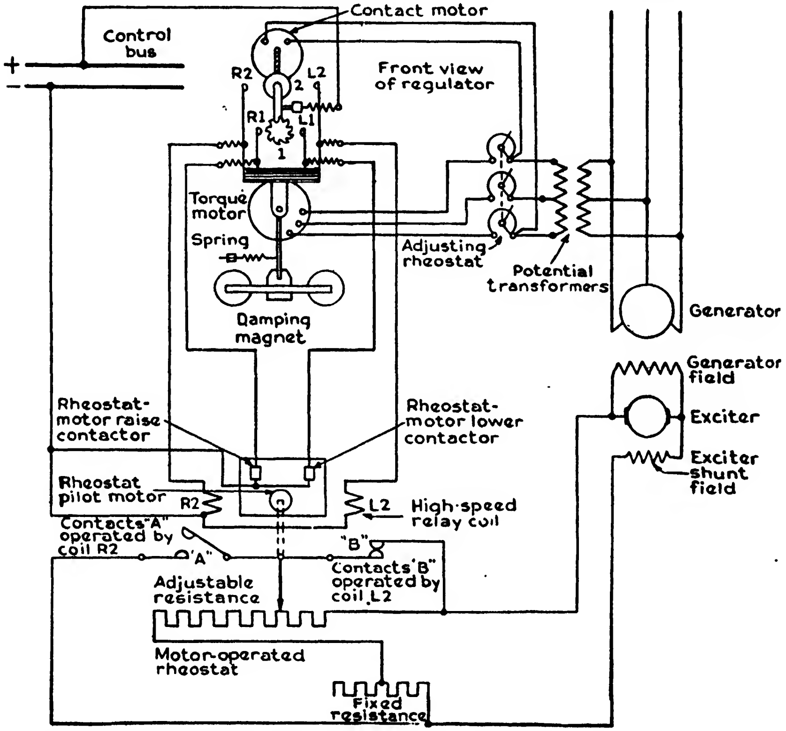

FIG. 91*b*.—Elementary connection diagram of General Electric Company type GFA-4 voltage regulator with face-plate-type series rheostat and self-excited exciter.

The resistance of the rheostat is varied by sectors rocking over and changing the point of contact on a stationary commutator to which the resistance steps are connected. The sectors are connected to short out the resistors as they move from one end of the commutator to the other. Rocking of the sectors is performed by a reversing motor through a precision gear reducer.

The resistance steps are mounted in a substantial welded-steel framework on the rear of the rheostat and are of nonbreakable construction.

One, two, three, or four commutators, each providing 100 steps, are used, depending on the current rating, amount of resistance required, and the fineness of voltage control desired. The range provides for control of the exciter voltage from maximum to minimum required by the machine.

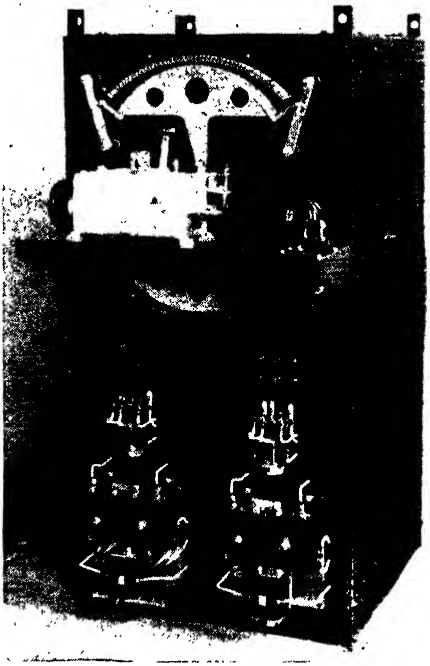

Fig. 92.—Rocking contact motor-operated exciter rheostat with high-speed field forcing contacts. (*Allis-Chalmers Manufacturing Company.*)

A Wheatstone-bridge circuit (see Fig. 93) forms another type of field rheostat. It is particularly applicable with pilot-exciter installations or separately excited main exciters. The bridge rheostat has two opposite legs of fixed resistance (*AD* and *BC*) and two opposite legs of variable resistance (*AB* and *DC*), as indicated schematically by diagrams *a*, *b*, and *c* in Fig. 93.

In diagram *a* (Fig. 93) it will be seen that the entire variable section of each leg is completely shunted by the movable arms of the bridge rheostat and the main-exciter field is connected directly across the terminals of the pilot exciter. This position of the rheostat gives full excitation in the positive direction to the main-exciter field.

In diagram *b* (Fig. 93) it will be noted that the two movable arms of the rheostat are shunting 10 ohms of each variable leg. In this position there are 50 ohms in each of the four sides of the bridge rheostat. It is readily seen that for this condition there will be no potential drop between points *B* and *D* of the rheostat and, therefore, no current will flow in the main-exciter field. This position of the rheostat, therefore, applies zero excitation to the main exciter.

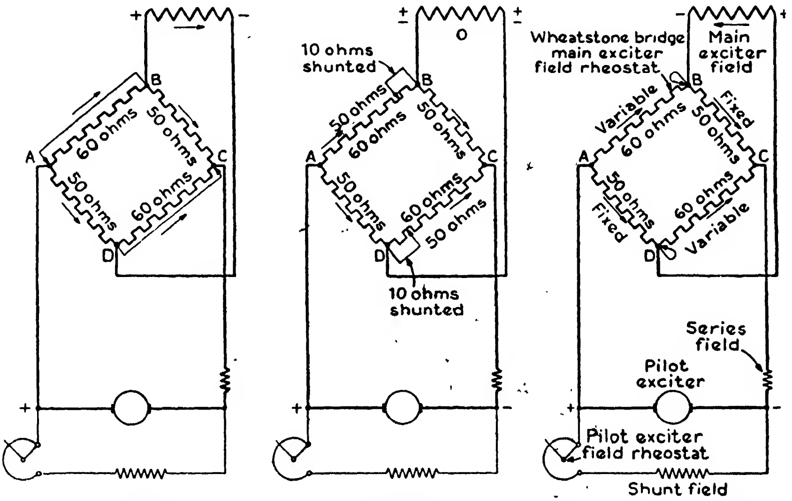

FIG. 93.—Principle of operation of Wheatstone-bridge rheostat for wide-range excitation control.

In diagram *c* (Fig. 93) the movable arms of the bridge rheostat are in the "all-out" position so that the total resistance of 60 ohms is inserted in each variable leg. The polarity of the main-exciter field is now in the opposite direction to that shown in diagram *a*. The resistance values of 60 ohms for each variable section and 50 ohms for each permanent section allow a slight reversal of excitation to the main exciter, to offset the main-exciter residual voltage. This, in turn, will give approximately zero voltage at the main-exciter terminals.

One manufacturer provides the main exciter with two field circuits, both being connected to the pilot exciter. The main field supplies most of the exciting m.m.f., while the second field supplies only a small percentage of the main field m.m.f. Furthermore, this second field is connected in magnetic opposition to the main field. As the main field m.m.f. is lowered, the effect of this differential field becomes more pronounced, in fact reducing the residual magnetic flux to zero in some cases, or even giving the main exciter a slight reversed polarity voltage.

In case the system voltage should take a sudden drop, the "quick-acting" contacts of the main control unit can be made to open the differential field circuit as well as short-circuit a fixed amount of main field circuit resistance, thus giving an unusually fast action toward recovering of the system voltage. The effect of the differential field winding is fundamentally to increase the speed of voltage adjustment.

**67. General Range of Application.**—The several manufacturers of large alternators have developed complete lines of rheostatic-type regulators to cover any generator application. The capacity and particular type of regulator to be used depend upon the amount of exciter field current to be controlled and the rate at which it must be controlled. Five to six sizes of the direct-acting type are available, and four to six sizes of the indirect type are in use, covering individual generator ratings from 1 to 200,000 kva. at speeds ranging from 80 to 3,600 r.p.m. The dividing line between direct-acting and indirect-acting regulators is not very clearly defined, being a function of both machine capacity and speed. In general, all alternators above 20,000 to 25,000 kva. require the indirect type, irrespective of the speed. As the alternator speed becomes lower than 3,600 r.p.m., it becomes necessary to apply the indirect-type regulator to alternators of lower than 20,000 kva. At 100 r.p.m., the indirect-acting type regulator would generally be applied to machines of capacities in excess of 500 kva.

**68. Pilot-exciter Voltage-limiting Equipment.**—For installations where the pilot exciter is direct-connected to the main shaft of a water-wheel-driven generator, dangerously high pilot-exciter voltages might be encountered unless some provision were made to protect this exciter during runaway conditions of the water-wheel. Figure 94 shows the connections of a protective system for installations of this kind.

The master relay whose contacts are normally open is set, by means of the adjusting spring, to close its contacts when the pilot-exciter voltage reaches some predetermined value above normal. This opens the contacts of the normally closed high-speed auxiliary relay, which inserts a block of resistance in series with the pilot-exciter field, thus reducing the voltage to a safe value during the abnormally high-speed conditions.

When steady-state conditions are again encountered, the relay automatically resets itself for normal operation.

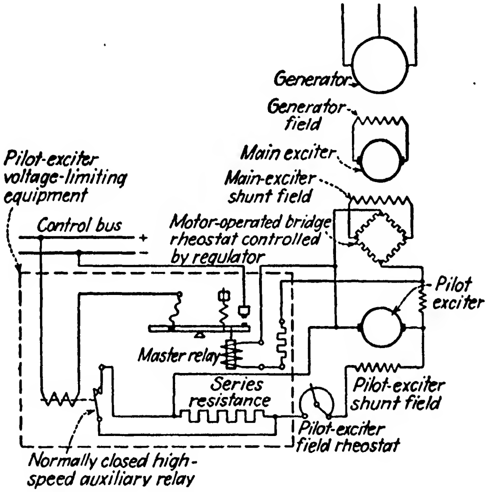

FIG. 94.—Pilot-exciter voltage-limiting equipment.

This method of protection does not interfere with the regulator, which serves as an overvoltage-protective device for the generator and main exciter as explained in the description of the Wheatstone-bridge exciter-field rheostat.

**69. Parallel Operation and Line-drop Compensation.** *a. Parallel Operation.*—The division of load among alternating-current generators operating in parallel is dependent on the power supply to each generator as controlled by the governor of its prime mover and is practically independent of excitation. The division of reactive current among generators is a function of the excitation.

In order to obtain successful parallel operation of two or more generators with individual voltage-regulator control, the regulators must perform two main functions: (1) they must hold the voltage constant, and (2) they must provide proper division of reactive kilovolt-ampere load among the generators.

In considering the application of a system of regulation to a number of alternating-current generators operating in parallel, it should be remembered that the change in excitation of any one of the generators does not appreciably affect the bus voltage. The chief effect is to change the reactive current supplied by that particular machine, as the other machines will tend to maintain the voltage level constant. Increasing the excitation will tend to make a machine supply more reactive current, and decreasing the excitation will make it supply less reactive current. To raise the station bus voltage, it is necessary to increase the excitation of all the machines.

In the past, stations having several paralleled alternating-current machines have frequently been controlled by a single voltage regulator. With this arrangement, the division of reactive current between alternating-current machines and the division of load between exciters was controlled by manual adjustment of the exciter or the generator-field rheostats.

The best engineering practice demands that alternating-current generators operating in parallel have individual exciters that do not themselves operate in parallel. This is known as the "unit-exciter system." The exciters operate independently, that is, nonparallel. Such an arrangement permits the most flexible operation. Each combination of generator, exciter, and regulator is separate from the other. Any number of alternating-current machines may be successfully operated in parallel in the same manner.

When alternating-current machines are operating in parallel, it is necessary that the reactive kilovolt-ampere outputs of the individual machines be equalized to prevent one machine carrying all the reactive kilovolt-amperes, with consequent overloading. It is therefore necessary to provide some means of correcting the excitation of the individual machines should they tend to take more or less than their proper share of reactive kilovolt-amperes. It is therefore necessary to bias the voltage element of each regulator with reactive current or some equivalent effect, so as to obtain for all load conditions proper division of reactive current among machines in parallel. Such biasing action is known as "cross-current compensation."

With solenoid types of regulators, this compensation is ordinarily obtained by means of a current transformer and compensating rheostat for each regulator, as shown in Figs. 88 and 89*a* for three-phase generators. The current transformer is connected in one lead, with the potential transformer across the other two leads. The phase relations are then such that the voltage drop across the compensating rheostat tends to add to the alternating-current potential on the regulator for lagging reactive kilovolt-ampere output of the generator, and subtract for leading reactive kilovolt-ampere output. This influences the regulator to reduce excitation for lagging current (overexcited generator) and increase excitation for leading current (underexcited generator). This action tends to divide the total reactive kilovolt-ampere load among any number of machines in proportion to their ratings and enables the regulators properly and automatically to control generators operating in parallel.

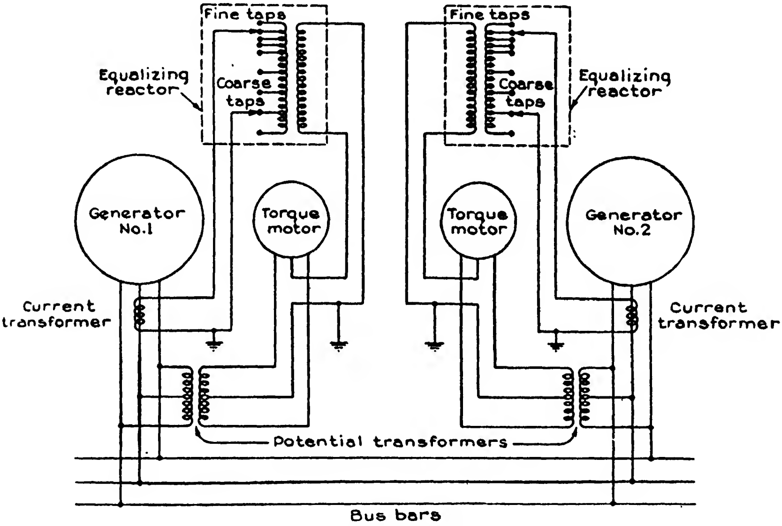

FIG. 95.—Individual scheme of connections of equalizing reactor for parallel operation.

For torque-motor type of regulators, the method of cross-current compensation is obtained by injecting a proper biasing voltage into one line of the three-phase torque motor (see Fig. 95). By means of the regulating reactor a proper amount of biasing can be obtained.

*b. Line-drop Compensator.*—The present-day practice of interconnected power systems has practically eliminated the need of line-drop compensation with generator voltage regulators. It is still used, however, in some special cases where constant voltage is desired at some distant point from the generator, rather than at the generator terminals.

The line-drop compensator is used to reproduce in miniature, at the regulator, the resistance and reactance drops to a predetermined point in the line. The function of the compensator is to lower the impressed voltage on the torque motor or solenoid unit as load comes on, thereby causing the regulator to maintain normal voltage at some predetermined point on the system regardless of the power factor of the load.

As far as physical appearance and general circuit connections are concerned, this device is very similar to the equalizing reactor described for cross-current compensation between machines operating in parallel. In addition to having a variable reactor and insulating current transformer, it has a variable resistor connected in series with the reactor. The resistance and reactance of the compensator are each divided into a suitable number of sections. Taps are brought out from these sections and connected consecutively to independently adjustable dial switches. By suitable adjustment of these two dials it is possible to obtain a voltage drop that is a miniature of the actual line drop to the predetermined point of the system. This compensator voltage is then injected into the regulator control unit in the same manner as was done for cross-current compensation, thereby biasing the control unit to regulate for constant voltage, not at the generator terminals but at a distant point from the station.

### Questions for Class Discussion

1. In a direct-current generating plant, are exciters required? Are exciters always required in alternating-current plants? For example, in one of the hydroelectric plants of a system using induction generators?

2. Discuss briefly the factors that determine the necessary exciter capacity in kilowatts for synchronous generators.

3. What are the standard voltages for which exciters are built?

4. Give the approximate limiting values of exciter capacity in percentages of the generator rating.

5. What is the general characteristic of a self-excited shunt-wound exciter? How does this characteristic differ from that of a standard direct-current generator designed for power service?

**6.** What is a pilot exciter? What are its characteristics?

**7.** What are the relative merits of shunt- and compound-wound exciters?

**8.** Name, in the order of their importance, some of the requirements that must be considered in laying out an excitation system.

**9.** What systems of excitation are in use in synchronous generator stations? Tabulate advantages and disadvantages.

**10.** How may reserve exciter capacity be provided in a station using individual exciters? Give several schemes for doing this.

**11.** Name three common methods of driving exciters. What are the advantages and disadvantages of each?

**12.** Would you consider a separate prime mover or a motor preferable for driving a spare exciter unit?

**13.** In a station having an exciter bus, would you consider it desirable to have all exciter units driven by motors? Consider cases of emergency.

**14.** Why is induction-motor drive for exciters preferable to synchronous motors?

**15.** What is the present tendency in exciter practice as regards system of excitation and method of drive?

**16.** Name two distinct types of voltage regulators, and state the field of application for each one.

**17.** What is the fundamental principle of operation of vibrating-type regulator? What is meant by the "time of contact engagement"?

**18.** What are the relative merits of the vibrating and rheostatic methods of voltage regulation?

**19.** Discuss the reason for high-speed excitation, and state how it may be obtained.

**20.** Explain the principle of operation of direct-acting regulators.

**21.** Explain the principle of operation of the Silverstat regulator.

**22.** Explain the principle of operation of the Diactor regular.

**23.** Explain the principle of the rocking-contact regulator.

**24.** How may the Silverstat, Diactor, and rocking-contact regulators compensate for line drop?

**25.** Describe the general principle of operation of the main control unit of the indirect rheostatic-type regulator.

**26.** What are the "field-forcing" contacts of the main control unit of an indirect rheostatic regulator?

**27.** Describe the operation of the Wheatstone-bridge type of regulating resistance.

**28.** What is the general range of application of the rheostatic type of regulators.

**29.** Describe the details of the pilot-exciter voltage-limiting equipment.

**30.** Older regulating circuits included a short-circuit protective device to limit the rise in alternator excitation under alternator short circuits. Why has this device been dropped from modern systems?

**31.** Why is it not advisable to use an automatic circuit-breaking device in an exciter circuit?

**32.** What is the purpose of the field-discharge switch? Of the field-discharge resistance?

# CHAPTER VI

## ELECTRICAL POWER-PLANT CIRCUIT LAYOUTS

**70. General Considerations.**—The particular layout adopted for a plant will be dictated by a number of factors, the most important being the following:

1. Flexibility.
2. Adequacy.
3. Reliability.
4. Simplicity.
5. Safety.
6. Space.
7. Cost.

In general the best engineering is represented in the simplest layout that can be used to accomplish the purpose desired in a safe and reliable manner. The plant layout must be reliable even if the particular demands will necessitate a complex and costly installation. In many plants, particularly in congested districts, the available space has a great deal to do with the final choice of the plant layout. It is impossible to give an example of all the different types of plant layouts, but a few general outlines are given which include the small plants as well as the very large plants.

**71. Classification.**—In general, power plants may be divided into three general classes as regards the distribution of power:

1. Power may be distributed at the same voltage as that at which it is generated.

2. Power may be distributed at a higher voltage than that generated.

3. Power may be distributed at several voltages, one of which may be the same as generated.

Several typical layouts are given in the following pages of this chapter which will give a general idea of the great diversity of possible systems that are now used. All the layouts are given in the standard single-line method, in which each line or symbol represents a three-phase circuit or device.

**72. Typical Power-plant Circuit Layout.**[1]—*Single-bus System* (Fig. 96).—Used for small stations where simplicity and economy are the primary requisites.

*Double-bus Single-circuit-breaker System* (Fig. 97).—This arrangement greatly increases the chances for continuity of service over that shown in Fig. 96. One busbar may be used as an auxiliary only, or one may feed a lighting load while the other feeds a power load.

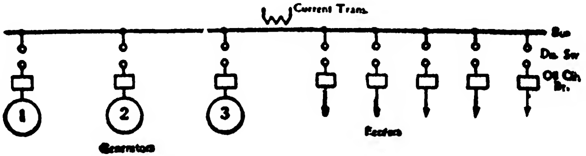

FIG. 96.—Single-bus, single-circuit-breaker system.

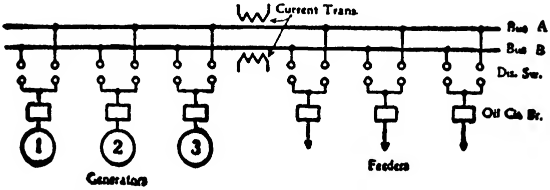

FIG. 97.—Double-bus, single-circuit-breaker system.

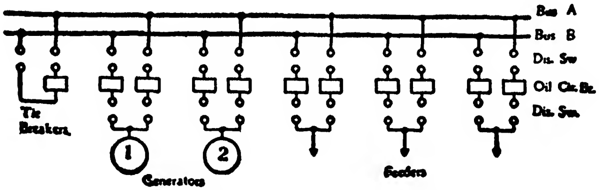

FIG. 98.—Double-bus, double-circuit-breaker system.

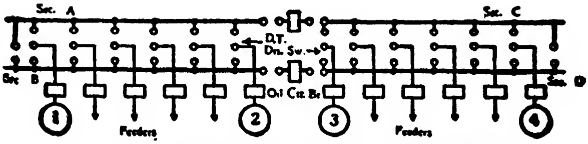

FIG. 99.—Ring-bus system, bus sectionalized.

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[1] Obtained from H. A. Travers, "Switching Equipment for Alternating-current Power Stations," published by the Westinghouse Electric Corporation.

*Double-bus Double-circuit-breaker System* (Fig. 98).—This arrangement gives the same advantage as Fig. 95, with the double assurance against shutdown due to circuit-breaker trouble.

*Ring-bus System, Bus-sectionalized* (Fig. 99).—Suitable for stations of medium size where great flexibility and maximum economy in cost are desired. This arrangement requires a relatively small amount of copper in the busbars.

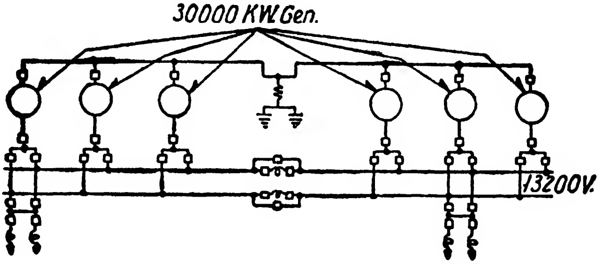


Fig. 100.—H-system.

*H System* (Fig. 100).—Large generating stations in cities, such as Philadelphia and New York, use this scheme Two-feeder circuits are served by a pair of selector switches from either of two busses.

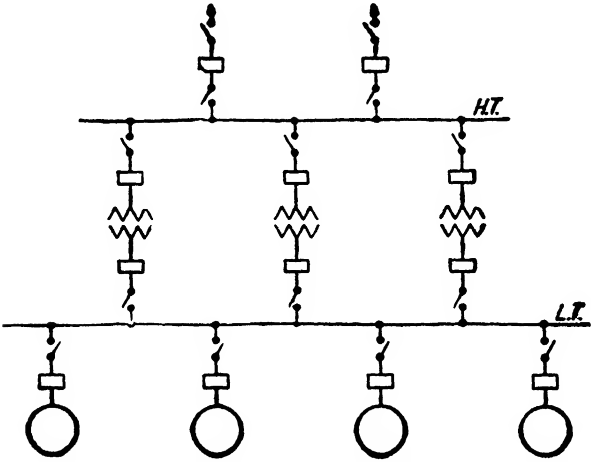


Fig. 101.—System using single low- and high-tension bus.

*Single Low- and High-tension Bus* (Fig. 101).—This system is the simplest scheme that is adaptable to plants supplying power over high-tension lines and also requiring a low-tension bus. It does not offer much protection against the possible spreading of trouble to the entire system.

*Single Sectionalized Bus System* (Fig. 102).—This system gives great flexibility of operation with minimum cost and is suitable for medium-sized plants. Dependence is placed on single cir-

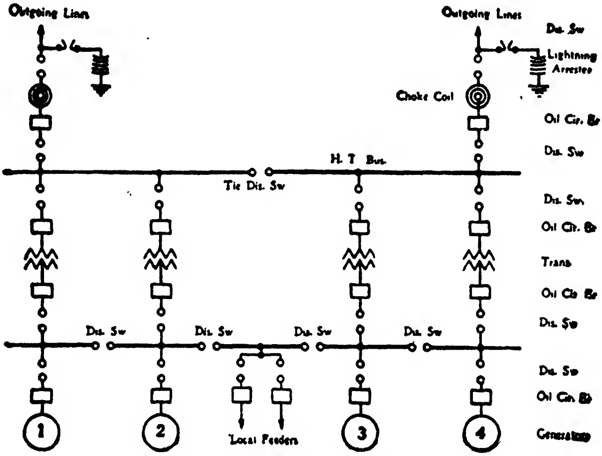


FIG. 102.—Single sectionalized bus system.

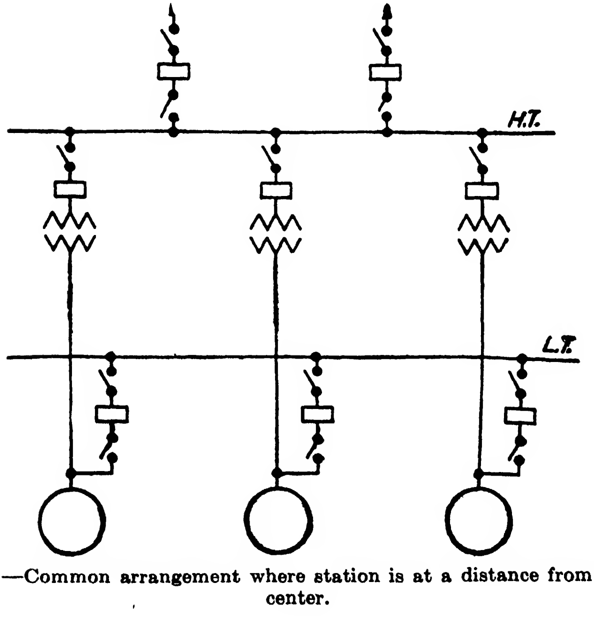


FIG. 103.—Common arrangement where station is at a distance from the load center.

cuit breakers. The station may be operated in separate independent halves, local feeders being fed from either half. Trouble arising in one part of the system can be better localized with this scheme.

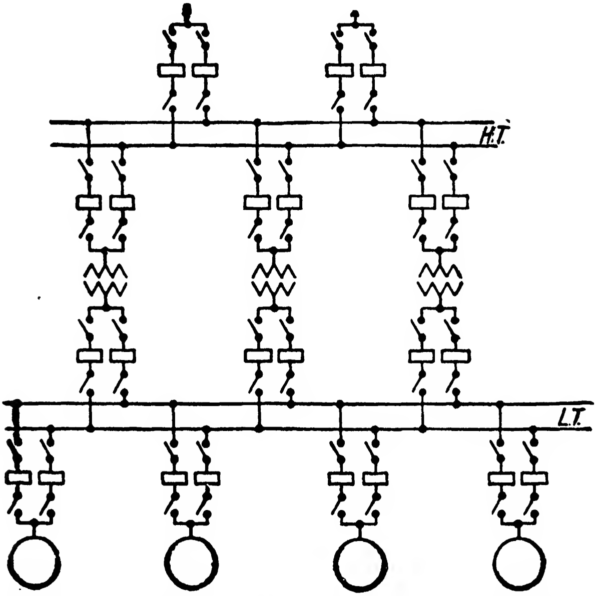


FIG. 104.—Bus system using double buses and double breakers.

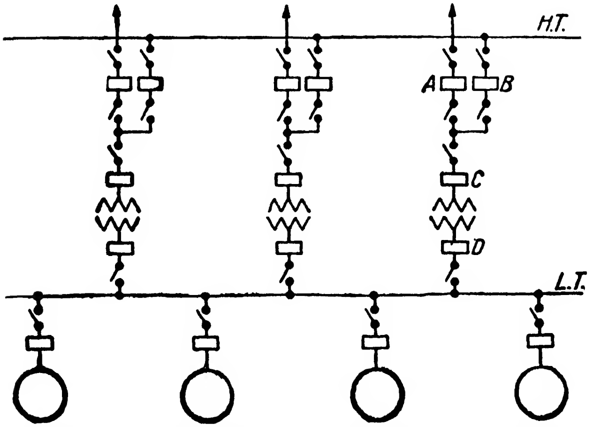


FIG. 105.—System whereby transformers are treated as a part of the transmission line.

*Single High-tension Bus Scheme, and Station Auxiliary Bus* (Fig. 103).—In this system the generator and transformer are treated as a unit, and all low-tension switching is thereby omitted. The station auxiliaries are fed from any generator or transformer circuit by means of the auxiliary bus.

*Double-bus Double-circuit-breaker System Throughout* (Fig. 104). This arrangement permits the use of any or all of the generators, without regard to which of the transformers may be in operation.

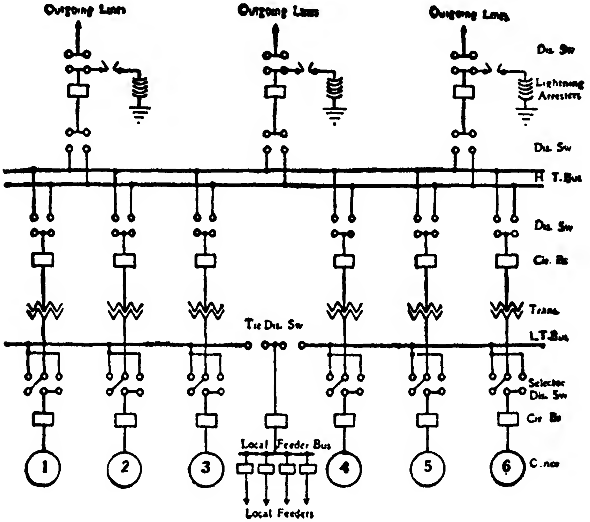


FIG. 106.—Single low-tension, double high-tension bus, single circuit-breaker scheme.

*System Whereby Transformers Are Treated as Part of the Transmission Lines* (Fig. 105).—The particular application of such a switching arrangement seems to lie with a station where power is to be transmitted over a number of lines to a single substation.

*Single Low-tension Double High-tension Bus Single-circuit-breaker Scheme* (Fig. 106).—In this system low-tension disconnecting switches permit the connection of a generator direct to a transformer (with or without connection to busbar), connection of generator to busbar with transformer dead, or connection of transformer to busbar with generator dead. A generator, transformer, or feeder may be taken out of service for the examination or repair of its circuit breaker. All the apparatus may be in service while the load is removed from either section of either busbar for repairs or additions.

*No Low-tension Bus, Double High-tension Bus* (Fig. 107).—This plan is suited to such stations as take the base load of the system. Each combination of generator and transformer is considered as a unit, having no switching devices between them. The high-tension bus is a straight double-bus double-circuit-breaker arrangement, which gives the maximum amount of flexibility. Station power must be supplied from the high-tension busses through step-down transformers.

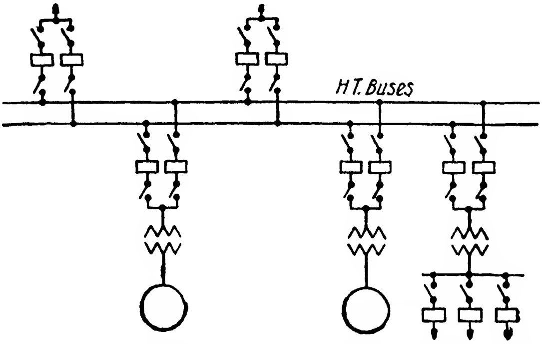


FIG. 107.—Bus system for large steam stations where power is fed into a high-tension network.

*Single Sectionalized Low-tension Bus with Two High-tension Busses, One of Which Is Sectionalized* (Fig. 108).—This station may be operated as four complete units (generator, transformer, and line separate), or any generator may feed any bank of transformers through the low-tension busbar. The step-down transformer for local or station service permits the low-tension busbar and circuit breakers to be taken out of service entirely without interfering with the load.

*Single-bus Feeder-group System* (Fig. 109).—This arrangement is suitable for stations employing large units, each supplying a number of feeders. Each unit and its group of feeders may be operated independently, or all may be operated from one main bus.

*Single Low-tension Transfer Bus, Double High-tension Bus* (Fig. 110).—With this scheme, the station may be operated in four separate parts, if desired, any or all of which may be connected together at will. The double-throw high-tension dis-

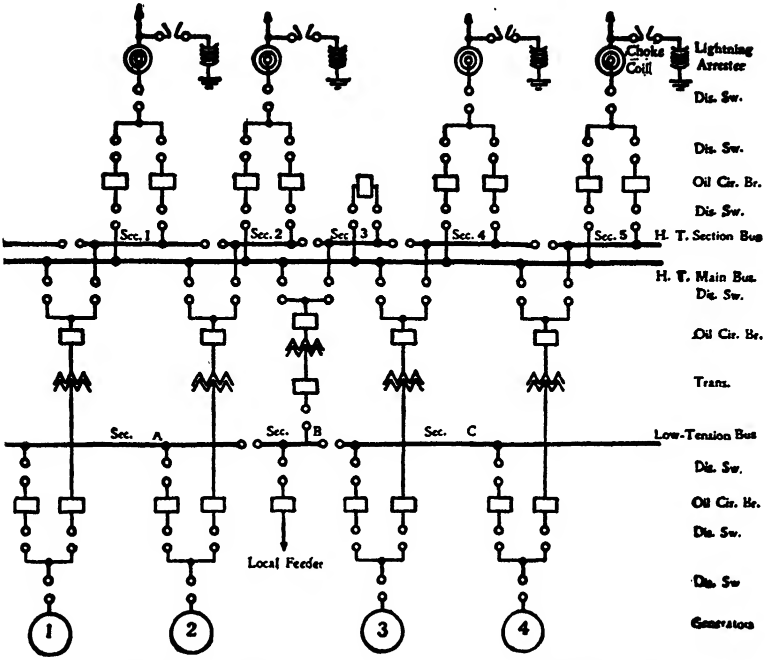


FIG. 108.—Single sectionalized low-tension bus, with two high-tension buses, one of which is sectionalized.

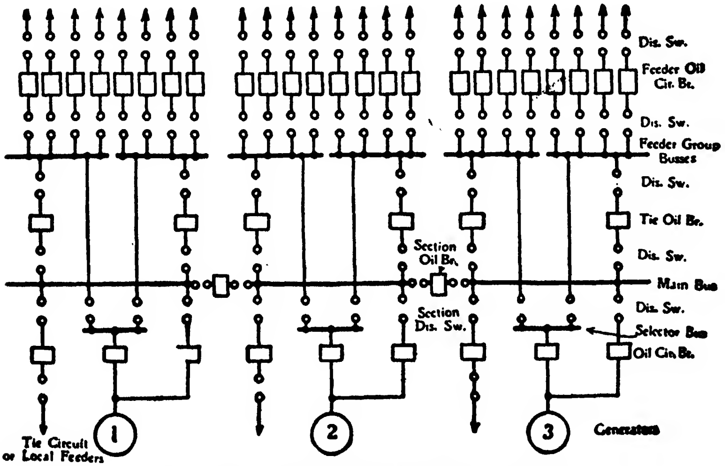


FIG. 109.—Single-bus feeder-group system.

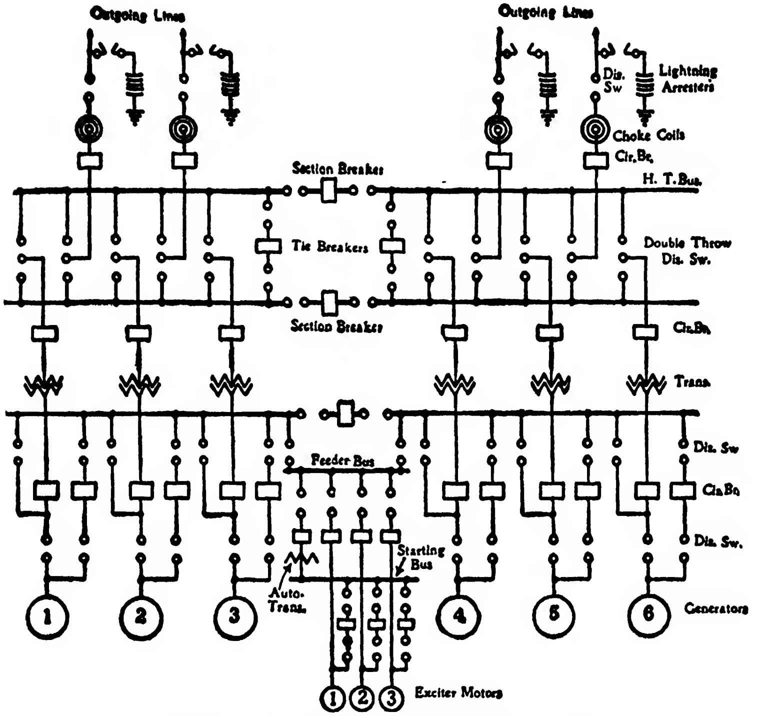


FIG. 110.—Single low-tension transfer bus, double high-tension bus.

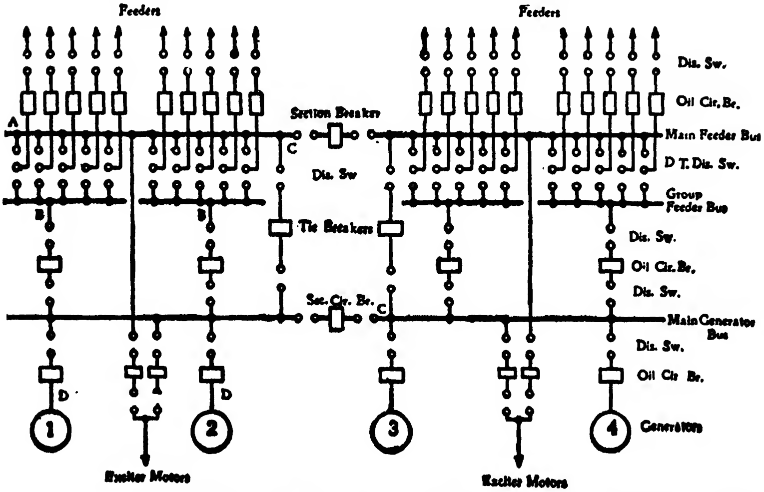


FIG. 111.—Sectionalized generator and main-feeder bus system with group-feeder bus.

connecting switches prevent interconnecting the high-tension busbars except by means of the tie circuit breakers. The low-tension connections make it possible to connect a generator direct to its transformer or to any other transformer through the transfer bus.

*Sectionalized Generator and Main-feeder Bus System with Group-feeder Bus* (Fig. 111).—By this system great flexibility may be obtained for large stations feeding a thickly settled community at generator voltage. The station may be operated in halves, or any feeder or group of feeders may be served from either half.

### Questions for Class Discussion

**1.** Name a few of the important factors that should be considered when planning the plant-circuit layout.

**2.** Draw single-line diagrams showing generators, oil circuit breakers, transformers, and feeders on the following plant-circuit layouts: (*a*) single bus, (*b*) single sectionalized bus, (*c*) double-bus single oil circuit-breaker system, (*d*) double-bus double oil circuit-breaker system, (*e*) ring bus; (*f*) feeder group system, (*g*) transfer bus system, (*h*) no low-tension bus system.

**3.** Tabulate advantages and disadvantages of the plant-circuit layouts called for in Question 2.

**4.** Locate the disconnecting switches in each of the systems called for in Question 2.

**5.** What is the unit arrangement of generators, transformers, and transmission lines?

**6.** In a 13,200-volt installation, is it preferable to use a relatively low-voltage generator and transforming equipment, or a 13,200-volt generator? Explain how this would be decided.

# CHAPTER VII

# TRANSFORMERS

**73. Elementary Theory.**—A transformer consists of an iron magnetic circuit upon which two or more coils are wound. If one winding is connected to an alternating-current supply, there will be set up in the iron core an alternating magnetic flux, which will induce a voltage in all the coils that enclose the magnetic flux.

The schematic circuit of a transformer is shown in Fig. 112*a*.

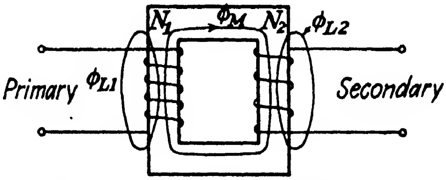


Fig. 112*a*.—Elementary transformer.

The mutual flux $\phi_M$ links with the primary and secondary windings, inducing in these windings voltages $E_1$ and $E_2$, which are related as follows:

$$\frac{E_1}{E_2} = \frac{N_1}{N_2} \tag{32}$$

In an ideal transformer without losses the voltage $E_1$ would be equal to the primary applied voltage and the voltage $E_2$ would be equal to the secondary terminal voltage. In the actual commercial transformer this is not quite true because the coil resistances and leakage reactances introduce corresponding voltage drops. For an ideal transformer, however, the primary mutual magnetomotive force must equal the secondary mutual magnetomotive force, or

$$I_1N_1 = I_2N_2$$

from which

$$\frac{I_1}{I_2} = \frac{N_2}{N_1} \tag{33}$$

Equations (32) and (33) give the two basic laws of transformers which can be used for all commercial types within engineering accuracy.

A more accurate picture of a transformer is that of Fig. 112*b*. In this figure the two coil resistances, and leakage reactances due to fluxes $\phi_{L1}$ and $\phi_{L2}$, are shown connected externally of the transformer itself.

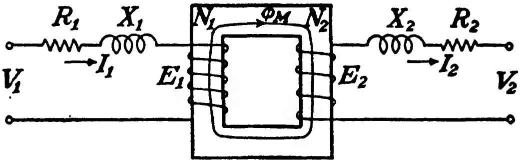


FIG. 112*b*.—Actual transformer circuit.

Most power-transformer calculations are carried out on the basis of an equivalent one-to-one turns ratio transformer. This can be accomplished by multiplying all secondary voltages by the turns ratio and dividing the secondary current by the turns ratio. Therefore, if $n = (N_1/N_2)$, the equivalent secondary quantities are

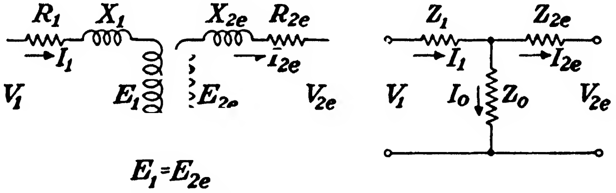


FIG. 112*c*.—Equivalent one-to-one circuit of a transformer.

$$V_{2e} = nV_2, \qquad E_{2e} = nE_2$$

$$I_{2e}R_{2e} = (I_2R_2)_e = nI_2R_2, \qquad I_{2e}X_{2e} = (I_2X_2)_e = nI_2X_2$$

$$I_{2e} \quad \genfrac{}{}{0pt}{}{I_2}{n}$$

Solving for $R_{2e}$ and $X_{2e}$, we find that

$$R_{2e} = R_2n^2 \qquad \text{and} \qquad X_{2e} = X_2n^2 \qquad (34)$$

This last result forms a basic proof of the general fact that transformer or circuit impedances as observed from the high- and low-voltage windings are in the ratio of turns squared.

It is now possible to represent a transformer by the equivalent one-to-one ratio circuit of Fig. 112*c*.

Since $E_1 = E_{2e}$ and $I_1$ differs only from $I_{2e}$ by the amount of current necessary to excite the iron core, it is now convenient to replace the coupled circuit of Fig. 112*c* by the shunt impedance $Z_0$. In this last equivalent circuit,

$$Z_1 = \sqrt{R_1^2 + X_1^2} = \text{primary leakage impedance}$$
$$Z_{2e} = \sqrt{R_{2e}^2 + X_{2e}^2} = \text{secondary leakage impedance}$$

and

$$Z_0 = \sqrt{R_0^2 + X_0^2} = \text{shunt exciting impedance}$$

where $R_0$ will account for the iron losses of the magnetic circuit and $X_0$ stands for the mutual flux reactance.

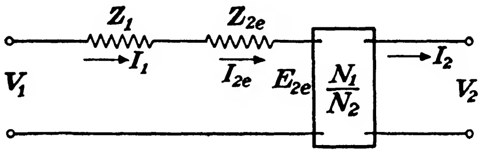


FIG. 112*d*.—Simplified transformer circuit.

In complex algebra,

$$Z_1 = R_1 + jX_1, \qquad Z_{2c} = R_{2e} + jX_{2e}$$

and

$$Z_0 = R_0 + jX_0$$

The current $I_0$ which flows through the impedance $Z_0$ is the exciting current of the transformer, obtainable by measurement without secondary load on the transformer.

The average power transformer is designed to draw an exceedingly small value of exciting current $I_0$. This corresponds to a particularly large value of $Z_0$ as compared with $Z_1$ and $Z_{2c}$, so much so that for many engineering applications a transformer may be considered as a simple series-equivalent circuit with the additional feature of voltage transformation, as shown in Fig. 112*d*. In this figure the voltage-transformation feature is indicated by the ratio device $N_1/N_2$.

**74. General Classification.**—Transformers may be classified according to:

**Type of magnetic circuit**.......
- Stacked laminations
  - Rectangular core
  - Cruciform core
  - Simple shell
  - Distributed shell
- Wound core

- Number of phases
  - Single-phase
  - Three-phase
- Arrangement of windings
  - Shell
  - Core type
    - Cylindrical coils
    - Disk coils
    - Cylindrical and disk coils
- Methods of cooling
  - Natural convection and radiation
  - Air blast
  - Oil-immersed self-cooled ✓
  - Oil-immersed water-cooled
  - Forced-oil cooling
- Type of service
  - Constant voltage
    - Power
    - Distribution
    - Metering
      - Current
      - Potential
    - Relay
    - Autotransformer
  - Constant current
  - Induction regulator
- Special features of construction
  - Conservator-type transformer
  - Inertaire transformer

**75. Types of Magnetic Circuit.**—Magnetic circuits may be classified into two general types: the "laminated," or "punched" type and the "ribbon-wound" type. The first type involves stacking individually punched sheet-steel laminations (see Fig. 113*a* to *e*), while the wound-core type is made up of continuous strips of steel wound into a tight coil (Figs. 113 *f* to *g*).

The wound-core type of magnetic circuit is one of latest developments in core manufacture. Some of its advantages are as follows:

1. Magnetic flux flows only in the direction of the grain of the steel, resulting in lower iron losses.
2. Core is assembled by machine methods and not by hand.
3. Greatly reduced air-gap reluctance, due to machine winding of core as well as the nature of the design.
4. Core is sturdy, symmetrical, and compact, well adapted to resist the mechanical strains caused by short circuits.
5. The better design reduces considerably the weight of the transformer.

As is generally the case, this design was first introduced in the smaller sizes of distribution transformers, and as manufacturing methods were improved, the design has been gradually applied to the large distribution transformers. The large power transformer is still built with a stacked laminated core. The size of the magnetic circuit is so large as to involve a very definite obstacle to wound-core design. Several manufacturer's produce

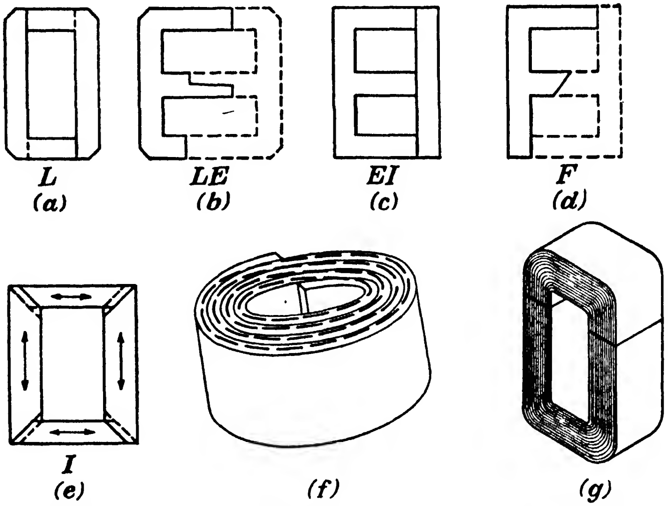
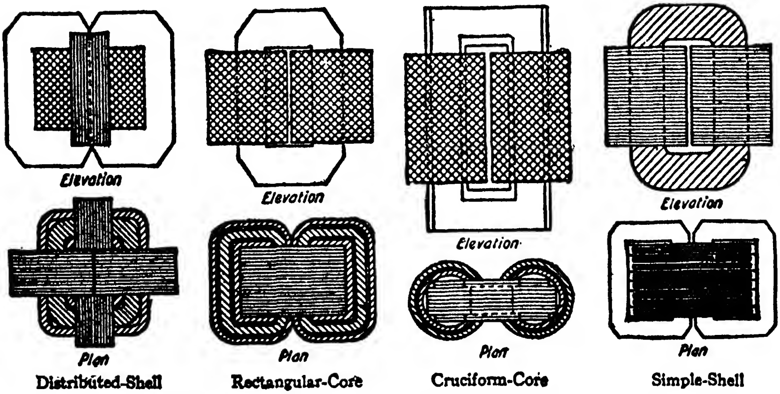


FIG. 113.—Types of magnetic core. *a, b, c, d* are *L, LE, EI*, and *F* punchings; *e* is an *I* punching with 45-deg. interlocking corners, individual laminations being cut along the grain of the metal. *f* and *g* show two forms of wound cores.



Distributed-Shell Rectangular-Core Cruciform-Core Simple-Shell

FIG. 114.—Diagrams of arrangements of coils and magnetic circuits of transformers. (In these diagrams, the coils are indicated by oblique or cross oblique lines; and the iron by horizontal or vertical lines or by unshaded portions.)

wound-core distribution transformers in one form or other, examples of which are shown in Fig. 120.

The laminated-core type of magnetic circuit may take on several general forms, a few of which are illustrated in the sketches of Fig. 114.

In the core type the copper windings surround the iron core, while in the shell type the iron circuit surrounds the copper windings (see Fig. 114). There are a few modifications of these two types of circuits, the most striking one being the so-called distributed-shell type. The core-type magnetic circuit can be made so that rectangular or circular coils can be used, these two being distinguished as rectangular-core and cruciform-core types.

There is no definite field of application for each of these types, but in general it may be said that the distributed-shell type is used for distribution transformers up to about 4,500 volts; the rectangular core, for distribution transformers up to about 23,000 volts; the cruciform core, for distribution and power transformers of higher than 23,000 volts; and the simple shell for distribution and power transformers of rather large current capacities. The cruciform core allows the use of circular coils, which are more adaptable to transformers that are subjected to heavy short circuits.

**76. Number of Phases.**—Three-phase transformers are built as either core or shell types, depending on the particular requirements (see Fig. 115). Since the three magnetic fluxes are out of phase with each other by 120 electrical degrees, it follows that the sum of the fluxes of any two phases will equal the flux of the third phase; hence those parts of the magnetic circuit which are common to two fluxes are of the same dimensions as the parts through which flows only one flux. This fact enables a most economical utilization of iron in the building of transformers. It follows, therefore, that a three-phase transformer is generally less expensive than a group of three single-phase units, because of the less weight of iron, a single tank instead of three, and fewer high-voltage bushings, since all connections between phases can be made inside the tank. The fact that all connections between phases can be made inside the tank simplifies the external connections a great deal, which for high-voltage installations is of considerable importance. The floor space occupied by a three-phase unit is less than the space occupied by an equivalent bank of three single-phase transformers. The cooling-water system is less complicated for the three-phase unit.

Notwithstanding, the apparent advantages of the three-phase over the single-phase transformer, there are certain requirements that can best be fulfilled by single-phase units. For large capacities single-phase transformers can be handled more easily, either during erection or during transportation. In case of damage to a phase of a delta-connected bank of single-phase transformers, the damaged transformer may be removed and service resumed on the remaining two transformers operating in open delta. A spare single-phase unit can be more easily handled and replaced for a damaged unit than in the case of three-phase transformers. For the large capacities demanded by modern systems it is practically necessary to use single-phase transformers connected in three-phase banks.

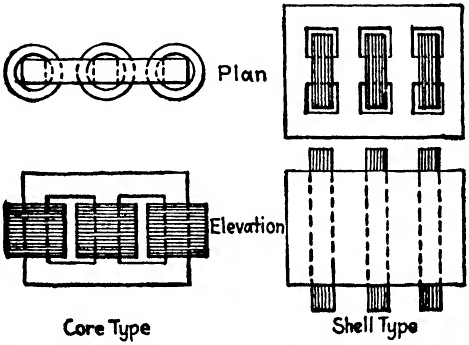


FIG. 115 —Three-phase core- and shell-type transformers.

**77. Arrangement of Windings.** *a. Shell-type Transformers.*—The windings for shell-type transformers are made up of groups of high- and low-voltage coils. These are wound with an insulated conductor consisting of one or more rectangular wires of suitable proportions to keep the eddy currents to a minimum. The coils are wound with one turn per layer, thus obtaining the minimum voltage stress between layers. The thickness of the coils is then the width of the conductor, and each conductor is exposed to the oil. Strips of insulating material are wound into the coil between adjacent turns. This insulation is gradually reinforced toward the line end of the winding until the last few turns adjacent to the line terminals are insulated to withstand the voltage incident to high-frequency disturbances on the line (see Figs. 116*a* and 116*b*).

Each coil is pressed to exact dimension in a former and is then dipped in insulating varnish and baked. This dipping and baking is repeated a sufficient number of times to give the coil a hard glossy surface. The varnish penetrates the insulation of the coil, binding the turns into solid and substantial coils, which can be readily handled and assembled without the possibility of displacing the turns or insulation. As no tape is used on the complete coil, each conductor is exposed directly to the cooling medium, permitting transfer of heat from the conductors to the oil with a minimum temperature difference. This effectively prevents hot spots. Groups of high- and low-voltage coils are assembled with barriers of high-grade insulating sheets and with angles and channels of the same material. The assembled groups of high- and low-voltage coils are insulated from ground by an enclosing housing made up of sheets of the same material.

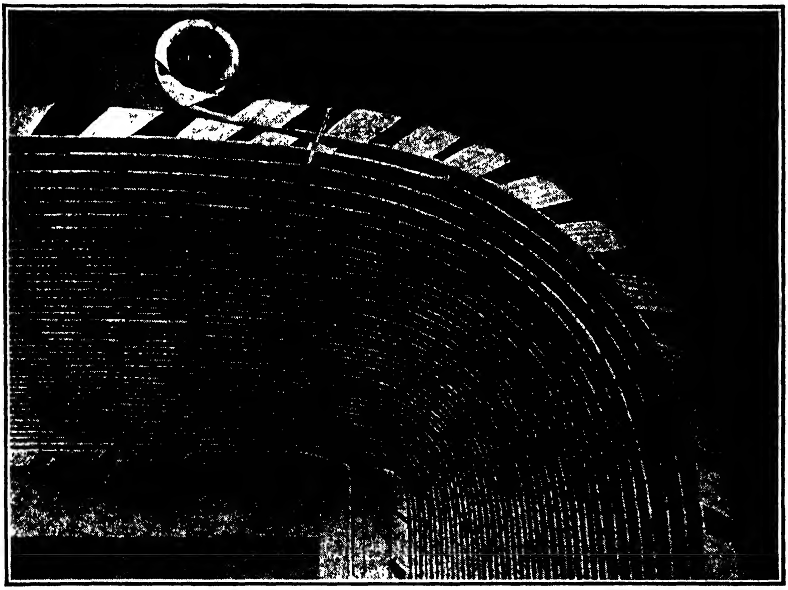


FIG. 116*a*.—Detail of coil for shell-type transformer. (*Westinghouse Electric Corporation.*)

These insulating sheets are of high-grade tough paper board and, when impregnated with insulating oil, have uniform high dielectric strength combined with high mechanical strength. Ample ducts, formed by inserting strips of insulating material between coils, are provided to allow the flow of oil along the face of each coil, leaving each conductor exposed to the oil. This method of spacing the coils has the following advantages:

1. Continuous ducts, offering very little resistance to the flow of oil.

2. A greater part of each conductor is exposed directly to the cooling oil stream, ensuring freedom from hot spots.

3. Positive support is afforded all conductors in each coil against short-circuit stresses.

Fig. 116b.—Coil for shell-type transformer. (*Westinghouse Electric Corporation.*)

*b. Core Type of Transformers.*—There are three general methods of arranging the coils of a core-type transformer, as illustrated by Fig. 117, which are known as:

*a.* Disk-coil windings.

*b.* Concentric cylinder-coil windings.

*c.* Concentric disk-cylinder windings.

The first of these arrangements is composed of alternate layers of secondary- and primary-coil groups placed around the legs of the core. Insulating cylinders prevent the windings from coming in direct contact with the iron core. Spacing blocks are used between disks, thereby providing an easy path for circulating oil.

In the second type of winding the primary and secondary coils on each leg are wound as complete units in the form of concentric cylinders, which are kept apart by insulating cylinders. The low-voltage coil is generally placed next to the iron core.

The last arrangement is a combination of the first two. Disk-type coils are used on the outside for the high-tension winding, while the low-tension coils are of cylindrical shape.

In all these cases the coils are wound with rectangular copper conductors, the width of the coils being that of one conductor. All coils are pressed to size, then dipped in insulating varnish or compound and baked in a similar way as used for shell-type windings. In general, the disk-coil arrangement is suitable for comparatively low voltages, while the concentric disk-cylinder arrangement of coils is probably best suited for high voltages, the other arrangement being used for medium voltages. There are two outstanding features of the core type of windings:

1. Cylindrical coils are the best to resist the stresses due to short-circuit currents.

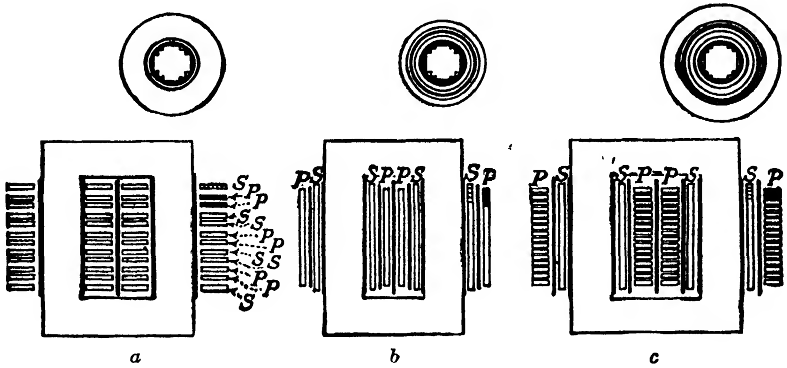


Fig. 117.—Core-type transformer.

*a.* Disk-coil windings.
*b.* Concentric cylinder-coil windings.
*c.* Concentric disk-cylinder coil windings.

2. The coils are completely exposed to the oil, thereby providing effective heat dissipation.

**78. Mechanical Construction.** *a. Shell-type Transformer.*—The laminations are held securely in place, being clamped between the top and bottom end frames. This clamping action is obtained by heavy tie bolts. The upper end frame is provided with eye bolts so that the core and coils can be lifted and handled as a unit. The lower end frame is provided with feet so that the core and coils can be set down without the use of external supports. The assembly of a large shell-type transformer is shown in Fig. 118*a*. Heavy steel plates are placed against the flat face of the coils where they extend beyond the iron core to prevent movement due to the mechanical stresses that tend to separate the coils under short-circuit conditions. Tie bolts passing through the ends of the plates hold them firmly against the coils and clamp the entire set of coils together. The short-circuit stresses, which may be accurately calculated, are in this way transmitted to the tie bolts designed to withstand the maximum stress that can be developed. The area of contact between the plates and coils is large, resulting in a low pressure per unit area, well within the value that the insulating material will stand.

FIG. 118a.—Assembly of magnetic core and windings of a large shell-type transformer. (*Westinghouse Electric Corporation.*)

To brace the coils against stresses acting in a plane parallel to the face of the coils and tending to separate the primary and secondary coils in that direction. T beams are inserted through the opening of the coils at the top and bottom. Heavy spreader bolts at the end of these T beams serve to force them apart and to brace the coils effectively in this direction. The assembled coils, insulation, core, end frames, and coil bracing are dried out by the application of heat while in a vacuum and are then thoroughly impregnated with oil.

*b. Core-type Transformer.*—In the case of the shell-type transformer, the coils are first mounted in place on the supporting frame, and the iron laminations are then built up around the coils (see Fig. 118*b*). As a contrast to this, in the core type the iron core must be first built up. In order to do this it is necessary to hold together the laminations by means of bolts or rivets. The upper cross member of the core must also be left off in order that the circular-form-wound coils may be put into place. The coils are finally held firmly in place by retaining bolts and steel plates. The upper and lower members of the magnetic core are securely clamped between heavy iron beams in order to make the entire structure perfectly rigid. The final assembly must be given as thorough a drying out as given to shell-type transformers. A typical assembly of core and windings for a core-type transformer is shown in Fig. 119.

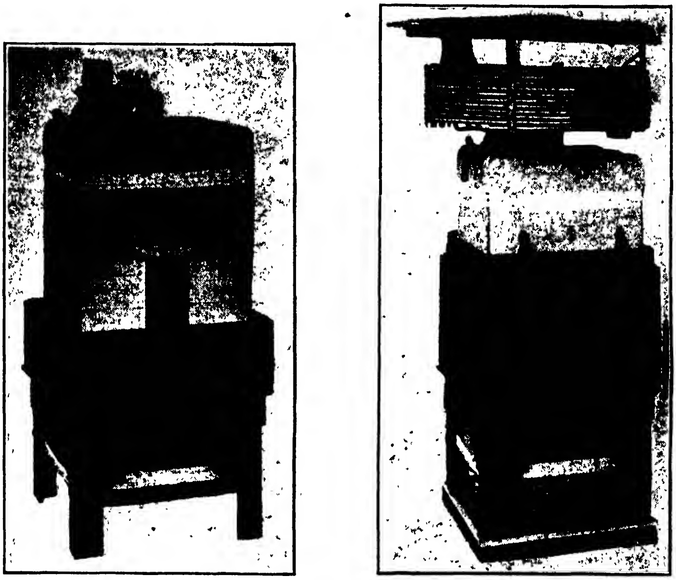


FIG. 118*b*.—Typical 1,500-kva. shell-type oil-insulated water-cooled transformer at two stages in its construction. Notice cooling coils at top. (*Westinghouse Electric Corporation.*)

*c. Wound-core Transformers.*—Several ingenious methods have been devised for assembling wound-core transformers.

In one method, used by the General Electric Company, the complete copper coils including primary and secondary sections are first assembled into a single unit. Two or more coils of steel ribbon are then spun into place around the copper coils.

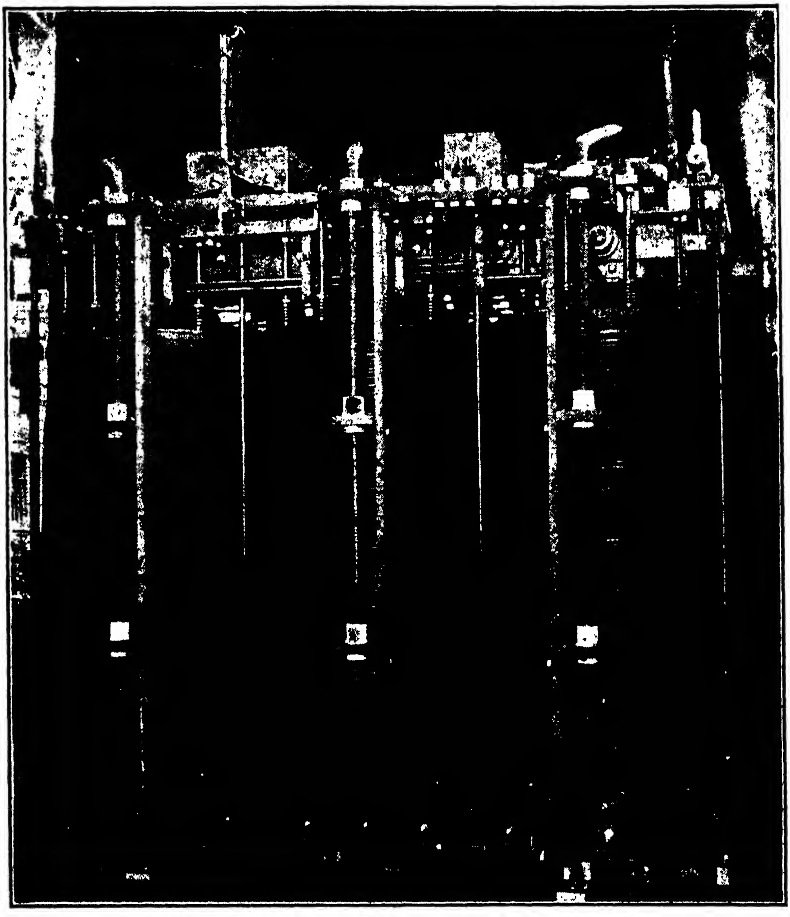


Fig. 119.—Three-phase core-type transformer, 110,000 to 13,200 volts. (*General Electric Company.*)

In a second method, used by the Line Material Company, the iron core is first wound into the proper shaped magnetic circuit. On each side of the iron core are assembled suitable spool forms.

These spools have sufficient clearance with the steel core so that they can turn freely. By a suitable driving mechanism these spools are rotated and thereby wound in a typical bobbin fashion with the copper windings forming the primary and secondary coils.

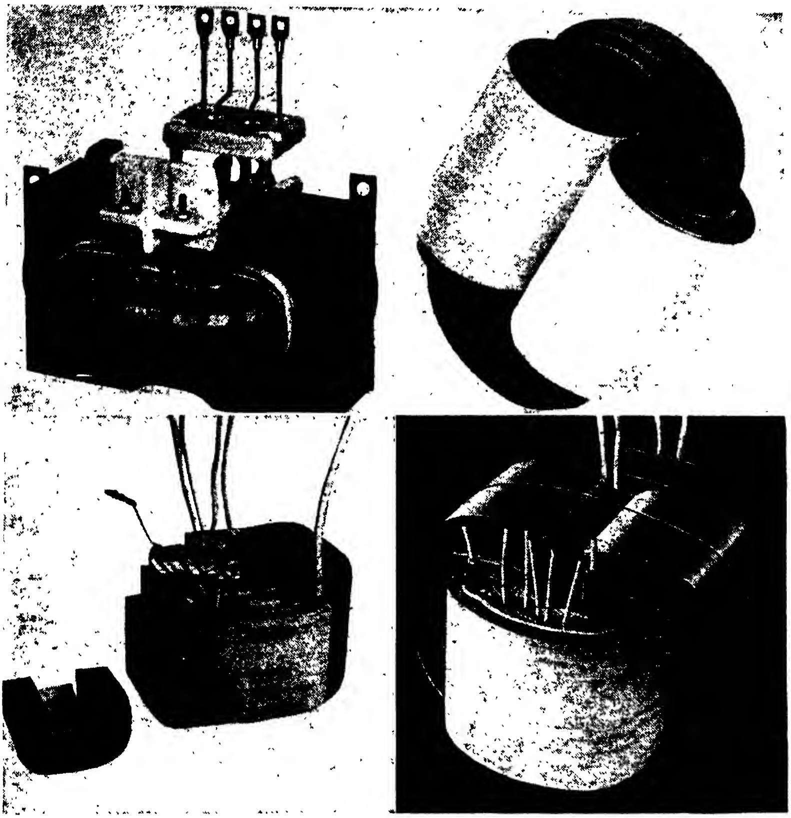


FIG. 120.—Types of wound-core transformers. (upper left) Spirakore (*General Electric Company*); (upper right) round wound core (*Line Material Company*); (lower left) ribbon-form core (*Westinghouse Electric Corporation*); (lower right) Bent Iron core. (*Kuhlman Electric Company.*)

A third method, used by Westinghouse Electric Corporation, involves winding the iron ribbon on rectangular mandrels. The wound coils are then annealed and bonded in an impregnating tank at high temperature. Pressure in the tank forces the bonding material between individual turns of the core. Core units are then cut into two U-shaped pieces, and the cut surfaces are machined flat so that they leave no air gap when the ends are fitted together in the copper coils.

These different types are shown in Fig. 120.

**79. Methods of Cooling.**—In general it may be said that the voltage capacity of a particular transformer is dependent on the section of iron, and the current capacity is dependent on the copper section; hence, the kilowatt capacity of transformers will vary approximately as the fourth power of one dimension. The losses, however, can be said to vary approximately as the cube power of a dimension, and the radiating surface as the square power of a dimension. It follows, therefore, that as the size of transformers increases, the amount of heat to be radiated per unit of surface increases, with a consequent complication of the problem of proper heat dissipation. There are essentially five general methods that are used in cooling transformers.

*a. Natural Convection of Air and Radiation.*—Small transformers, generally used for metering purposes, rely in the natural convection of air and radiation for their cooling. The application of this method of cooling is, however, very limited and cannot be used for transformers of any considerable capacity.

*b. Air-blast Transformers.*—In the air-blast transformer, air is forced through vent ducts, which are properly located among the windings and core, in the same manner as in the case of large alternating-current generators. Figures 121*a* and *b* illustrate such a transformer. The air is generally brought to the transformer through proper ventilating ducts, entering at the bottom of the transformer and being expelled from the sides and top.

It is extremely important that the air be clean and free from dust; otherwise the vent ducts will be clogged up and the transformer will run hot. By means of dampers placed at the top of the case it is possible to distribute the air through the core and coils to the best advantage. Air-blast transformers are particularly adaptable to congested locations where there is a possible danger of fire and explosion of oil-insulated units with a consequent burning of oil. The disadvantage of such transformers is found in the fact that forced-air fans and the accompanying ventilating ducts must be provided.

*c. Oil-immersed Self-cooled Transformer.*—By far the greater majority of transformers have their core and windings completely immersed in a tank containing a good grade of insulating coil.

The cooling takes place by the convection currents set up by the upward motion of the heated oil. In order that the oil be effective in properly cooling the windings, it is necessary that the oil flow directly against the hot conductors; hence proper circulating ducts must be provided. These ducts should be in a vertical plane in order to be fully effective. The heated oil must in turn give up its heat to the case or tank, which in turn must radiate its heat to the air.

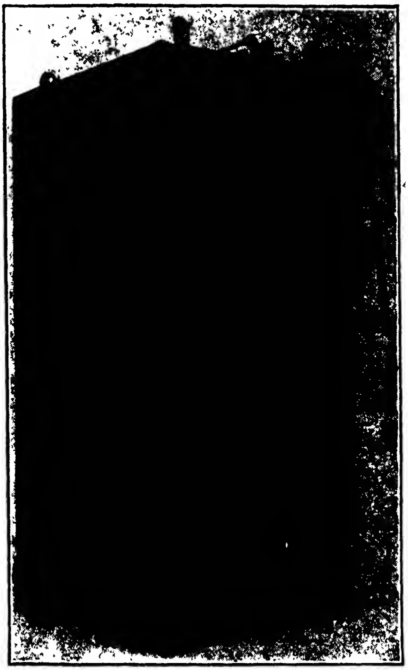


FIG. 121*a*.—A 2,800-kva. air-blast transformer, single phase, 25 cycles, 12,500 volts high tension, 6,600 volts low tension. (*Westinghouse Electric Corporation.*)

Small transformers of this type are enclosed in a perfectly plain tank; as the capacities become larger, however, it is necessary to provide greater radiating surface. A common method of increasing the radiating surface that is exposed to the air is to build the tank walls of corrugated sheet iron as shown in Fig. 122. Another method that has been employed is to surround the tank with one or more jackets, all connected to the tank at the top and bottom by tubular openings that permit a constant

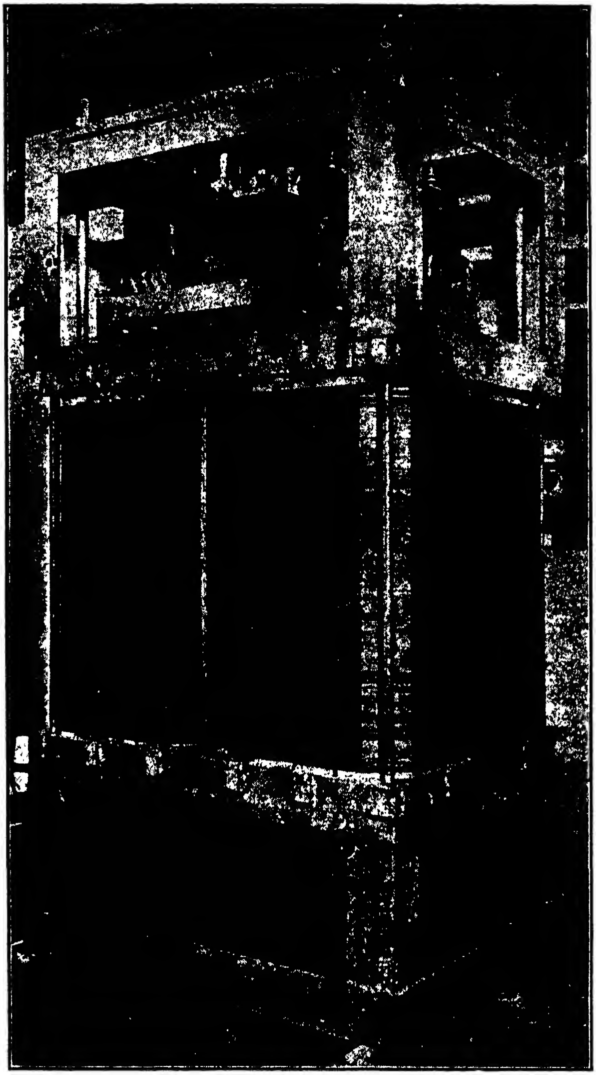


FIG. 121*b*.—A 2,800-kva. air-blast transformer showing the core and frame construction and the bracing of the end winding. (*Westinghouse Electric Corporation.*)

circulation of oil between the tank jackets. The annular spaces between the tank and jackets serve as flues, providing a large, rapid circulation of air, which quickly diffuses the heat losses.

The tubular and radiator types of tanks are probably the most effective types in the class of self-cooled units. The great advantage offered by the radiator type is in the fact that the radiators may be removed from the tank during transportation, while the tubes are generally welded to the case forming a complete unit. The radiator type also affords somewhat larger radiating surface. A radiator type of transformer is shown in Fig. 123, the radiators being about 12 ft. high. In Fig. 124 is shown a transformer in a tubular type of tank.

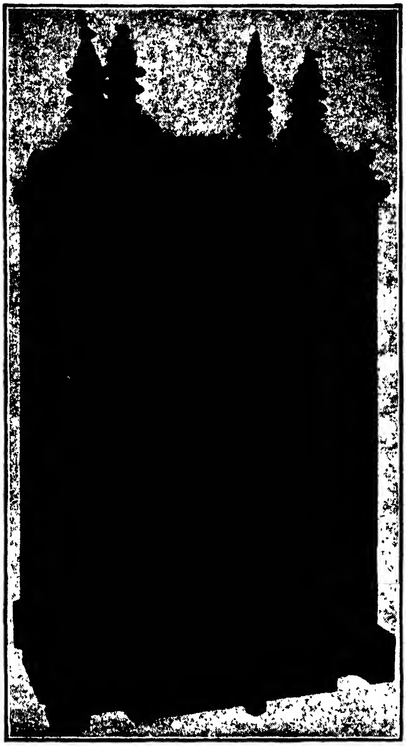


FIG. 122.—Transformer with corrugated tank. (*Westinghouse Electric Corporation.*)

*d. Oil-immersed Water-cooled Transformers.*—For the larger sizes of transformers it becomes necessary to resort to other means of cooling. Some of the transformers that are being built today are so large that artificial cooling must be used. The standard method of accomplishing this is to place water-cooling tubes in the upper part of the tank, as shown in Fig. 118*b*. The cooling coil should preferably be completely immersed in the oil; otherwise, owing to the low temperature of the water passing through, moisture will deposit on the coil and get into the oil. In case it is impossible that the coil be completely submerged, it is essential that all exposed parts of the coil be heavily lagged with heat-insulating material to prevent condensation of moisture.

The cooling coils are generally made of seamless copper tubing, (see Fig. 118*b*), and all connections inside the tank should be absolutely tight; preferably, these connections should be welded or brazed in order to prevent water leakage. Special care must be taken during the winter that water does not freeze in the coils and thereby damage them.

FIG. 123.—An 18,500-kva. transformer of the radiator type. (*Westinghouse Electric Corporation.*)

*e. Forced-oil Cooling.*—A final method which can be used is that of circulating the oil through the windings and out through a cooling tank of some sort. A system of this kind might consist of a tank in which is placed a large copper coil, the coil being connected through a suitable pump to the top and bottom of the transformer tank. By maintaining a constant flow of water around the cooling tube, the circulating oil can be very effectively cooled. The disadvantage of such a method is in the handling of oil and the great outlay of auxiliary equipment necessary; hence it is not used to a great extent.

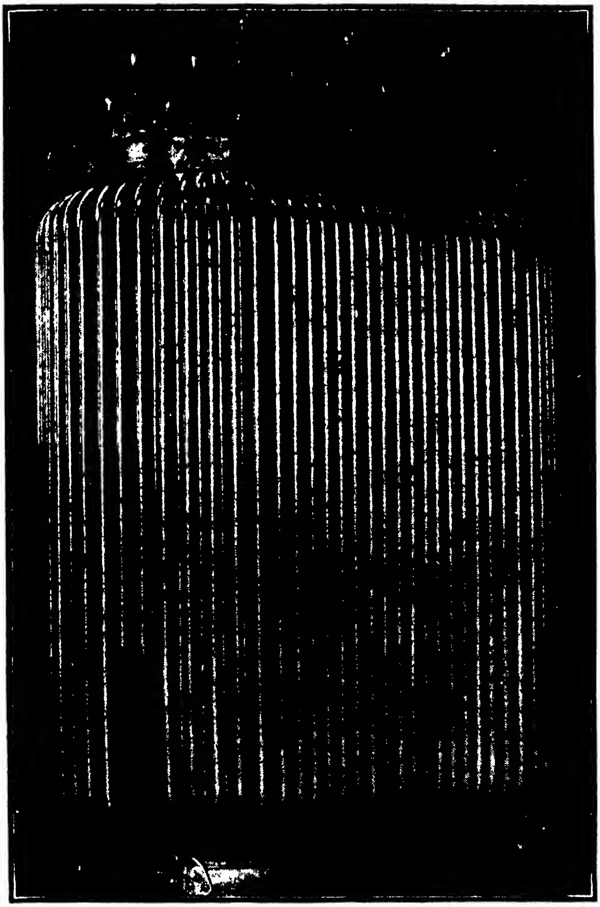


Fig. 124.—Transformer with tubular type of tank. (*General Electric Company.*)

**80. Power and Distribution Transformers.**—There is essentially no difference in the fundamental design of transformers for these two types of service. Power transformers are, of course, larger in capacity since they must handle large amounts of power and must therefore be carefully designed. Power transformers are built either single- or three-phase and cooled by any of the methods outlined in Art. 79 except by natural convection. They may be of either the shell or core type. The common voltages used for three-phase power systems are as follows:

| | | | | |
|---|---|---|---|---|
| 2,200 | 13,200 | 33,000 | 88,000 | 154,000 |
| 6,000 | 16,500 | 44,000 | 110,000 | 220,000 |
| 11,000 | 22,000 | 66,000 | 132,000 | 275,000 |

In most cases power transformers are designed for outdoor service on account of the high cost of the necessary building and wiring if such units are placed indoors. Transformers for outdoor service must be watertight, and generally the bushings are larger and spaced farther apart than in the case of indoor transformers.

Distribution transformers should be designed with very small no-load losses, since such losses are always present even though no load is being delivered. They may be of the core, shell, or in small sizes of the distributed-shell type. Standard lighting and power-distributing transformers are designed for a primary voltage of 2,300 volts and secondary voltages of 230 and 115 volts, or 460 and 230 volts. They may be for pole, platform, or manhole mounting. Manhole transformers are built in the same way as transformers for other types of service but must have very strong tanks with ample radiating surface. The cover must be air- and watertight. To protect the transformer from damage due to the high pressure that might be developed inside, it is customary to provide a vent that is covered by a thin airtight metal diaphragm, which will be ruptured in case of excessive internal pressure. The outlet bushings should all be moisture-proof but simple, in order that the transformer may be easily disconnected.

**81. Instrument Transformers.**—Instrument transformers may be classified as metering and relay transformers, and may be either current or potential transformers. Instrument transformers are used for two reasons: (1) to protect station operators from contact with high-voltage circuits and, (2) to permit the use of instruments with a reasonable amount of insulation and a reasonable current-carrying capacity. The function of instrument transformers is to deliver to the instruments a current and voltage that shall always be proportional to the primary current and voltage and that does not exceed a safe potential above ground. Generally, the secondary of a voltage transformer is designed for about 115 volts, and the secondary of a current transformer for 5 amp.

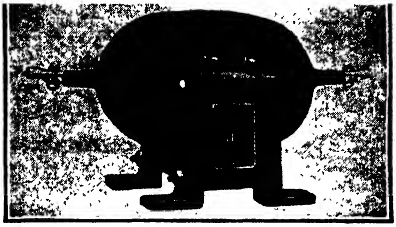


FIG. 125.—Type KA switchboard current transformer, dry type. (*Westinghouse Electric Corporation.*)

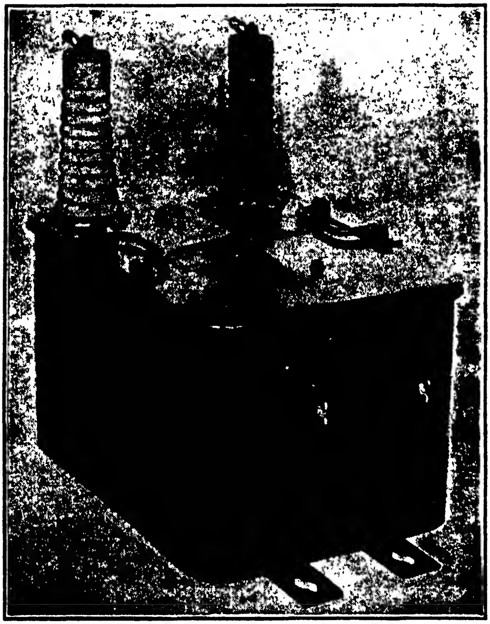


FIG. 126.—Instrument potential transformer, 13,200 to 110 volts. (*General Electric Company.*)

There are two general classes of instrument transformers, dry and oil insulated. Dry-type voltage transformers can be obtained up to about 6,600 volts across the primary. A few typical instrument transformers are shown in Figs. 125 to 130. All instrument transformers should be grounded on the secondary side as an extra precaution against danger from the high voltage in case the insulation should be punctured by lightning or other abnormal stresses. In polyphase groups, any point of the secondary may be grounded, but it is preferable to use a neutral point.

Fig. 127.—Outdoor current transformer for 25-kv. circuits. (*General Electric Company.*)

*a. Voltage Transformers.*—Voltage transformers are used with voltmeters, wattmeters, watt-hour meters, power-factor meters, frequency meters, synchroscopes and synchronizing apparatus, protective and regulating relays, and the no-voltage and over-voltage trip coils of automatic circuit breakers. One transformer can be used for a number of instruments at the same time if the total current taken by the instruments does not exceed that for which the transformer is designed and compensated.

Voltage transformers are generally designed for a capacity of about 200 volt-amp., but are seldom compensated for more than 40 or 50 volt-amp., since these values represent the average load demanded of a voltage transformer. There are two causes of errors in voltage transformers, namely, ratio error and phase-angle error. The part of these errors due to the exciting current is constant for any particular voltage. It can be reduced to a minimum by choosing the best quality of iron and working it at a low magnetic density. The part of the errors due to the load current varies directly with the load and can be minimized by making the resistance and reactance of the windings very low.

In any transformer, the ratio error can be neutralized for one particular condition of load by "compensating" the transformer.

This means that the actual ratio of turns differs from the marked ratio of the transformer by an amount just sufficient to make up for the voltage drop at the specified load. The effect of the phase displacement of the secondary voltage need not be considered when using voltmeters, frequency meters, synchroscopes, or protective and regulating relays which depend on voltage only. With wattmeters, watt-hour meters, and similar apparatus, whose indications depend not only on the voltage but also on its phase relation to the line current, the phase error has some effect. The effect of the phase displacement cannot, therefore, be compensated for in the transformer, as it depends not only on the constants of the transformer, but on the power factor of

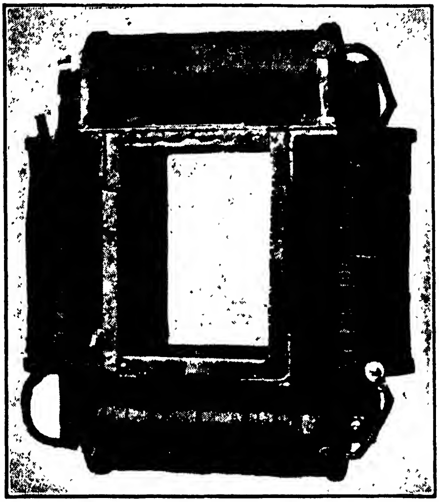


Fig. 128.—Current transformer (through type). Indoor service. (*Westinghouse Electric Corporation.*)

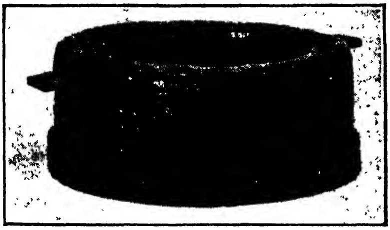


Fig. 129.—Bushing-type current transformer. (*Pacific Electric Manufacturing Company.*)

the load to be measured as well. By making the phase displacement as small as possible by proper design, its effect on readings for commercial purposes is negligible. In general, both ratio and phase-angle errors are very small in first-class voltage transformers and may be neglected in most commercial measurements. If extreme accuracy is required, ratio and phase-angle curves must be obtained for the particular transformer in use at the particular load condition that exists, and correction must be made as has been indicated.

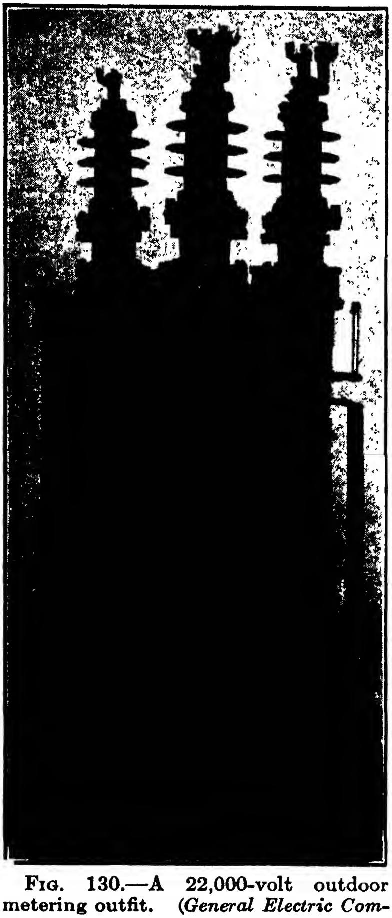


FIG. 130.—A 22,000-volt outdoor metering outfit. (*General Electric Company.*)

Voltage transformers are compensated for their iron losses at their rated voltage. When used on some other voltage, either higher or lower, an error is introduced. In general this error will not be more than 0.15 per cent when the applied voltage is 50 to 110 per cent of rated voltage. A voltage transformer should never be used on a circuit whose voltage is more than 10 per cent above the rated voltage of the transformer.

The secondary terminals of a voltage transformer should never be short-circuited. If they should become short-circuited, a heavy current will flow which, if continued, will burn out the windings. In order to protect the system against sustained short circuits in the transformer circuit, it is generally recognized as good practice to introduce into the primary circuit a resistor and fuse, these being connected in series. The resistors are designed to limit the current to about 20 to 40 amp., while the fuses are designed to open such a current. In normal operation the resistors carry only the very small primary current of the voltage transformer, and the drop in voltage that they cause is inappreciable.

*b. Current Transformers.*—Current transformers are used with ammeters, wattmeters, power-factor meters, watt-hour meters, compensators, protective and regulating relays, and the trip coils of circuit breakers. One current transformer can be used to operate several instruments, provided that the combined burden does not exceed that for which the transformer is designed and compensated.

The ordinary voltage transformer or distribution transformer is connected across the line, and the magnetic flux in the core depends upon the primary voltage. For a given voltage the flux is, therefore, fixed, while the current in the winding rises and falls as the load of the secondary winding changes. The current transformer, however, is connected directly in series with the line. For a fixed number of instruments in the secondary (which is the usual condition), a rise or fall in the line current requires a corresponding rise or fall in the secondary voltage to force the secondary current through the impedance of the meter load. The magnetic flux in the iron, which supplies this voltage, thus follows the rise and fall of the primary or line current.

In any transformer, the primary ampere turns may be considered as made up of two parts, one small element that supplies the magnetizing and core-loss current, and another element that supplies the "working current." The working-current ampere turns are always exactly equal to the secondary ampere turns. As generally used, the current transformer steps down from a large current to a small one, so that the primary winding consists usually of few turns and the secondary of many turns.

The current transformer is also subjected to two causes of errors, namely, ratio and phase angle. Current transformers are compensated to give, as closely as possible, the correct ratio at 65 per cent of its rated current. As meters and transformers should be selected with a rating 50 per cent greater than the normal current of the circuit in order to allow for peaks and overloads, the full-load current of the circuit represents about 65 per cent of the current rating of the transformer and meter. Therefore, the greatest accuracy of meter readings is attained with full-load current in the circuit.

The instruments connected in the secondary circuit of the transformer are placed in series, so that the secondary current will pass through each instrument. As instruments are added, higher voltage is required to force the current through the instruments. This requires a high magnetic density in the iron. A higher magnetic density increases both the iron loss and the magnetizing current; hence both the ratio and the phase-angle errors are magnified. For the sake of accuracy, therefore, there is a limit to the number of instruments that should be placed on a single-current transformer.

The secondary circuit of a current transformer should never be opened while the primary is carrying current. If it is necessary to disconnect instruments, the secondary should first be short-circuited. If the secondary circuit is opened, a difference of potential is developed between terminals which is dangerous to anyone coming in contact with the meters or leads. The cause of this high voltage is that with open secondary circuit all the primary ampere turns are effective in producing flux in the core, whereas normally but a small portion of the total performs this function. The danger is magnified by the fact that the wave form of this secondary voltage is peaked, producing a high maximum value. A high flux produced in this way may also permanently change the magnetic condition of the core, so that the accuracy of the transformer will be impaired.

*c. Through-type Transformers.*—Transformers of this type have no primary winding but use the current carried by the cable or busbar to energize the core (see Fig. 128). Through-type transformers are usually regarded as suitable for instrument use if the ratio is 500:5 amp., or larger. Special designs have been made, however, to give good instrument accuracy at ratios considerably below this. In cases where accuracy is required over a limited range only, as for relays or trip coils, the use of this type of transformer is entirely satisfactory for ratios as low as 100:5 amp. It is satisfactory to use a through-type transformer of this ratio with an ammeter if they have been calibrated together.

The momentary current due to a heavy short circuit on a large system is extremely great, and the mechanical stresses set up between the primary and secondary windings of a current transformer by this current are very large. In the through-type transformer, these stresses are balanced within the transformer itself.

This is a good type, therefore, to apply where there is a liability of short circuits.

*d. Bushing-type Transformer.*—A special form of through-type transformer is the bushing type, or ring type. This is made in the form of a hollow cylinder, built up of ring-shaped iron punchings on which the secondary winding is wound. The transformer is mounted over the terminal bushing of a circuit breaker to supply current for the tripping coil or tripping relay (see Fig. 129). The accuracy limitations of ring-type transformers are similar to those mentioned above for other through-type transformers. But, since ring-type transformers are used for tripping circuit breakers, accuracy at small currents is not important if the transformer will respond to large currents. Circuit breakers are satisfactorily tripped with bushing-type transformers with ratios as low as 50:5 amp. The application of this type of transformer is illustrated in Fig. 214.

*e. Metering Outfits.*—It is possible to combine the necessary current- and voltage-transformer elements, which are needed to measure the power flowing over a three-phase line, all in one tank, thereby simplifying the outside connections and installation very much. Such an outfit is shown in Fig. 130.

**82. Autotransformer.**—An autotransformer is built in the same general manner as any other transformer, but it has only one winding. The primary includes all the turns, while the secondary includes only a portion of the total turns. Since the current flowing in the common part of the winding is equal to the difference of the instantaneous values of primary and secondary current, it follows that the amount of copper in the windings is less than in an equivalent two-circuit transformer.

Autotransformers are used as motor starters, as balance coils on three-wire systems, and also to tie together two different systems at different voltage. They are not adaptable to general distribution work, because for this type of service it is generally desired to keep the secondary and primary coils electrically insulated from each other. The application of such transformers to large systems will be given more in detail in Chap. VIII.

**83. Constant-current Transformer.**—Constant-current transformers are used to supply constant current to series circuits, the most important application being for series street lighting. The main difference between a constant-current transformer and a constant-voltage transformer is that the secondary of constant-current transformers is free to move in a vertical plane (see Fig. 131). Figure 132 shows the distribution of magnetic flux in the core of such a transformer, together with the relative directions of the primary and secondary currents. The voltage induced in the secondary coil will depend on the amount of flux that interlinks with the secondary coil which will be determined by its position. When the secondary coil is located near the primary coil, the leakage flux is very small; while, when the secondary coil is at the top of the core, the leakage flux is a maximum. The repulsion force between the two coils is proportional to the product of the primary and secondary currents, but since the secondary coil is free to move, it will always take up a position

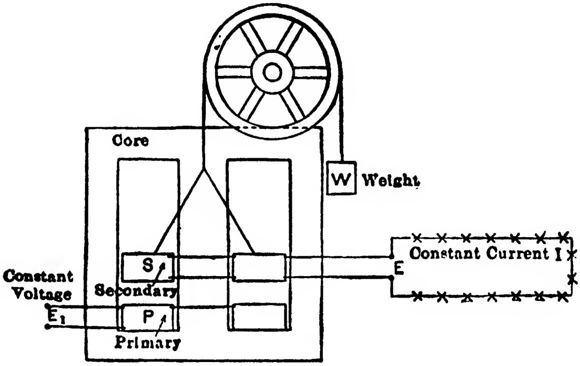


Fig. 131.—Constant-current transformer.

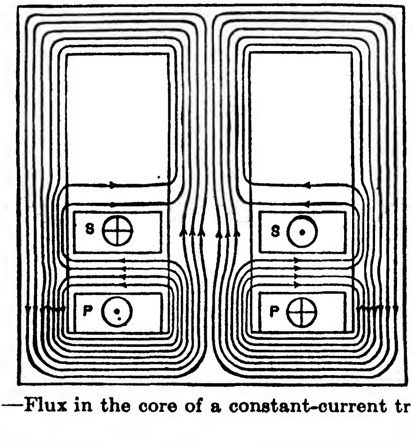


Fig. 132.—Flux in the core of a constant-current transformer.

where the repulsion force plus the force due the weight *W* is just equal to its own weight. It follows, therefore, that the repulsion force between coils must be constant for a given weight *W*, or in other words the transformer will always deliver a constant current, the magnitude of which is determined by the size of the weight.

Consider such a transformer in operation and the load suddenly decreased, as would happen if one lamp were short-circuited. The current through the remaining lamps will tend to increase owing to the excess voltage supplied to the circuit, but an excess current will cause an increase in the repulsion force between the two transformer coils, thereby causing the secondary coil to rise until its voltage drops to a value just sufficient to maintain the normal current through the lamps.

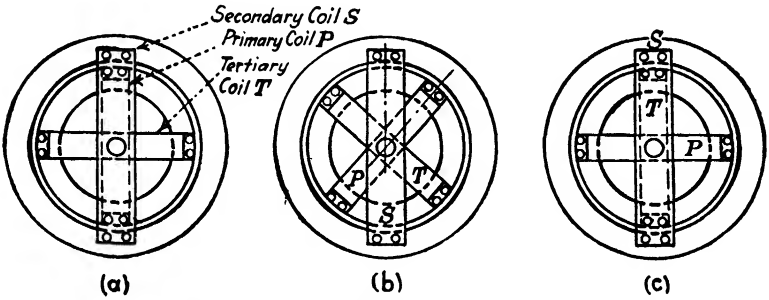


Fig. 133.—Single-phase induction regulator.

**84. Induction-voltage Regulators.**—Induction regulators are nothing more than constant-voltage transformers, one winding of which can be moved with respect to the other, thereby obtaining a variable secondary voltage. They are used at the end of distribution lines to maintain constant voltage. The primary, or movable, coil is connected across the line, while the secondary, or stationary, coil is connected in series with the line. There are two types of induction regulators, namely, single-phase and polyphase.

*a. Single-phase Regulators.*—A single-phase regulator is illustrated in Fig. 133. The primary exciting current produces an alternating flux that induces an alternating voltage in the secondary coil *S*. The secondary voltage can, however, be varied from a positive maximum to a negative maximum by rotating the primary coil through 180 electrical degrees from the position shown in Fig. 133*a*. When the primary coil is located at right angles to the secondary coil (Fig. 133*c*), there can be no voltage induced in the secondary winding since no flux threads through

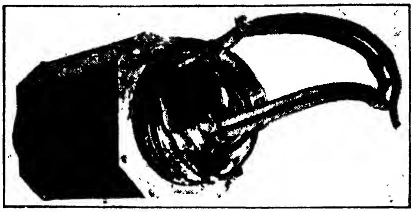


Fig. 135.

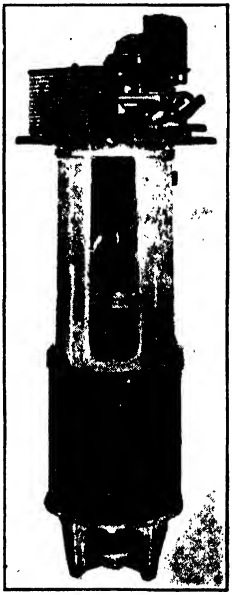


Fig. 134. Fig. 136.

Fig. 134.—Rotor of a 46-kva. single-phase induction regulator. (*Westinghouse Electric Corporation.*)

Fig. 135.—Stationary or secondary winding of single-phase induction regulator. (*Westinghouse Electric Corporation.*)

Fig. 136.—Assembly of rotor and stator of induction voltage regulator, showing control mechanism at the top. (*Westinghouse Electric Corporation.*)

this winding. At other positions of the primary, for example as shown in Fig. 133*b*, only a portion of the flux due to the primary coil threads through the secondary, and hence the secondary voltage is only a fraction of its maximum value. The secondary voltage, however, is always in phase or in opposition to the impressed voltage, since the voltage induced in the secondary always reaches a maximum at the same time when the impressed voltage is a maximum.

When the two coils are at right angles, the two m.m.fs. cannot oppose each other; hence another coil called the "tertiary" is placed on the rotor at right angles to the primary. This coil is short-circuited; hence the current flowing through it will produce the required opposing m.m.f. and thereby reduce the reactance of the windings to the value corresponding to the leakage flux. At intermediate positions of the rotor the secondary m.m.f. is partly balanced by the m.m.f. set up by the tertiary and partly by the m.m.f. of the primary windings. A typical single-phase induction regulator is shown in Figs. 134 to 136. The assembly shown in Fig. 136 is finally enclosed in a tank filled with oil.

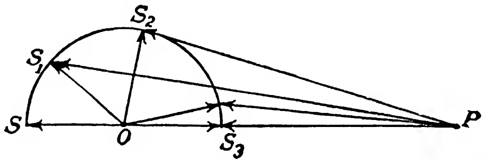


FIG. 137.—Vector diagram of one phase of a three-phase induction voltage regulator.

*b. Polyphase Induction Regulators.*—Polyphase regulators are wound with polyphase windings on both the rotor and stator in the same general manner as a wound-rotor induction motor. The primary windings can be connected in either star or mesh, while all terminals of the secondary windings must be brought out, since these windings are connected in series with the line. When polyphase currents flow in the primary windings, a revolving field cuts the secondary windings, thereby inducing e.m.fs. in them which are of the same frequency as the impressed voltage. As the primary is turned, the magnitude of the revolving field is not changed; hence the value of the secondary e.m.fs. must remain constant, but their phase relation to the primary voltages will change, as shown in Fig. 137. In Fig. 137, $PO$ is the primary voltage per phase, while $PS$, $PS_1$, $PS_2$, and $PS_3$ represent different phase voltages supplied to the load for different positions of the rotor.

Induction regulators are used to regulate the voltage of feeders, to regulate the voltage supplied to converters, and in connection with high-voltage oil-testing transformers. For most applications the rotor of induction regulators is controlled by a motor. By the use of a contact voltmeter it is possible to make the operation of the regulator entirely automatic, maintaining a predetermined value of voltage at all loads. When used in connection with high-voltage oil-testing transformers, the regulator is generally hand operated. When used to regulate the voltage of a feeder, it is possible to compensate for line drop by means of a line-drop compensator as described in Art. 69*b*.

Induction regulators are enclosed in tanks, which may be of plain, corrugated, tubular, or radiator type. They are cooled in any one of the ways used for transformers. The operating-motor and control relays are placed on top of the case (Fig. 136), and by means of a proper cover the entire equipment can be made waterproof, suitable for outdoor installation. Small- and medium-capacity regulators are suitable for pole mounting in a manner similar to pole-type transformers. Polyphase regulators are mostly three-phase, but for synchronous-converter operation it may be desirable to use six-phase regulators.

**85. Conservator-type Transformer.**—In small-capacity and low-voltage transformers it is general practice to leave a small air space above the oil level. In such transformers the oil is exposed to oxidation through its contact with the air. Practically all transformers of this type "breathe" new air into this space when there is a contraction in the volume of the oil owing to a load reduction and lower oil temperature. Oxidation of transformer oil shows itself in its simplest form in a darkening of color and in its more aggravated form under abnormal temperature conditions by developing sludge, which settles on the coils or tank walls and acts as a heat insulator. The continued breathing action also introduces moisture into the tank which condenses in the air space and finally settles into the oil.

The voltage gradient of oil decreases very rapidly when moisture is introduced, so that in the case of power transformers for the higher transmission voltages, it is essential that the oil be kept free from moisture and also sludging. In some of the higher voltage transformers the oil is actually broken up into its constituents by the formation of corona or arcing, such as might occur through a failure in the windings or at the submerged terminals.

Hydrogen forms the greater portion of the liberated gases. The combination of these gases with air, if in the right proportions, will form a mixture that is explosive.

One method that is used to limit sludging and prevent moisture from entering the transformer tank is to provide an auxiliary tank that is connected to and located above the transformer case, the main transformer tank being completely filled with oil (see Fig. 138). Such a transformer is known as a "conservator" type. Variations in volume of the oil due to temperature changes cause air to be drawn into and expelled from this expansion or conservator tank. A relatively small surface of oil is exposed to this breathed air, and consequently there is much less sludging and very little moisture collected. The air that enters the conservator tank can be dried by the addition of a calcium chloride breather. Practice has shown that where such a chloride breather has been cared for, very satisfactory results have been attained, but in most cases the chloride is left to deteriorate and is of no value. Most of such transformers are provided with a diaphragm at the end of a pipe which is connected to the transformer case, which in case of excess internal pressures will be ruptured, thereby preventing damage to the main transformer case.

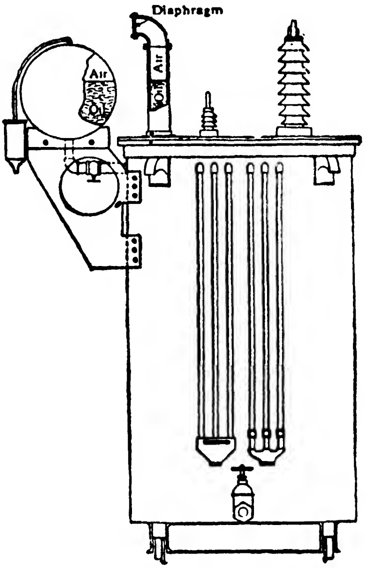


Fig. 138.—Sketch of a transformer equipped with an overflow or expansion tank.

**86. Gas-sealed Transformers.**—It has been pointed out that transformer sludging with its accompanying ills is due to the breathing action of transformers, thereby exposing the surface of the oil to moisture and air. This bad feature of operation can be overcome by having the upper part of the transformer tank filled with dry nitrogen gas. This gas seal is supplied from a standard cylinder of dry nitrogen and is automatically controlled, so that all joints in the tank and cover are always subjected to a slight outward pressure. This will prevent oxygen, moisture, dust, or any other fumes from entering the transformer tank.

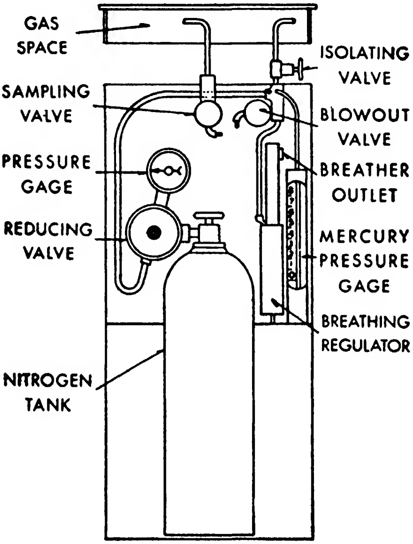


FIG. 139.—Details of gas-sealed transformer.

Suitable mercury-sealed valves and automatic pressure control is provided between the supply cylinder of nitrogen and the transformer tank, in order to take care of the fluctuations in internal tank pressure which will take place during cycles of load changes (see Fig. 139).

Nitrogen is a harmless inert gas that will not combine with any other substance within the transformer case and will not injure any material used in its construction. It will not burn, nor will it support combustion. For these reasons it is an ideal element for the elimination of the danger of explosions or fire and for the prevention of oxidation of the oil.

**87. Transformer Oil.**—Since the oil in which transformers are immersed is intended largely to furnish the necessary insulation and to dissipate the heat due to the core and copper losses, its selection is a matter of great importance, and a transformer should not be put into operation if there is any doubt as to the quality of the oil or its condition as regards moisture, etc. Transformer oil should be free from acid, alkali, and sulphur; should be nonvolatile; should not carbonize or sludge when heated; must be of high dielectric strength; and should be of low viscosity, good thermal conductivity, and high specific heat so that rapid circulation and good cooling may be obtained.

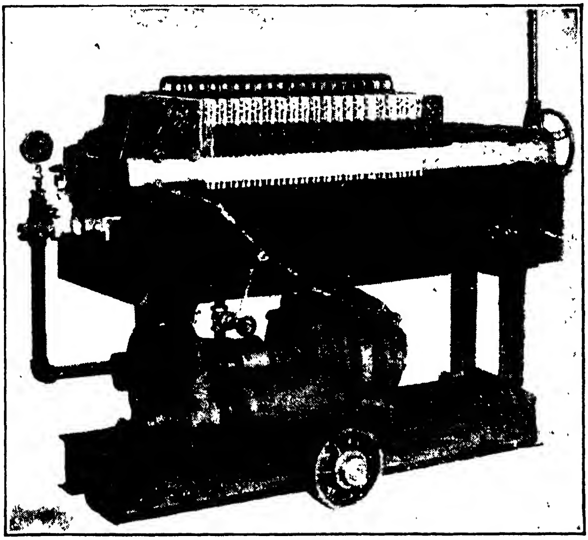


FIG. 140.—Portable transformer-oil dryer and filter. Filtering area 30 sq. ft., capacity 30 gal. per minute, maximum pressure 90 lbs., with 2-hp., 3,600-r.p.m., 60-cycle motor. (*General Electric Company.*)

**88. Purification of Transformer Oil.**—As has been indicated, the main causes of the deterioration of insulating oil in service are water and oxidation of the oil caused by air. The standard dielectric test for insulating oils is 22,000 volts between submerged terminals, 1 in. in diameter and 0.1 in. apart. A water content of 8 in 1,000,000 of oil, by volume, will lower the dielectric strength below 22,000 volts. Fine dust, especially if metallic, is almost as effective as water in reducing the dielectric strength. Sediment, which may result from long-continued heating, should also be removed in order to preserve the normal viscosity of the oil and to prevent accumulations on interior parts of the transformer and consequent clogging of the oil channels. Two types of equipment are in general use for purifying oil, the blotter filter press and the centrifugal purifier.

*a. Blotter Filter Press.*—The complete outfit shown in Figs. 140 and 141 consists of filter press, motor pump, oil strainer, pressure gauge, and piping. The oil is forced through several thicknesses of filter paper which take up the water and screen out the sediment. In order to obtain the best results it is necessary that the filter paper, when first placed on the filter press, be absolutely free from water; so it is dried in an oven before being placed in the outfit. An electric drying oven is commonly used for this purpose. If the oil contains only a small amount of water, all sediment and water should be removed by passing the oil once through the outfit. If any water remains, it indicates that the filter papers are saturated with water and must be renewed. No rule can be given as to how often the filter paper should be changed, as this depends entirely upon the amount of water and carbon in the oil.

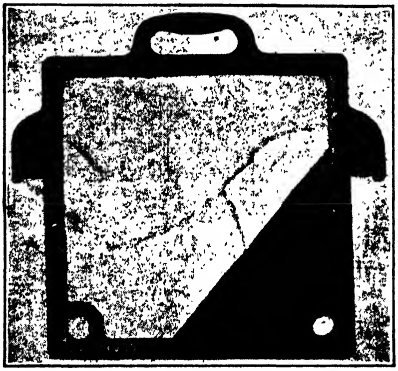


FIG. 141.—Frame, blotting paper, and filter plate of the 12-in. oil dryer and purifier outfit. (*General Electric Company.*)

Transformers are generally provided with two or three outlets, one at the top and two at the bottom of the tank, in order that a filter press may be connected to the tank. In some of the larger central stations it has been found best completely to pipe up all transformers into an oil system, so that the oil of any transformer tank may be readily filtered.

*b. Centrifugal Purifier.*—Figures 142 and 143 show the details of a centrifugal oil purifier. The oil containing moisture and sediment is forced by a gear pump into a receptacle at the top of the machine. It then flows down into the bowl which rotates at approximately 6,000 r.p.m. The impurities being heavier are thrown to the periphery by centrifugal force, while the oil is forced inward and up to the outlet provided. The application of the centrifugal purifier is about the same as the blotter filter press, except that the capacity of the centrifugal purifier is generally higher.

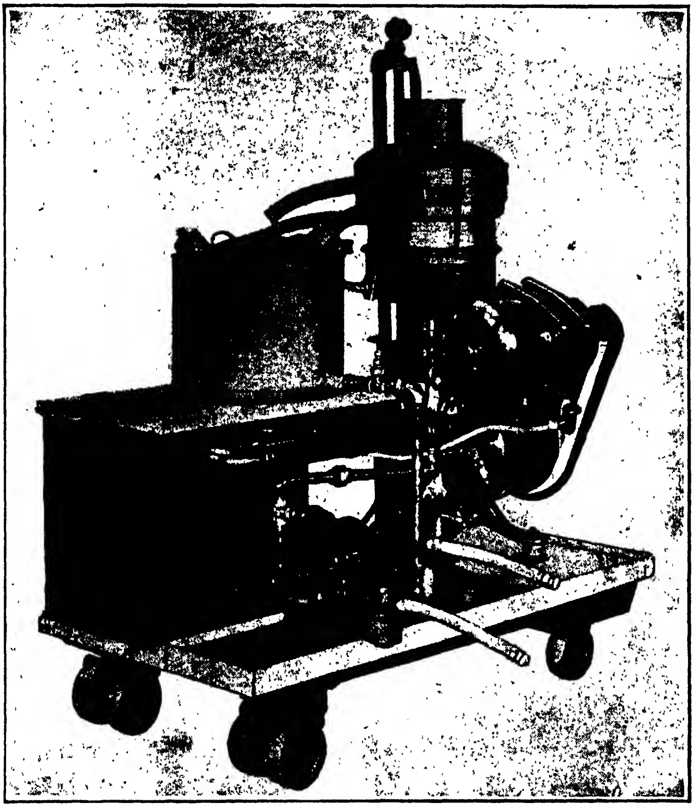


FIG. 142.—The DeLaval Separator Company's No. 600 portable transformer-oil purifier equipped with General Electric 2-hp., 110–220-volt, 60-cycle motor. (*General Electric Company.*)

**89. Transformer Bushings.**—The most serious difficulties encountered in the design of transformers and other apparatus for high potential is in the insulation of the leads where they pass through the case. Failure is likely to occur either by puncturing the insulation separating the live-metal conductor from the grounded case or by flashing over the surface of the terminal from the conductor to the grounded flange. There are two general types of bushings that are used for high-tension equipment;

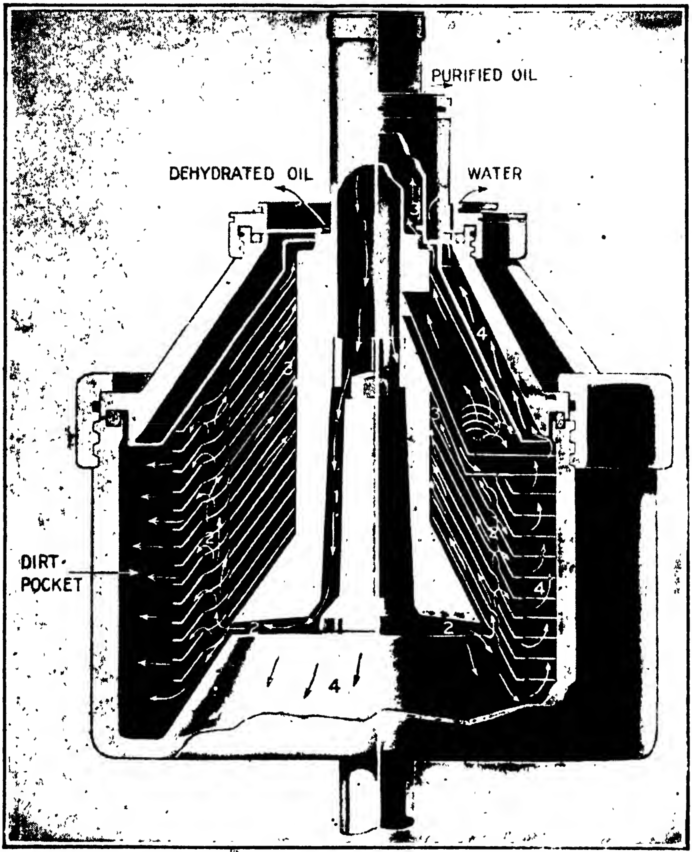


Fig. 143.—Cross section of centrifugal oil-purifier bowl. The arrows indicate the course of the oil through the bowl as follows: (1) inflow of dirty oil into the central feed shaft; (2) delivery of incoming oil beyond that which has already been partially purified; (3) upward passage of the pure oil from the inner ends of the disks to the oil outlet; (4) upward passage of the water from the outer ends of the disks to the waste outlet. As explained in the text, the solid impurities are retained in the sediment pockets of the bowl. (*General Electric Company.*)

the condenser bushing and the oil-filled bushing. Solid bushings are generally used for voltages up to about 70,000 volts.

*a. Condenser Bushing.*—The condenser bushing consists of concentric cylinders of insulating material with layers of metal foil between them. The surfaces of the consecutive layers are so proportioned that the potential gradient is uniform over the outer surface from step to step and decreases gradually and uniformly through the insulating wall from the inside outward. Such a bushing is composed of a large number of condensers connected in series between the high-potential conductor and ground, the voltage drop across these condensers being practically uniform.

*b. Oil-filled Bushing.*—This type of bushing consists of a porcelain shell, generally in the form of petticoat insulators through which extends a copper tube (see Fig. 144). The space between the porcelain shell and this copper tube is filled with oil, an oil glass gauge being provided at the upper end for inspection purposes. The conductor consists of a flexible conductor that is located inside of the copper tube. The porcelain shell is generally made in two sections held together by means of a metal sleeve which forms the section of the bushing that comes in contact with the transformer tank.

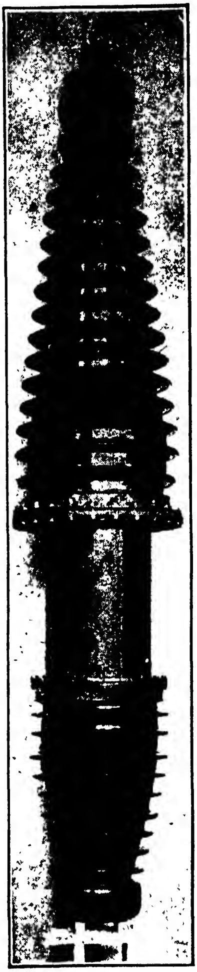


Fig. 144.—Oil-filled interchangeable high-voltage bushing. (*General Electric Company.*)

### Questions for Class Discussion

**1.** Name four general types of magnetic circuits used for transformers.

**2.** Discuss how single-phase and three-phase transformers differ in construction, and compare their advantages and disadvantages.

**3.** Describe the general details of a three-phase core and a three-phase shell-type transformer.

**4.** Would you install three-phase transformers or banks of three single-phase transformers in a large power station? Justify your answer by comparing the two schemes.

**5.** How are the coils of shell-type transformers wound and insulated?

Why is the insulation thickness generally increased toward the line terminal of the winding?

**6.** Name three types of windings used in core-type transformers. Illustrate each by a suitable sketch.

**7.** Why is the problem of cooling large transformers more difficult than for smaller ones?

**8.** What methods of cooling transformers are in common use?

**9.** Why should distribution transformers be designed for a minimum value of no-load losses?

**10.** State the purpose of each of the following types of transformers and give examples of their application to power work: (*a*) power, (*b*) distribution, (*c*) metering, (*d*) constant current, (*e*) induction regulator.

**11.** Why is it objectionable to open the secondary of a current transformer that is in service? Is the transformer liable to be injured? Is it harmful to short-circuit a current transformer?

**12.** Is there any danger similar to that in current transformers in keeping the secondaries of potential transformers open? Would it be safe to short-circuit the secondary terminals?

**13.** Explain the fundamental principle of operation of a constant-current transformer.

**14.** Explain the fundamental principle of operation of: (*a*) a single-phase induction regulator, (*b*) a three-phase induction regulator.

**15.** Discuss "breathing action" of tranformers. What is an "oil conservator"? Explain its advantages.

**16.** What is a "gas-sealed transformer"? Explain.

**17.** The exciting current of a transformer consists largely of a magnetizing component that is reactive. What then is the disadvantage of a large exciting current? Is there any further disadvantage if the transformer is at the end of a transmission line?

**18.** State some of the necessary qualities that oil must have in order to be suitable for transformer insulation?

**19.** Name and explain two methods that are used to purify transformer oil.

**20.** Name three general types of transformer bushings. Explain the construction of each.

**21.** Is the voltage gradient along the radii of a bushing uniformly distributed?

**22.** How is uniform potential gradient obtained along the outer surface of a condenser-type bushing?

# CHAPTER VIII

# TRANSFORMER CONNECTIONS

**90. General.**—There is practically no limit to the possible ways in which transformers may be connected. In this chapter only a few of the standard methods will be discussed. Transformer connections may be divided into two general classes, depending on the function performed, namely, voltage transformation and phase transformation. As indicated in Art. 58 a polyphase system cannot be obtained from a single-phase system without the use of revolving machinery, but one polyphase system can be obtained from another polyphase system by proper transformer connections. Invariably a phase transformation also involves a voltage transformation.

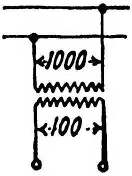


Fig. 145.

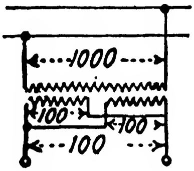


Fig. 146.

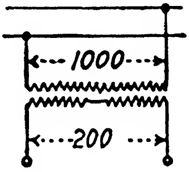


Fig. 147.

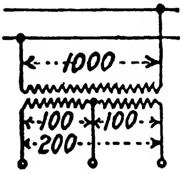


Fig. 148.

**91. Single-phase Connections.**—Standard single-phase transformers for distribution service are wound with one or two secondary coils. The simplest application of such transformers is to general distribution for lighting, in which case there are only one primary coil and one secondary coil. Such an installation is illustrated by Fig. 145. It is, however, of advantage to have two low-voltage coils, thereby obtaining a greater flexibility out of a given transformer. The two secondary coils can be connected either in parallel or series as the particular requirements demand. Such connections are shown in Figs. 146 and 147. It is often desirable to have two voltages available on the secondary, in order that small power and lighting loads may be served from the same transformer; hence the connections of Fig. 148 are often used. Lighting loads are supplied from the middle and either outside lines, while power loads are supplied from the two outside wires.

In order to protect the secondary circuit from high potentials, which might be caused due to the breakdown of the insulation between the primary and secondary coils, it is general practice to ground some point of the secondary circuit. In the case of a two-wire single-phase system either one of the lines may be grounded, while in the case of the three-wire system it is best to ground the middle or neutral line.

**92. Two-phase Connections.**—Two-phase connections commonly found in practice may be of three, four, or five wires as shown in Figs. 149 to 152. Above each diagram of connections are indicated the secondary-voltage relations. The primary circuit has been shown as a four-wire system, but any of the connections shown for the transformer secondaries are also applicable to the primary. A common primary connection, which is also used besides the one shown, is the three-wire system as illustrated for the transformer secondaries in Fig. 149.

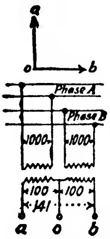


FIG. 149.

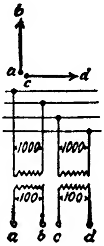


FIG. 150.

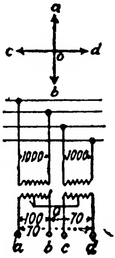


FIG. 151.

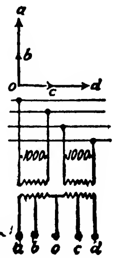


FIG. 152.

Two-phase circuits are obtained from two independent single-phase circuits that are displaced from each other by 90 electrical degrees. In practice, two-phase distribution systems are obtained by the use of two single transformers, the terminals of which are interconnected in any one of the methods of Figs. 149 to 152. The three-wire method of Fig. 149 has the distinct advantage that only three wires are needed. It will be noticed that the voltage across *ab* is 1.41 times the phase voltage. If a balanced two-phase load is being supplied it also follows that the current flowing in the common line is 1.41 times the current in either of the outside wires.

In Fig. 150 each phase is kept entirely separate, hence amounting to two separate single-phase systems. The main disadvantage of such a system is the necessity of four wires. By interconnecting the mid-points of the two secondaries, a four-wire interlinked system is obtained (see Fig. 151). Such a system is in reality a four- or quarter-phase circuit. The advantage of this method of connection is the fact that several values of voltage are obtainable. It may be desirable to bring out the neutral point, thus obtaining a five-wire two-phase circuit. As will be explained later, a neutral line is desirable in connection with the operation of synchronous converters.

Another method of obtaining a five-wire circuit is shown in Fig. 152. This system is similar to that of Fig. 149 with the addition of the two extra lines brought out from the mid-points of the two transformers. The advantage offered by a five-wire system is that several voltages are available; hence several types of loads can be supplied from the same transformers, thereby increasing the transformer load factor. The neutral point of two-phase circuits is generally grounded for the same reasons as given for single-phase circuits.

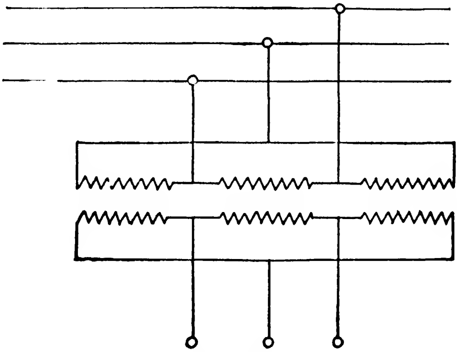


FIG. 153.

**93. Three-phase Connections.**—The most important combinations of transformer connections for this service are delta-delta, Y-delta or delta-Y, Y-Y, open-delta, T-connection, and autotransformer.

**94. Delta-delta Connection.**—This type of connection is illustrated in Fig. 153. Assuming a balance load the current and voltage relations of a delta-connected transformer are as follows:

$$E_L = E_p \text{ and } I_L = \sqrt{3}\, I_p$$

where $E_L$ = voltage between lines
$E_p$ = voltage per phase
$I_L$ = current flowing in each line
$I_p$ = current flowing in each phase

It is, therefore, apparent that each phase of delta-connected transformers must be wound for full line voltage. On the other hand the current-carrying capacity of each phase is only 58 per cent of the line current.

Assuming that three delta-connected transformers have the same ratios and impedances, it follows that the resultant voltage acting around the closed delta must be zero, since the three-phase voltages are 120 electrical degrees apart. It is also apparent that the vector sum of any two voltages is equal to the third voltage; hence it follows that a delta-connected transformer will continue to deliver power in case one phase is omitted. If, however, the ratios or impedances of the three phases are not alike, there will be a circulating current in the closed delta, and the load will therefore not be equally divided among the three phases.

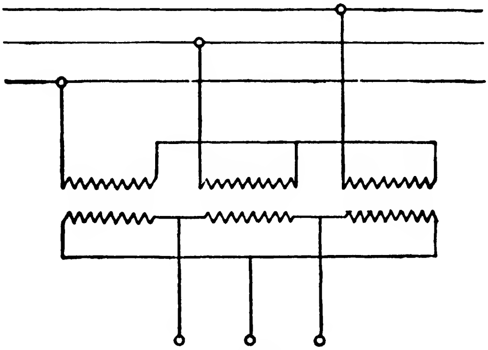


FIG. 154.

**95. Y-delta or Delta-Y Connection.**—The delta-delta connections are not used much because both the primary and secondary windings must be wound for full voltage. The Y-delta or delta-Y connection as shown in Fig. 154 is very common, the Y-connection being generally used on the high-voltage side. The simple current and voltage relations for the delta side of Fig. 154 are the same as given for the delta-delta-connected bank, but the Y-relations are as follows:

$$E_L = \sqrt{3}\, E_p \qquad \text{and} \qquad I_L = I_p$$

where the nomenclature is the same as used for the delta-delta case.

For high-tension transmission lines it is general practice to ground the neutral of the Y solidly; hence the voltage between any one phase and ground is highest at the line terminal. A great saving in insulation and hence cost can therefore be made when high-voltage transformers are designed to operate with the Y neutral grounded. For comparatively low-voltage distribution it is sometimes advantageous to bring out the neutral, thus making a four-wire three-phase system, thereby obtaining two voltages.

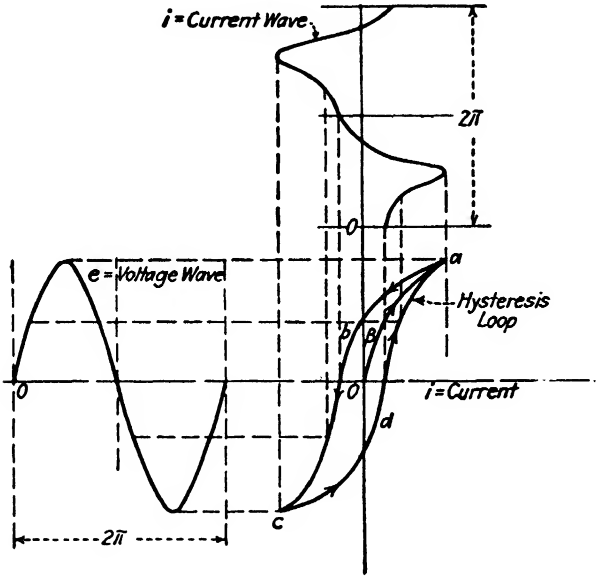


FIG. 155.—Transformer-exciting current.

**96. Y-Y Connection.**—Transformers connected in Y-Y are sometimes desirable when connecting two systems of rather high voltage, or when it is desirable to maintain the same relative phase positions on both primary and secondary sides. It is, however, necessary to add another winding, known as a tertiary winding, to each transformer of such a bank in order that the operation be satisfactory. In order to explain the function of the tertiary winding, a brief discussion of the properties of iron will be given.

**97. Transformer-exciting Current.**—Figure 155 shows a typical hysteresis loop for magnetic steel. Assuming a sine wave of induced voltage, hence a sine wave of flux density, it will be noticed that a peaked wave of exciting current is required. An analysis of this current wave will reveal the presence of a pronounced third harmonic with other higher odd harmonics (fifth, seventh, ninth, etc.) of much smaller amplitudes. If the magnetizing current does not contain all the harmonics necessary to produce a sine wave of voltage, then the voltage wave will contain those harmonics which the magnetizing current lacks.

Third-harmonic currents cannot flow in an ungrounded Y transformer, but they will flow if the neutral of the Y transformer is connected to the generator neutral through a solid ground of small impedance. A flow of third-harmonic currents through the ground causes serious interference with telephone lines and hence should be avoided. Third-harmonic voltages of all three windings are in phase. This is the reason why delta-delta or Y-delta voltage transformations can be accomplished without any distortion of the voltage wave. The best method by which Y-Y voltage transformation can be accomplished, therefore, is to place a tertiary winding on each transformer core, the three tertiary windings being connected in delta so that the third-harmonic exciting current can be furnished and thus sine-wave voltages obtained in the secondaries.

By properly designing the delta-connected tertiary windings, it is possible to supply a load from them, as, for example, a synchronous condenser at the end of a transmission line. Since the object of the tertiary windings is merely to supply a closed circuit for the harmonic magnetizing currents, they can be designed for any voltage, and hence can be easily designed to carry an additional fundamental load current. The connections are as shown in Fig. 156.

**98. Y-connected Autotransformers.**—In single-phase distribution it is generally desired to keep the primary and secondary circuits electrically insulated from each other for reasons of safety. In primary power feeders or transmission lines, a transformation between rather high voltages is often needed as, for example, between 150,000 and 220,000 volts. In such a case a great saving in cost can be obtained by using autotransformers connected in Y as shown in Fig. 157 rather than Y-Y-connected transformers. Such a method of tying two high-voltage systems has been used to a considerable extent in late years. As in the case of Y-Y transformers, a delta-connected tertiary is needed to supply the necessary harmonic exciting currents. By solidly grounding the neutral of these transformers, the insulation can be decreased at that point.

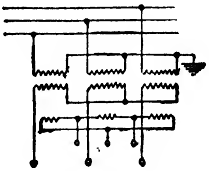


Fig. 156.

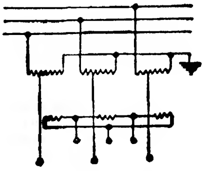


Fig. 157.

**99. Three-phase Open-delta Connection.**—In Art. 94 it was stated that, in a delta-delta-connected bank, power could still be delivered in case one phase were damaged. It follows, therefore, that a three-phase voltage transformation can be made with only two transformers connected in open delta or V on both primary and secondary sides (see Fig. 158). Such a scheme is sometimes used as a temporary connection with the intention of completing the delta when conditions of load warrant the addition of a third transformer. Potential instrument transformers are often connected in this manner when it is desired to read all three voltages of a three-phase system. A serious disadvantage of the open delta is the fact that under load the line voltages become unbalanced.

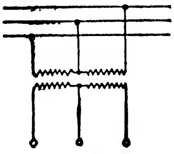


Fig. 158.

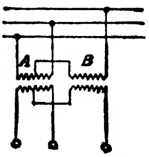


Fig. 159.

**100. Three-phase T-connection.**—This scheme of connections is similar to the V or open-delta method in that only two transformers are needed. One transformer must be supplied with a mid-point tap, as shown by *A* in Fig. 159. The transformer having the mid-point tap is connected across two lines, while the second or "teaser" transformer is connected to the mid-point of the first transformer and the third line. Similar transformers are generally used for the T connection, and if both are equipped with a mid-point tap they can be interchanged. Where T-connected transformers are installed, they may later be changed to delta with the addition of another transformer. The T connection, however, is seldom used, as it does not offer any decided advantages over some of the other three-phase connections.

**101. Polyphase to Single-phase Connections.**—Single-phase loads can be supplied from any polyphase system merely by using any two terminals, but when a large number of single-phase loads are thus supplied, they should be properly distributed among the different phases in order not to unbalance the polyphase system too much.

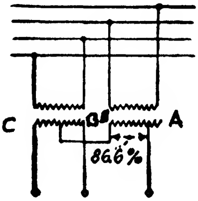


FIG. 160.

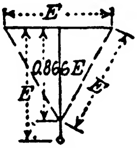


FIG. 161.

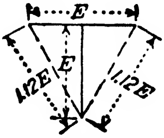
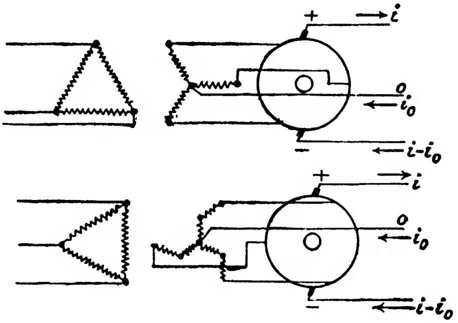


FIG. 162.

**102. Two-phase to Three-phase Connections.**—There are a number of schemes that have been developed for the transformation between two- and three-phase systems, but the scheme most generally used is the so-called "Scott" or "balanced" T connection. This scheme of connections is shown in Fig. 160 with the corresponding voltage relations in Fig. 161. Two transformers are used, connected to the two-phase supply. The secondary of transformer *B* is connected to the mid-point of transformer *A*. Transformer *B* must be supplied with an 86.6 per cent tap as shown in order that equal delta voltage may be obtained.

In some cases it may be desirable to obtain three-phase from a two-phase system where a transformer having an 86.6 per cent tap is not available. In such a case two alike transformers can be used, the resultant delta-voltages being slightly unbalanced, as shown in Fig. 162. Such a scheme will be suitable as an emergency connection to supply an isolated three-phase load from a two-phase system, but cannot be connected in parallel with any balanced three-phase circuit.

**103. Two- and Three-phase Transformer Connections Supplying Synchronous Converters.**—Synchronous converters are frequently installed in connection with Edison systems, where three-wire direct current is required. The three-wire feature is readily obtained by connecting the neutral wire of the direct-current system directly to the neutral point of the secondary windings of the step-down transformers, if such are furnished.



FIGS. 163–164.

In Fig. 163 is shown a three-phase Y-connected secondary supplying a converter, the neutral wire of the direct-current system being obtained from the Y-transformer neutral. In case the direct-current load is unbalanced, a resultant direct current will flow in the neutral wire. It is evident that in this case each transformer secondary will receive one-third of the

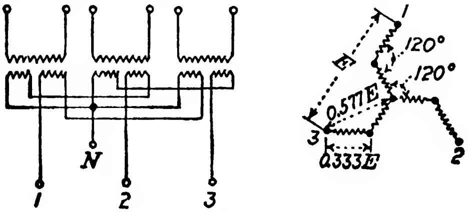


FIG. 165.

neutral current, and if this current is not small, as compared with the exciting current of the transformers, it will cause an increase in the magnetic-flux density in the iron core. A system with a distributed Y secondary as shown in Fig. 164 has, however, been devised, and will eliminate the effects of the unbalanced direct current in the neutral. Figure 165 shows in detail the connections necessary. The winding consists of two coils on each leg, cross-connected as shown. The direct-current m.m.f. due to one coil on each leg will neutralize that due to the other coil on the same leg, and the only flux in the iron core will be that due to the alternating magnetizing current. Owing to the general appearance of such a scheme it has been termed the "zigzag" system of connections.

The T connection as shown in Fig. 166 can also be used for three-phase converters. The neutral is then brought out from a point at one-third the height of the teaser transformer. The advantage of the T connection is that two transformers can be used instead of three, but it has the disadvantage that the triple-harmonic exciting current is not short-circuited.

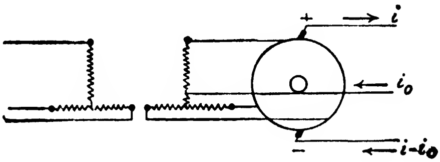


FIG. 166.

For two-phase or quarter-phase converters the connections are made as shown in Fig. 167. In this case the direct current divides into four equal branches which tend to magnetize the transformers in opposite directions, thereby neutralizing their magnetic effects.

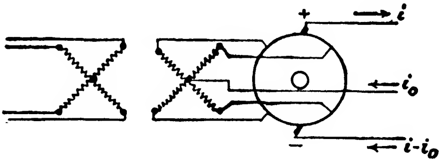


FIG. 167.

Delta-connected secondaries may also be used to supply converters if no neutral direct-current line is desired.

**104. Two-phase to Six-phase Connection.**—Six-phase systems are of advantage for the operation of synchronous converters (see Art. 55) and power rectifiers (see Art. 57); hence it may often be more economical and desirable to convert a two- or three-phase supply into six-phase, thus using six-phase converters.

The standard connection for transforming two-phase into six-phase is shown in Fig. 168. The scheme amounts to a double

T-connected secondary. The primary and secondary voltage relations are shown in Figs. 169 and 170. Both transformer secondaries must be wound with two separate windings, and in addition the secondaries of one transformer (see *A*, Fig. 168) must be equipped with mid-point taps. The secondaries of transformer *B* must be wound to give only 86.6 per cent as much voltage as the secondaries of transformer *A*.

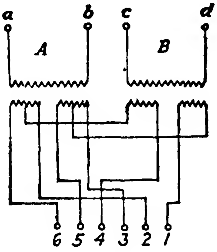


Fig. 168.

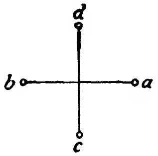


Fig. 169.

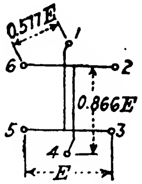


Fig. 170.

**105. Three-phase to Six-phase Connection.**—Three-phase to six-phase transformation may be accomplished in four ways: (*a*) double T, (*b*) double delta, (*c*) double Y, and (*d*) diametrical connections.

The first three methods given require double secondary windings, while the diametrical connection requires only one secondary coil on each transformer; hence the diametrical connection is the one that is most often used.

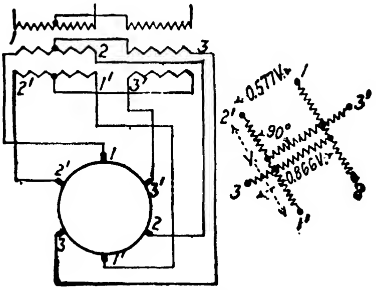


Fig. 171.—Six-phase double T.

*a. Double T Connections.*—This scheme is shown in Fig. 171. It consists of two secondary circuits, each one connected as indicated in Art. 100, but displaced 180 electrical degrees from each other.

*b. Double Delta Connections.*—This scheme of connections is shown in Fig. 172. It consists of two delta-connected secondary circuits that are displaced from each other by 180 electrical degrees. The main disadvantage of such a scheme is that no neutral wire can be obtained from the secondaries.

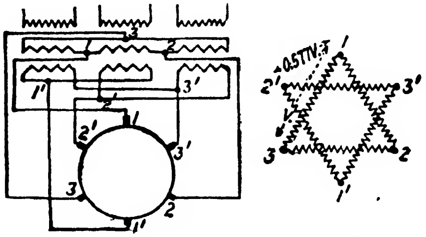


FIG. 172.—Six-phase double delta.

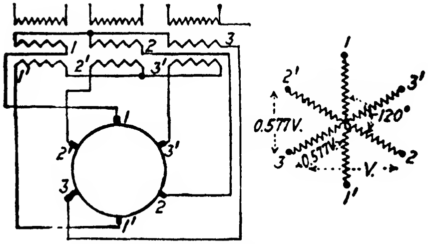


FIG. 173—Six-phase double Y.

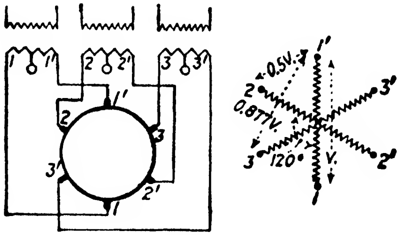


FIG. 174.—Six-phase diametrical.

*c. Double Y Connections.*—The secondary circuit of this scheme is composed of two sets of Y-connected coils, displaced from each other by 180 electrical degrees (see Fig. 173).

*d. Diametrical Connections.*—In this case only one secondary coil per transformer is needed (see Fig. 174). This fact simplifies the necessary connections for starting converters, such as switches and transformer taps. If the secondary coils are provided with a mid-point tap, these may be connected together and a neutral wire brought out for a three-wire direct-current system.

The six-phase double-Y or diametrical connection is adaptable to six-phase power rectifiers, since the two neutrals or mid-points of the secondaries can be connected to become one side of the rectified direct-current circuit (see Art. 57).

**106. Operation of Three-phase Transformer Banks.**—In Art. 94 it was shown that a delta-delta-connected bank of transformers will continue to deliver power when either a primary or secondary coil becomes damaged. Under these conditions each phase will carry line current; hence the capacity of the open-delta bank is reduced to 58 per cent of the closed-delta bank. Delta-Y- or Y-delta-connected transformer banks are, however, used more extensively than delta-delta banks; hence it is important to understand how such systems will operate under similar conditions. Consider a transmission line equipped with delta-Y step-up and Y-delta step-down transformers (Fig. 175).

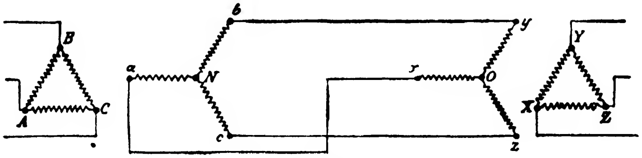


Fig. 175.

Consider the following windings disconnected:

*a. Winding ZY.*—Three-phase operation will be maintained, the transformer secondaries operating in V or open delta. The capacity, however, is reduced to 58 per cent of the original value.

*b. Winding XO.*—If this winding were removed, the remaining windings *YO* and *OZ* will be operating in series across line voltage; hence three-phase operation will cease. If, however, the neutral points *N* and *O* are solidly grounded and the ground has zero resistance, the phase relation of windings *YO* and *OZ* will be maintained. The system will therefore continue to deliver three-phase power. The same thing would be true in case winding *aN* were disconnected.

*c. Winding AC.*—If the neutrals *N* and *O* are grounded, three-phase operation will still be maintained. It is essential, however, that the neutrals be well grounded and the ground be of low resistance, in order that such operation be satisfactory.

**107. Parallel Operation of Transformers.**—Transformers may be operated in parallel provided the polarity, phase rotation, and angular displacement of the two units are alike and also if the ratios and impedances of the two units are of proper magnitude. In Table X are given the possible parallel combinations of three-phase transformers or single-phase transformers in three-phase banks.

The ratios of turns must be such that the required line voltages be obtained. For example, consider a delta-Y bank and a Y-delta bank. In order that these two transformer banks may be connected in parallel, it is necessary that the ratio of primary to secondary turns in the Y-delta bank be one-third of the ratio of primary to secondary turns in the delta-Y bank. The other possible schemes given in Table X require transformers of equal ratios for all parallel banks.

TABLE X.—POSSIBLE THREE-PHASE TRANSFORMER COMBINATIONS

| Bank *A* | Y-Y | Y-delta | Delta-delta | Delta-Y |
|---|---|---|---|---|
| Bank *B* | | | | |
| Y-Y | Yes | | | |
| Y-delta | No | Yes | | |
| Delta-delta | Yes | No | Yes | |
| Delta-Y | No | Yes | No | Yes |

In case the impedances are not of the proper magnitude, the terminal voltages of the two banks will not be alike and, therefore, when connected in parallel, a circulating current will flow between the separate banks in the same manner as in the case of two generators which are operating in parallel with unequal induced voltages.

It is possible to estimate the proportional division of load between two single-phase transformers of the same turns ratio by using the simple equivalent series circuits of the two transformers. From basic circuit analysis we know that the currents of two parallel impedances divide in the following ratio:

$$\frac{I_1}{I_2} = \frac{Z_2}{Z_1}$$

where $I_1$, $I_2$, $Z_1$, and $Z_2$ represent, respectively, the complex algebra value of currents and series impedances of the two transformers operating in parallel.

If $I_1 + I_2 = I_T$ = total load current, then by proper substitution

$$\frac{I_1}{I_T} = \frac{Z_2}{Z_1 + Z_2}$$

$$\frac{I_2}{I_T} = \frac{Z_1}{Z_1 + Z_2}$$

From these equations it will be seen that if two transformers of the same turns ratio are operated in parallel the load division will take place in the inverse ratio of impedances.

**108. Tap Changing of Transformers under Load.**—Undoubtedly, voltage regulation of system transmission or distribution lines is the most important feature of good operation unless it should be cost of service. Any line can be designed to give constant voltage, but initial cost and operating expense may be too excessive. Induction-type regulators as discussed in Art. 84 are ideal for circuits operating at a rather high load factor. The exciting current of induction regulators is quite high and would therefore cause considerable line-voltage drops under light loads. Furthermore, the induction regulator is quite expensive; hence for some applications, voltage control must be obtained by other means.

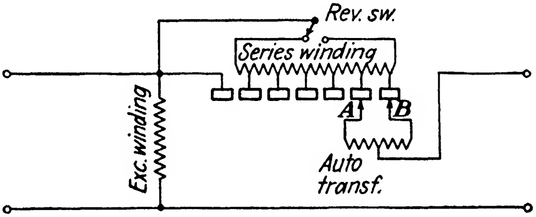


FIG. 176a.—Simple step-type regulator.

Many schemes of tap changing of transformers have been devised. For the lower capacity units it is accomplished by providing taps to the transformer winding with some type of movable or rotating set of contacts. The basic circuit is illustrated in Fig. 176a. In this case the secondary is connected in series with the line in an additive or subtractive manner as determined by the position of the reversing switch. The secondary circuit is completed through the contacts $A$ and $B$ and the small autotransformer. The contacts $A$ and $B$ are movable and make contact with any one or any two adjacent taps of the series winding. The autotransformer is used to prevent excessive circulating current from flowing when the movable contacts $A$ and $B$ are in contact with adjacent taps of the series winding.

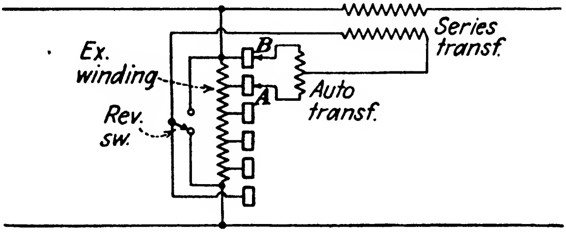


FIG. 176b.—Step-type regulator with series transformer.

In the case of high currents it is preferable to use a scheme similar to Fig. 176b, in which the movable contacts are placed on the primary or exciting winding, reducing the current handled by the tap-changing mechanisms. The operation of this type of tap changer is basically the same as that of Fig. 176a. Contacts $A$ and $B$ may be made to move in a circular path or in a straight line path, depending on the particular arrangement of the tap contacts.

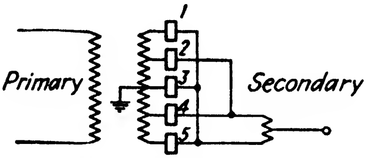


FIG. 176c.—Step-type tap changer with individual oil switches.

Movable contacts are adaptable to relatively small transformer capacities. For large power units it is necessary to use a series of independent switches operating in a predetermined sequence.

In Fig. 176c is shown the schematic diagram of connections of a transformer secondary with all necessary switches.

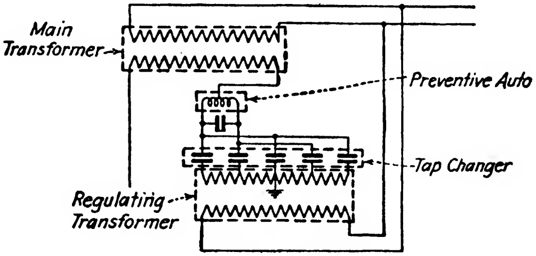
To obtain the full winding voltage, switch 1 is closed to connect one-half of the autotransformer to tap 1.

To change taps one step, it is only necessary to close switch 2, which places the autotransformer across two taps, giving a voltage on the mid-tap of the preventive autotransformer halfway between the two actual tap voltages.

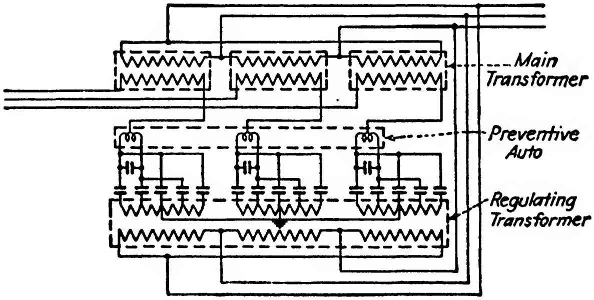
To change taps another step, the only operation required is to open switch 1, which leaves switch 2 closed, thus obtaining a voltage corresponding to tap 2.

The standard voltage range for tap changing under load is from 110 to 90 per cent of normal voltage in eight 2½ per cent steps.

**109. Separate Tap-changing Units.**—For high-voltage installations it becomes advisable and also convenient to use a standard transformer with the tap-changing transformer as a separate unit. A single-phase application is shown in Fig. 177*a* and a three-phase installation in Fig. 177*b*.



(*a*) Single phase.



(*b*) Three phase.

FIG. 177.—Tap-changing units.

**110. Phase Shifting under Load.**—In three-phase systems it is possible by proper connections to obtain regulated voltages that are in phase quadrature with the main transformer phase voltages. By this method it is possible to obtain a phase shifting of the voltages as well as a change in magnitude. This feature is of value when two lines of dissimilar capacities and constants are operated in parallel, the division of load between the two lines being controllable in such cases.

### Questions for Class Discussion

1. Illustrate by means of sketches the application of single-phase transformers to distribution service.

**2.** Illustrate by sketches the various possible connections of two-phase transformer banks.

**3.** Draw wiring diagrams for transformers connected Y-Y, delta-delta, Y-delta, V-V, and T-T. What are the relative merits of each of these schemes of connection?

**4.** Why does a Y-Y bank of transformers with neutrals not grounded require a set of delta-connected tertiary windings? Explain clearly. Are delta-connected tertiary windings required in case one neutral is grounded? Explain. Can a load be supplied from the delta-connected tertiary?

**5.** Illustrate by diagram the connections involved in a bank of autotransformers connected in Y. Are delta-connected tertiary windings required in this case?

**6.** Would you install an autotransformer to supply a 110-volt lighting circuit from a 2,200-volt line? Why?

**7.** Would the above transformer be suitable to boost the voltage of a 2,000-volt line to 2,100 volts? Draw a diagram of connections. Could a standard 2,200-volt 110-volt lighting transformer be used for this purpose?

**8.** With transformers connected in Y and the neutral not grounded, is it possible to get the full line voltage impressed on the transformer insulation? Explain. Can this happen with a grounded neutral?

**9.** Tabulate advantages and disadvantages of (*a*) Y and delta connections, (*b*) grounded and ungrounded neutral. Draw vector diagrams for two banks of transformers in parallel: delta-delta with Y-Y, etc.

**10.** Draw a diagram of the Scott connection for two- to three-phase transformation. How many single-phase transformers are needed, and what voltage taps are necessary?

**11.** What is the customary way of obtaining a three-wire Edison system from a converter?

**12.** What are the disadvantages of unbalancing the loads of a three-wire Edison system when supplied with a neutral wire from the neutral of a Y-connected transformer secondary?

**13.** How can the above difficulty be overcome? Are there any disadvantages in this scheme?

**14.** Name four possible schemes of connection by which six phases may be obtained from a three-phase supply. What power application requires six-phase supply?

**15.** Three-phase power is delivered through a bank of transformers. One of the windings burns out. Will the system continue to operate for the following cases: Primary, (*a*) delta, (*b*) delta, (*c*) Y, (*d*) Y? Secondary, (*a*) delta, (*b*) Y, (*c*) delta, (*d*) Y? One primary winding burns out? One secondary burns out?

Will the results be different with neutral gounded or undergrounded?

**16.** State what combination of Y-Y, delta-delta, Y-delta, and delta-Y transformers can be operated in parallel.

**17.** Discuss the methods of changing taps on transformers under load.

**18.** How are the tap-changer contacts embodied in the transformer design?

**19.** Discuss phase shifting under load. Explain how this may be accomplished on a three-phase system.

# CHAPTER IX

## SWITCHBOARDS AND SWITCHBOARD LAYOUTS

**111. Classification.**—Switchboards may be classified according to service, control, framework, panel material, and arrangement.

**112. Service.**—It is practically impossible to cover every type of switchboard application, but a few of the most important ones are given below.

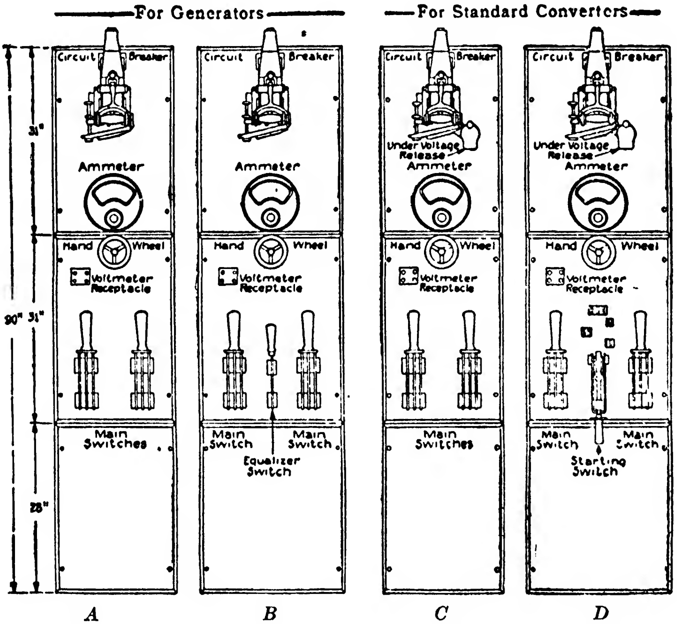
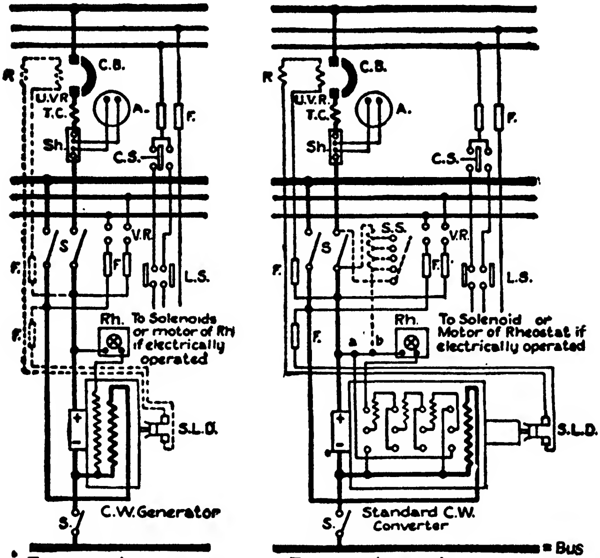


Fig. 178.—Two-wire direct-current generator and converter switchboards.

*a. Direct Current.*—Direct-current panels may be for generator, converter, or general lighting and power service. In Figs. 178 and 179 are illustrated a few typical examples of direct-current switchboards for two-wire generator and compound-wound converter service. For two-wire systems it is general practice to use only one circuit breaker, thereby simplifying the necessary connec-



For two-wire generator panel (dotted lines show under-voltage release when added).

For two-wire synchronous converter panels (dotted lines apply only to panels which provide for direct-current starting. When dotted lines apply, the connections between points marked *a* and *b* are omitted).

FIG. 179.—Typical switchboard wiring diagrams for panels shown in Fig. 178.

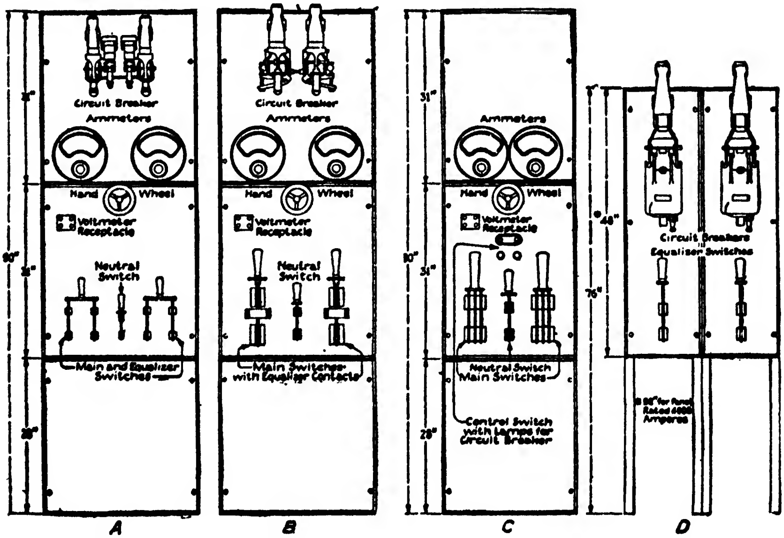
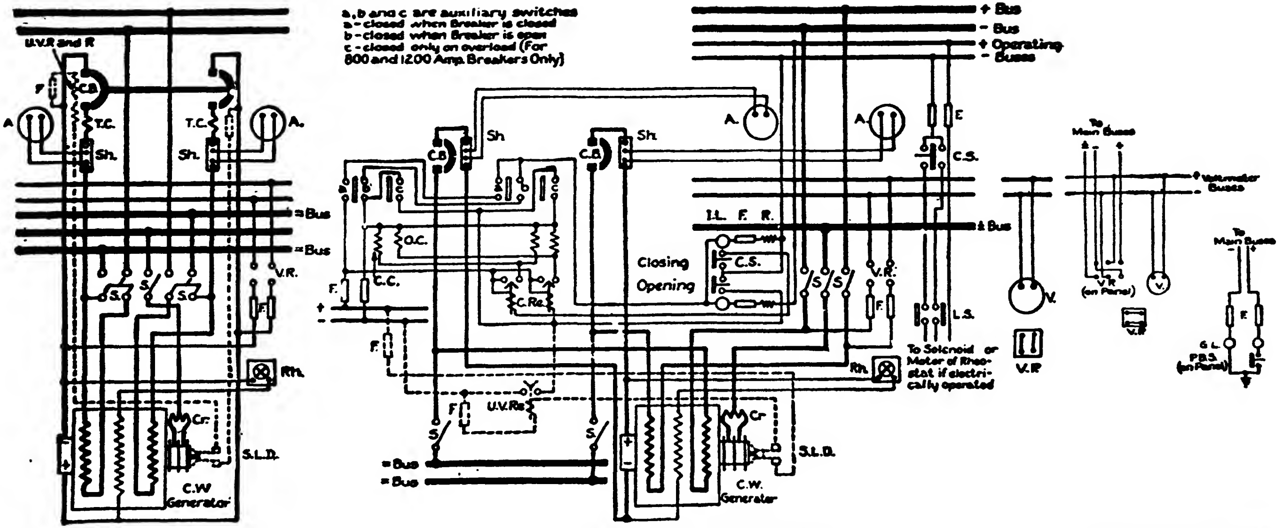


FIG. 180.—Three-wire direct-current generator switchboards.



With hand-operated breaker

With solenoid-operated breaker

Equipments on bracket

——For 3-wire generator panels (dotted lines show under-voltage release or relay when added).——

SYMBOLS USED ABOVE

A.—Ammeter.
C.B.—Circuit breaker.
C.C.—Closing coil.
C.Re.—Control relay.
Cr.—Compensator.
C.S.—Control switch.
D.R.—Discharge resistance.
F.—Fuse.
F.S.—Field switch.
G.L.—Ground lamp.
I.L.—Indicating lamp.
L.S.—Limit switch.
M.—Motor (for rheostat).
O.C.—Opening coil.
P.B.S.—Push-button switch.
R.—Resistance.
Rh.—Rheostat.
S.—Lever switch.
Sh.—Ammeter shunt.
S.L.D.—Speed limit device.
S.S.—Starting switch and starting resistance.
T.C.—Trip coil.
U.V.R.—Under-voltage release.
U.V.Re.—Under-voltage relay.
V.—Voltmeter.
V.P.—Voltmeter plug.
V.R.—Voltmeter receptacle.

FIG. 181.—Typical switchboard wiring diagrams for panels shown in Fig. 180.

tions. In all direct-current switchboard installations it is important that the carbon circuit breakers be mounted at the top of the panel in order that the arc produced when breaking a heavy current will not damage any other equipment on the board. The circuit breakers may be equipped with tripping coils so that the circuits may be opened under short circuits, under voltage, or under other abnormal conditions. Figures 180 and 181 illustrate typical arrangements for three-wire direct-current generator panels. For such installations it is necessary to use two circuit breakers and also two ammeters, which are placed in the two outside lines. The equalizer switch may be mounted on the control panel or on a pedestal which is generally placed near the machine. A combination switch having two sets of contacts is sometimes used in the main line and equalizer circuits as shown at *B* in Fig. 180. For large-capacity installations it may be

Fig. 182.—Direct-current switchboard with carbon circuit breakers mounted on panels. (*Westinghouse Electric Corporation.*)

advisable to mount the circuit breakers on a separate panel which may be placed near the generator or at some other convenient place in the power plant. Such an installation is represented in Fig. 180 by *C* and *D*, and in Fig. 181. The circuit breakers are solenoid operated and controlled from the main switchboard panel as in *C* in Fig. 180.

Fig. 183.—Lighting panels. (*Westinghouse Electric Corporation.*)

Voltmeters are not as a general rule mounted on the switchboard panels, but on swinging brackets on the end panel, the voltage of any particular machine or circuit being read by means of a plugging arrangement. The field rheostats may be controlled by a small hand wheel on the panel itself. In some cases motor-operated rheostats controlled by proper switches located on the main panels are used.

A large direct-current power switchboard is shown in Fig. 182 and a medium-size lighting switchboard in Fig. 183.

**Fig. 184.**—Manually operated switchboard with switching equipment mounted in the rear. (*Westinghouse Electric Corporation.*)

**Fig. 185.**—Remote-control electrically operated switchboard of all-steel construction, equipped with miniature busses. (*Westinghouse Electric Corporation.*)

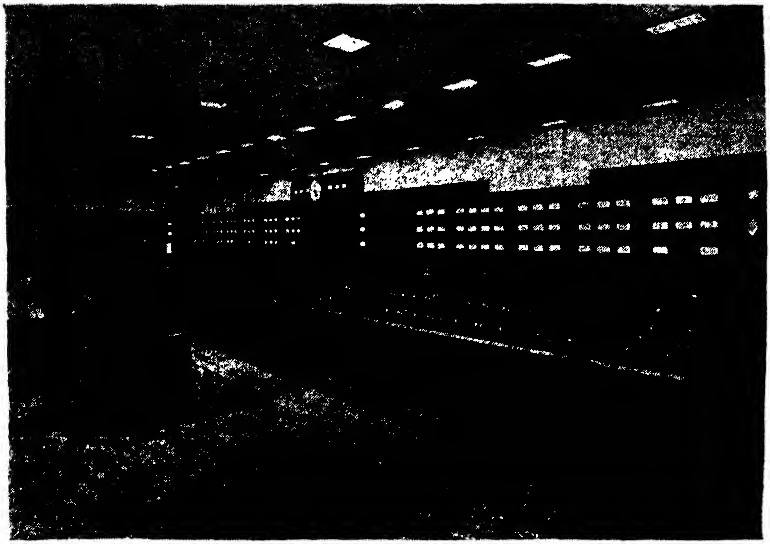


Fig. 186.—Control desk with instrument panels. (*Westinghouse Electric Corporation.*)

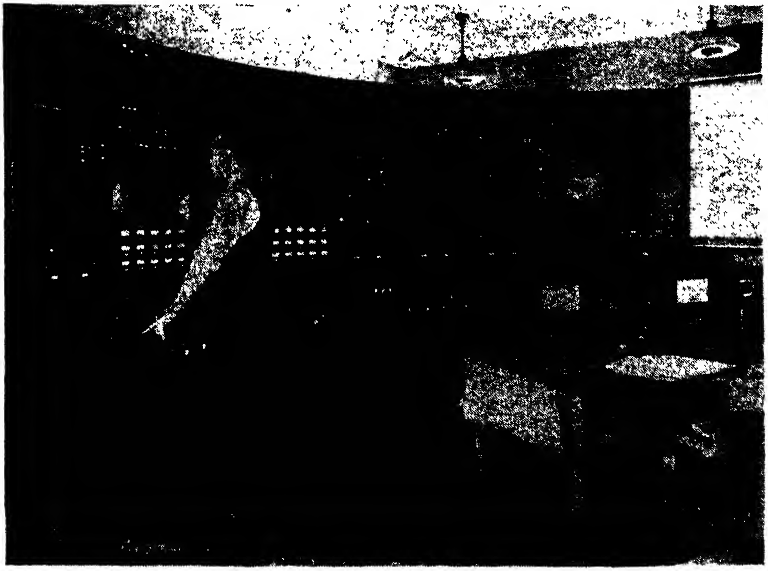


Fig. 187.—Circular-control switchboard, equipped with miniature busses. (*Westinghouse Electric Corporation.*)

*b. Alternating Current.*—There is no definite classification which can be given that will cover all types of alternating-current switchboards. Every application must be studied by itself and the proper type, construction, and arrangement of panels and equipment made accordingly. In the remainder of this chapter, however, a few of the outstanding types of alternating-current switchboards that are commonly found in power plants are discussed, no mention being made of the large number of special applications.

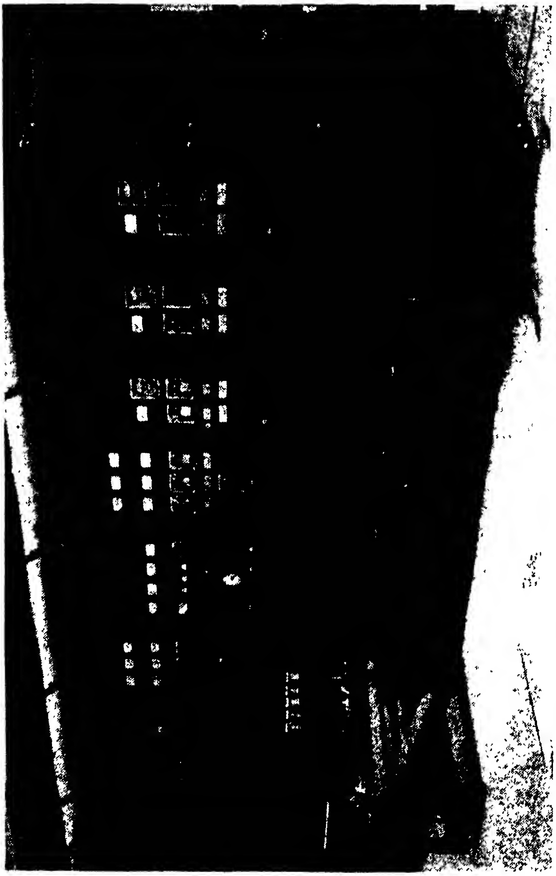


Fig. 188.—Truck-type switchboard. (*Westinghouse Electric Corporation.*)

**113. Methods of Control.**—The control of switchboards may be "direct manual," "manual remote," or "electrical remote."

The advantages and disadvantages and field of application of these three types of switchboard will be discussed in Chap. X. Electrical remote panels are shown in Figs. 185 to 187. A manual remote panel is shown in Fig. 184, while the rear view of a direct manual board is seen in Fig. 191.

**114. Switchboard Framework.**—The two standard types or frames used for switchboards are made of angle iron and tubular iron. The angle frames are made of standard 3- by 2- by ¼-in. angle iron, and the tubular frames are made up of 1¼-in. wrought-iron pipe. For small boards the tubular frame is undoubtedly the best selection. The lower part of these frames, which appears between the panel section and the floor, does not require any special covering to give a finished appearance. For large multisection panels the angle-iron frame offers some advantages. Where angle frames are used, the panel sections and the two panel uprights form a unit and may be handled as such in shipping and erecting; hence each unit can be completely wired by the manufacturer before delivery. For the tubular frame, however, one upright is common to two adjacent panels; hence, as a general rule, such panels are shipped unassembled.

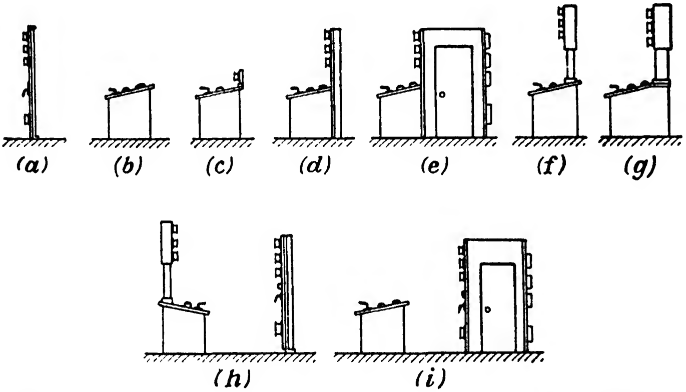
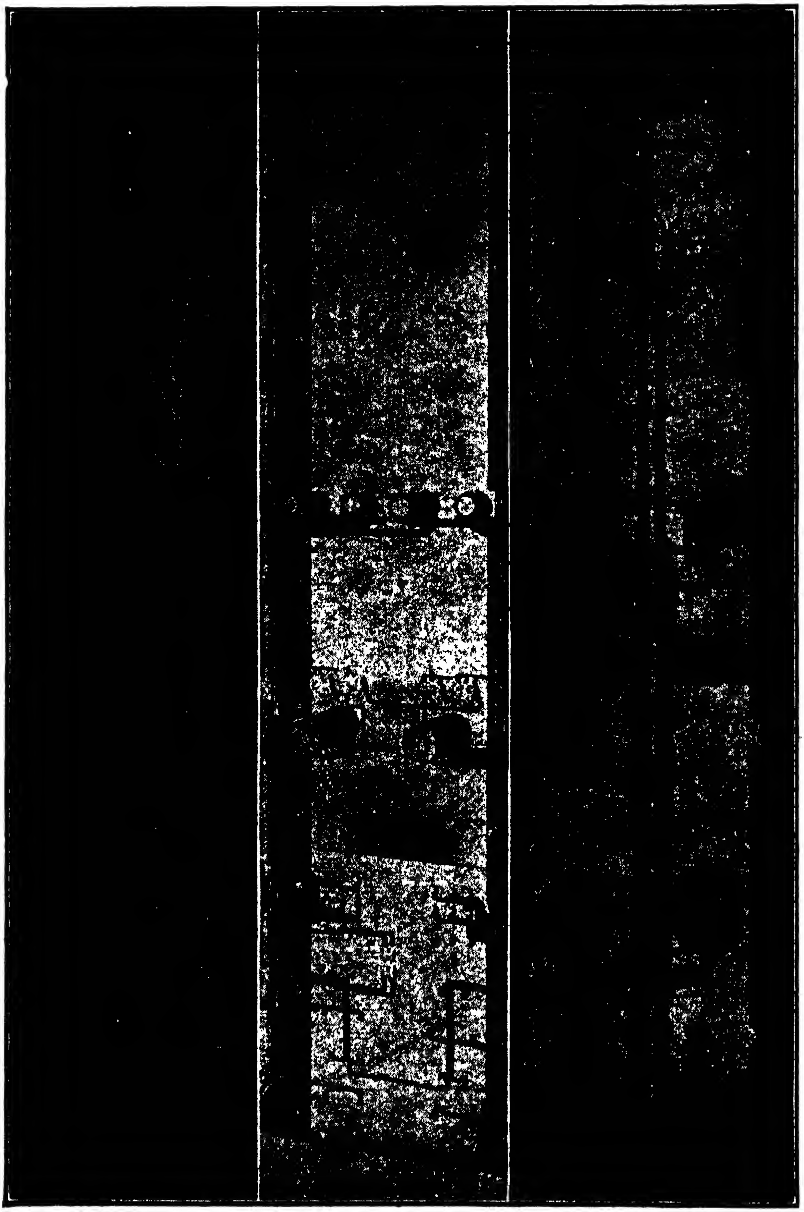


Fig. 189.—Various forms of control switchboards for electrically operated equipment. (*Westinghouse Electric Corporation.*)

**115. Panel Material.**—The materials generally used for switchboard panels are slate and asbestos ebony. In recent years all-steel switchboards have been built for boards that are subjected to very low potentials only.



*A*. Flat panel wiring. *B*. Angle-iron wiring. *C*. "L" bracket wiring.

FIG. 190.—Methods of wiring electrically operated switchboards. (*Westinghouse Electric Corporation.*)

*a. Slate.*—Natural black slate or black marine-finished slate are the two most common materials used for switchboard panels. Natural black slate is more expensive than the black marine-finished slate but has better electrical properties. Cheaper grades of slates are rubbed with oil to give a dull velvety black finish, known as black marine finish. Such a panel does not show oil stains and hence is well adaptable to boards that have oil circuit breakers mounted directly on the rear of the panels. Slate boards are not desirable for voltages over 600 to 1,200 volts.

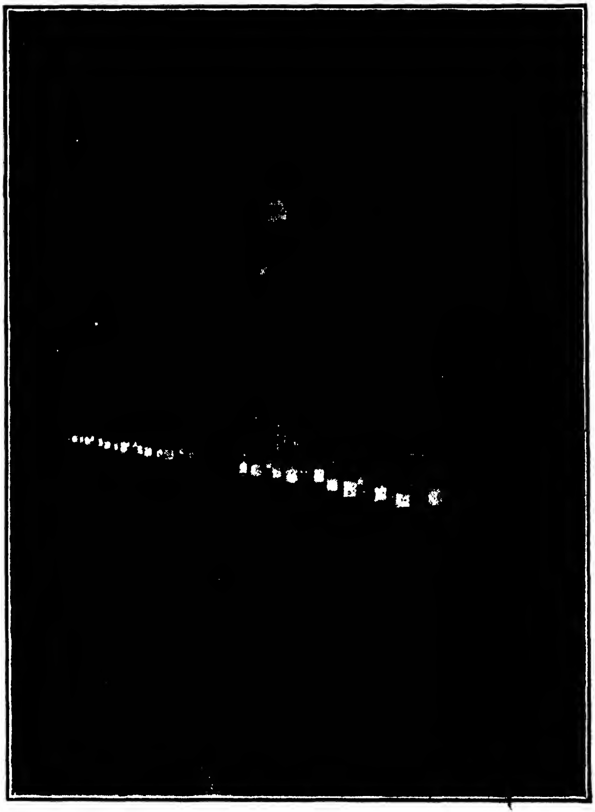


FIG. 191.—Rear view of 440-volt switchboard, showing circuit breakers mounted direct to the panels. (*Westinghouse Electric Corporation.*)

Marble may also be given a black marine finish similar to slate; hence certain high-voltage sections of slate switchboards may be made of black marine-finished marble.

*b. Asbestos Ebony.*—This material, which is manufactured by Johns-Manville Inc., is available in the form of sheets or simple molded forms made up of asbestos fiber thoroughly impregnated with binding cements under heat and pressure into a compound of very high dielectric strength. In appearance it resembles highly surfaced ebony or hard rubber. A few of its outstanding merits, according to the manufacturers' claims, are as follows: high dielectric strength, good insulation, ability to stand shocks and vibration, uniform density, light weight. It is unaffected by rapid temperature changes; does not shrink, crack, or buckle, is readily cut and drilled; and is not generally affected by chemicals. Other similar switchboard materials are also offered by other companies.

*c. Steel.*—With the absence of live parts, such as knife switches, on the front of modern electrically operated switchboards, steel panels are especially adaptable to this class of work. Comparing the steel panels with slate, some of the outstanding features in favor of the steel panels are as follows:

1. Lower cost in manufacture, shipment, erection, and maintenance.
2. About five times as light in weight.
3. Simplicity in erection, as the steel panel forms its own framework.
4. Easily maintained.
5. Unbreakable.

Where an occasional knife switch or other live part must be taken care of, the switch parts are mounted on an insulated base located behind the steel panel and actuated from the front by means of an insulated operating handle. Meters, relays, and other instruments must have their terminals properly insulated from the board by means of insulating bushings, or else suitable clearances are given the holes through which protrude the electrical conducting studs. An all-steel board is shown in Fig. 185.

**116. Arrangement.**—There are a large number of possible ways in which a switchboard may be arranged, but arrangements are generally made up of one or more of the following elements:

1. Vertical panels.
2. Control desk.

In Fig. 189 are shown a few typical arrangements. The simplest form shown by *a* is a vertical panel board, examples of which are shown in Figs. 182 to 185. The general arrangement of equipment on such a board is to place all essential meters at the top, all relays and nonessential meters at the bottom, and the control equipment halfway between the top and bottom of the board (see Figs. 184 and 185). A control desk may be used alone as shown at *b*, when there are only a few instruments which can be of the flush type. A slight improvement over arrangement *b* is obtained in *c* by placing the instruments on a small vertical panel at the back of the desk. For medium-sized plants the arrangement shown at *d* is common. In such a case all control equipment is located on the top of the desk and all essential meters on the vertical panel (see Fig. 186). In order to accommodate a large number of relays and nonessential meters, another vertical panel may be used in conjunction with arrangement *d*, such as illustrated at *e*. Sometimes switchboards are located in a gallery above the main generator-room floor in order that the operator may see the units that he is controlling. For such conditions, arrangements *f*, *g*, and *h* are well suited. Switchboards *f* and *g* are made up of control desk and a meter panel mounted above the desk by means of columns. Arrangement *h* is a combination of *f* and *a*. For large plants, where the number of circuits is large, an arrangement similar to *i* must be used, which is an expansion of *e*.

Any of the above arrangements may be mounted in a straight line, known as a linear switchboard, as illustrated by Figs. 185 and 186; or in the arc of a circle, known as a semicircular switchboard, as shown in Fig. 187. The semicircular switchboard has the advantage that all parts of the board can be seen by the operator with the least trouble. Its use, however, requires a large space and hence is sometimes rejected on that account. For small switchboards it does not offer any advantages over the linear type of board.

A special arrangement used for industrial substations and for central-station auxiliary circuits commonly known as the truck-type panel is shown in Fig. 188. The busbars are mounted in a steel housing, and the panel, circuit breaker, and instrument transformers are on a removable truck. Truck-type panels are equipped with either manually operated or electrically operated circuit breakers. The panels are usually made of steel. The principal advantages of the truck-type panels are as follows:

1. All live parts are totally enclosed, and mechanical interlocks prevent mistakes in operation.

2. All parts requiring inspection are on a removable truck which is "dead" on all sides when removed from the housing.

3. A truck may be replaced by a spare one in a few moments' time and the circuit breaker inspected without a prolonged interruption of service.

**117. Wiring of Electrically Operated Switchboards.**—The wiring of electrically operated switchboard panels should be done in a neat and orderly manner in order that extensions or repairs may easily be accomplished. Three typical methods in use are illustrated in Fig. 190.

**118. Instruments and Control Equipment.**—Below are listed the general instruments and other equipment that may be found on different types of switchboards.

*a. Alternating-current Generator Circuits.*—One alternating-current ammeter for balanced loads. For unbalanced loads one ammeter with a switching arrangement for reading the current in all lines should be used (see Art. 150), or a better scheme is to use one ammeter in each line.

One alternating-current voltmeter (may be omitted if common plant voltmeter is used).

One direct-current ammeter for alternator field (optional, but highly desirable).

One indicating wattmeter (optional).

One reactive volt-ampere meter (optional).

One power-factor meter (optional).

One frequency meter (optional).

One watt-hour meter (optional).

One field switch with discharge resistance clips.

One voltmeter switch for reading all phase voltages, with removable handle or plug.

One mechanism or control switch for controlling the generator field rheostat. If a separate exciter panel is not used, a mechanism or control switch for the control of the exciter-field rheostat is also essential.

One synchronizing outfit (not required for a single generator).

One control device for prime-mover governor (optional).

One control mechanism or control switch for operating generator oil circuit breaker.

Relays for generator protection (optional).

*b. Feeder Circuits for Motor or Power Service.*—One alternating-current ammeter for balanced loads, or one ammeter with ammeter switch, or one ammeter per phase.

One reactive volt-ampere meter.
One power-factor meter (optional).
One watt-hour meter (optional).
One circuit-breaker control, either mechanical or electrical.
Relay equipment.

*c. Transmission Lines to Substations or Tie Lines to Other Power Plants.*—Three ammeters or one ammeter with polyphase switching device.

One indicating wattmeter.
One reactive volt-ampere meter.
One power-factor meter (optional).
One voltmeter or voltmeter receptacle (optional).
One watt-hour meter (optional).
One synchronizing outfit (required for tie line only).
One control for oil circuit breaker.
Relays (optional).

*d. Synchronous Motor Panel.*—One alternating-current ammeter.

One direct-current field ammeter.
One indicating wattmeter (optional).
One power-factor meter (optional).
One field-rheostat control.
One field-discharge switch or switch control.
One synchronizing outfit (not required if motor is self-starting).
One control for oil circuit breaker.
Relays.

*e. Synchronous Condenser Panel.*—One alternating-current ammeter.

One direct-current field ammeter.
One wattless indicating volt-ampere meter.
One field-rheostat control.
One field-discharge switch or switch control.
One control for oil circuit breaker.
Relay equipment.

**119. Miniature Bus.**—For the proper and efficient operation of electrically operated switchboards, a miniature bus is desirable.

The miniature bus is a skeleton or single-line diagram of all main circuits of the station, with devices for indicating the relative location of all circuit breakers, disconnecting switches, generators, power transformers, and feeder circuits. The miniature bus is generally made of polished copper strap run along the top of the control desk or, in the case of a vertical board, on the face of the panel (see Fig. 185). For stations having circuits at different voltage it is highly desirable to indicate the different voltages by means of different finishes given to the miniature bus. Red and green lamps are generally placed in the miniature bus to indicate the position of switches, circuit breakers, or other equipment. The red light generally indicates that the switch or oil circuit breaker is closed, and the green light the open position.

### Questions for Class Discussion

**1.** Describe the general arrangement and type of equipment usually found on switchboards for direct-current service; for two- and three-wire generators, for general lighting, and for general power panels. Why should carbon circuit breakers be placed at the top of the panel?

**2.** When several direct-current generators are operated in parallel, why is the equalizer switch often mounted on a separate pedestal located near the machines?

**3.** How can alternating-current switchboards be classified with respect to their mode of control?

**4.** Is the tubular or the angle-frame construction the better for large switchboards? Why?

**5.** Tabulate the advantages and disadvantages of slate, and steel as panel materials.

**6.** What physical characteristics of slate makes it unsuitable for high-voltage switchboards?

**7.** What general considerations must be kept in mind in grouping various switchboard panels?

**8.** Name four distinct types of switchboard arrangements, and give some of the more common combinations that are found in practice. What factors go to determine the particular arrangement for a given installation?

**9.** What is the maximum voltage that is generally allowed on the switchboard of a remote electrically controlled installation?

**10.** Describe the general methods of wiring remote electrically controlled switchboards.

**11.** What are the relative merits of linear-type and semicircular switchboards?

**12.** In the case of a vertical-panel and control-desk type of installation, what is the general arrangement of meters, relays, and control equipment? How would this equipment be placed on a single vertical-panel installation?

**13.** Name the principal measuring instruments used in central stations. Which are used for direct-current installations? Which for alternating-current installations? Which for both?

**14.** What additional features must be taken into account in the equipment of alternating-current switchboards over those of direct-current boards?

**15.** An indicating wattmeter is not necessary on a direct-current generator panel. Why is it necessary on an alternating-current board?

**16.** If a wattmeter is used on an alternating-current board, why is an ammeter also required?

**17.** Name the meters and other equipment that are generally found on the following switchboard panels: (*a*) alternating-current generator, (*b*) feeder circuits, (*c*) transmission lines, or tie lines, (*d*) synchronous motor, (*e*) synchronous condenser.

**18.** Explain the purpose of a miniature bus. How are circuits of different voltages distinguished from each other? How are the relative position and operation of circuit breakers and switches designated?

# CHAPTER X

# SWITCHING EQUIPMENT

**120. General Considerations.**—Switching equipment of a plant or a system includes all the busbar structures, switch houses or cells, operating circuits or mechanisms of circuit breakers or switches, switchboards, or in other words the entire system that has to do with the control and distribution of power in a plant. The selection of suitable switching equipment for any power plant or system, whether for direct current or alternating current, will be governed by many conditions, their relative importance being different for different installations. The most important are named below:

1. Maximum safety to life and property.
2. Continuity of service.
3. First cost.
4. Available space.
5. Desired operating features.
6. Voltage of plant and system.
7. Capacity of plant and system.

**121. Types of Switching Equipment.**—The heart of the control system of a plant is its switchboard; hence it is to be expected that the type of switching equipment is to a great extent determined by the class of switchboard used. The classification given below is therefore the same as the one given for switchboards (see Art. 113).

*a. Direct Manual.*—In this system all switches, circuit breakers, busbars, and other apparatus of control are mounted either upon the back of the switchboard panels or upon frame work directly back of the panels.

*b. Manual Remote.*—In this system the oil circuit breakers and busbar structures are mounted at some distance from the switchboard, the circuit breakers being operated by hand through connecting rods, chains, bell cranks, etc. (see Fig. 192).

*c. Electrical remote control,* which uses electrically operated equipment located apart from the switchboard and operated by means of control switches mounted on the panels.

**122. Applications and Limitations of the Different Types of Switching Equipment.** *a Direct Manual Control.*—Practically all the direct-current switching will fall under this class. The capacities of direct-current stations are rather low, the maximum voltage seldom exceeding 1,500 volts. Direct-current installations can be divided into two general classes: those for relatively large capacities, such as direct-current railways systems, lighting and power for large industrial plants, hotels, central stations, etc.; and those for small capacities which include a very large field, such as for lighting and power in small industrial plants, small hotels, and small central stations, together with a large number of special applications of direct current, such as for battery-charging sets, and elevators.

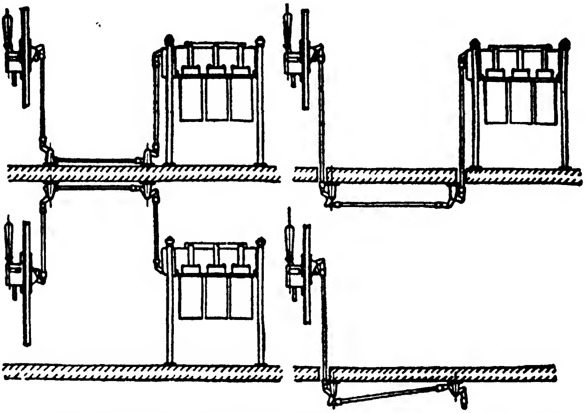


FIG. 192.—Standard arrangements of manual remote control.

In the case of alternating-current installations, experience has shown that for the usual conditions of service this class of switchboard should not be applied to stations whose capacity exceeds 3,000 kva. in the case of three-phase, 2,000 kva. in the case of single-phase, and 4,000 kva. in the case of two-phase stations. Moreover it is considered good practice to confine its application to 2,500 volts or less and only in rare cases go to higher voltages with 6,600 volts as the limit. The reason for this limitation lies in the danger to attendants from high-voltage apparatus when in close proximity to low-voltage control and instrument wiring, rheostats, etc., which require inspection and occasional repairs; and also in the necessity, with the higher voltages, of longer and higher switchboards to gain sufficient spacing distances. It is recommended that the size of individual circuit breakers and switches for this type of switchboard be limited to 800 amp. or less per pole at 2,500 volts because of the following reasons:

1. The advisability of limiting the amount of power handled by one circuit breaker mounted directly on the panel.

2. The difficulty in obtaining adequate installation distances between the heavy busbars and connections required for larger capacities.

3. The mechanical strains imposed upon the panels by the large capacity circuit breakers with their heavy connections due both to their dead weight and to the shock of operation.

*b. Remote Manual Control.*—The advantages gained by the use of remote manual control over that of the self-contained direct-control boards may be summarized briefly as follows:

1. As a "safety-first" feature all high voltages are removed from the panels, thus allowing ready inspection of the instrument and control wiring and preventing the chance of injury to attendants.

2. The panel board can be located to much better advantage when considering the remainder of the installation, because less space and protection are required.

3. Panels are not subject to the mechanical strains due to automatic operation or to dead weight of heavy switchgear.

4. Violent explosions may sometimes occur, on opening severe short circuits, by circuit breakers, but they will not injure the panels nor be communicated to other circuits, if the circuit breakers are sufficiently spaced or enclosed in fireproof cells.

5. Panel widths may be reduced 15 to 50 per cent, this saving quite frequently offsetting the additional expense of the remote-control mechanisms.

6. The more compact arrangement of meters, instruments, and switches, resulting from the use of narrow panels, greatly assists the operators, approaching more nearly the compact and efficient arrangements obtained by the use of control desks.

7. Decrease in length of main cables from machines and feeder outlets by locating the circuit breakers in close proximity to the bus structures.

8. Isolation of exposed high-voltage wiring and bus structures in separate switch rooms.

In comparison with the electrically operated board, the remote mechanically operated board usually occupies 5 to 50 per cent more space, although the circuit breakers and busbars for a given capacity will be practically identical. Many of the plants of smaller capacity which could readily have used panel-mounted apparatus have felt justified in incurring the small extra expense necessary to provide the remote mechanical control. Many of the large central stations and transmission companies, while using electrically operated equipment in their main generating and transforming stations, have adopted remote control for the same class of apparatus in their substations.

Remote manual-control switchboards are restricted in their application by mechanical, rather than electrical, characteristics. They are applicable where the simplicity of connections or accessibility desired cannot be obtained with panel-mounted apparatus, where station capacity or voltage is so high as to make it desirable to mount oil circuit breakers apart from the panels, and where station arrangement permits the use of manually operated remote-control oil circuit breakers.

The mechanical limitations in applying these switchboards are (1) the distance from the switchboard panels to the corresponding oil switching device, and (2) the power required to operate the switching devices through the system of bell cranks and connecting rods.

It has been found from experience that this type of switchboard should be confined to the use of circuit breakers of 2,000-amp. capacity or less and of 50,000 volts or less, indoor service, and to stations whose capacity does not exceed 25,000 kva., three-phase. In general, remote manual control is not recommended for outdoor stations. This is on account of the long operating rods usually required and, for stations in northern climates, the difficulty in properly protecting bell cranks, shafts, etc., against ice and sleet. If outdoor stations are of any appreciable importance and size, electrically operated breakers are justified even though they cost 25 per cent more.

*c. Electrically Remote Control.*—As in the application of the self-contained or remote manually controlled switch-board, there is no well-defined field to which any of the different combinations of electrical control is confined. More than in any other type of switchboard does the electrically operated panel approach the ideal of the designing engineer, as it is almost entirely uninfluenced by the form of apparatus that it controls. This fact accounts for the great variety of combinations of panels. The actual detail of some of the panels in use, together with the meters and controlling devices, are covered in Chap. IX. There are certain general conditions that influence a choice of design and that must be recognized before a satisfactory arrangement of switching layout is obtained. The most important of these are the following:

1. The capacity of the station.
2. The number of generators, feeders, bus ties, and exciter units to be controlled.
3. The relative proportion of feeder to generator circuits.
4. The scheme of busbars and interconnections.
5. The location and arrangements of the switchboard gallery or room as regards the location and arrangements of the station apparatus.
6. The first cost and maintenance cost.
7. The number and kind of instruments and control devices to be used.

There is practically no limitation to the application of the remote electrically controlled switchboard, if the necessary control source is available. It finds its greatest use, however, in plants of heavy capacities requiring electrically operated apparatus, or where the distance between the board and switching devices makes the application of hand-controlled apparatus undesirable or even impossible.

**123. Methods of Mounting Switching Equipment.**—The choice of the proper form of structure for the apparatus that is to be manually remote controlled and the satisfactory arrangement of the apparatus thereon present a more difficult problem than do the design and arrangement of the panels themselves. The reason lies in the many practical forms of structure and the large number of arrangements of the apparatus which may be made upon each of the various forms. As a general rule, the methods of mounting the equipment may be classed under one of the following five heads:

1. Wall mounting, in which all apparatus and busbars are either mounted directly on or supported from a wall of the building.

2. Framework mounting, in which all apparatus and busbars are mounted on a framework of iron-pipe or structural-steel shapes or a combination of the two.

3. Combination wall and framework mounting.

4. Concrete or masonry structure mounting, in which all apparatus and busbars are mounted in cells or compartments.

5. Combination concrete and structural mounting, in which circuit breakers are mounted in concrete cells; remaining apparatus and busbars on iron framework, which may be either pipe or structural-steel shapes.

Many modifications of these arrangements are made as conditions and surroundings warrant. Cells of asbestos, lumber, slate, soapstone, molded concrete, or other suitable materials are frequently used to enclose circuit breakers and busbars.

**124. Remote Manual-control Mechanism.**—The remote mechanism that is used in most cases for switches and circuit breakers consist of a series of levers and rods. The direction of the operating force is always linear, changes in direction being made by means of short levers on a fixed fulcrum commonly known as "bell cranks." The connecting rods are commonly made of ¾-in. iron pipe, as it is cheap, usually easy to obtain, and naturally well suited for the purpose. Wooden rods are sometimes used because of their light weight, and in some cases such as for field switches or disconnecting switches, on account of their insulating properties.

**125. Bus and Switch Structures.**—In discussing bus and switch structures of power plants, distinction should be made between the low-tension and high-tension structures. There are a number of installations in which the high-tension bus structures are placed indoors, notwithstanding the fact that there is a general tendency in modern power-plant design to place all the step-up transformers and high-tension switching equipment outdoors, leaving only the low-tension equipment indoors. All outdoor switching structures take the general form of outdoor substations, which are covered in Chap. XIX.

**126. Low-tension Bus Structures.**—In Art. 123, five different methods of mounting switching equipment were given. The first three methods comprise very low voltage and capacity systems which are, therefore, relatively unimportant. The last two, however, are applicable to large central stations and will therefore be discussed more in detail.

As higher generator voltages and capacities are used, it becomes practically necessary to enclose completely the busses and switching equipment, in order to guard against personal injury, and also maintain all circuits of different polarities apart from each other, thereby minimizing the possibility of short circuits between phases. In addition to promoting safety of operation, enclosing the bus structure also gives to the plant a finished and orderly appearance, which is conductive to better operation and maintenance. The actual cost of properly enclosing all the bus structure is small in comparison with the cost of the entire plant. The particular type of construction chosen will depend to a great extent on the particular type of plant-circuit layout (see Chap. VI), but operating and local conditions will also have a great influence in determining the actual structures. A few typical arrangements are shown in Figs. 193 to 196. Some of the important features of the system, which must not be overlooked, are as follows:

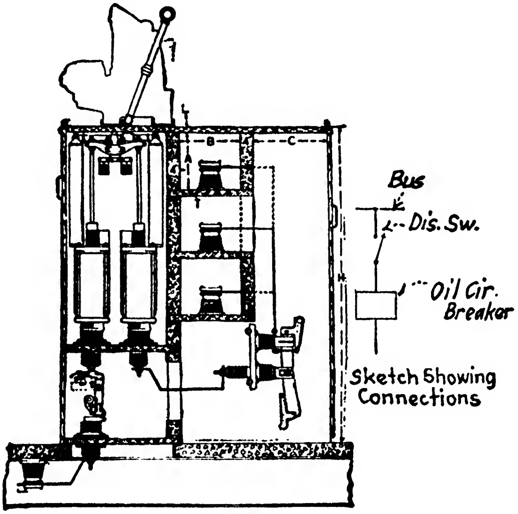


FIG. 193.

1. All dimensions of the cells or compartments must be adequate. The dimensions are determined by the minimum allow-

able distance between conductor and ground which is dictated by the voltage of the system.

2. All openings, such as at the circuit-breaker compartments, should be provided with doors of strong but light and fireproof material and should be removable to allow free access when repairs are necessary.

3. Circuit breakers should be placed in such positions that the least amount of damage is done in the case of an explosion of the breaker tank.

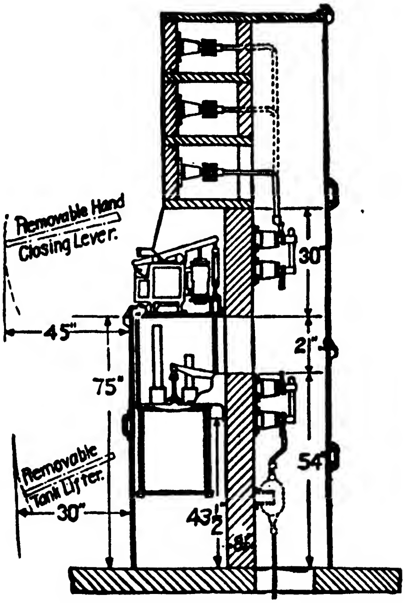


Fig. 194.

4. Disconnecting switches must be located in easily accessible places, so that they may be opened or closed without difficulty.

5. Ample provision must be made for the location of current and potential transformers, which are essential for metering and protective purposes.

6. All busbar supports must be accessible in order that damaged supports may be easily replaced. For this purpose openings in the busbar cells are generally left at the points where the supports are located.

7. Allowance must be made for busbar expansion and contraction.

8. Sufficient radiating surface must be provided. For heavy currents it is common practice to laminate the busbars.

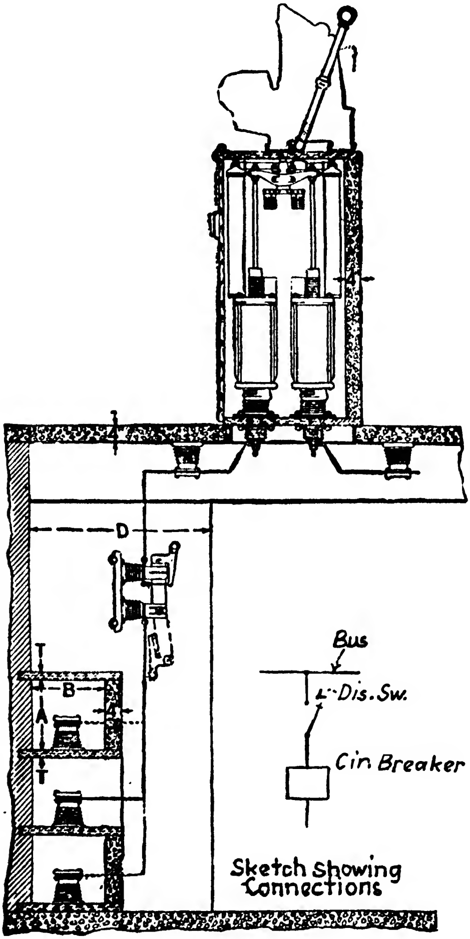


Fig. 195.

9. Busbar supports must be securely clamped or bolted to the framework or cell walls and placed at enough points properly to resist the stresses set up during heavy short circuits.

In the case of medium-capacity systems a much cheaper arrangement can be used, such as a combination of cell and framework as shown in Fig. 197. Such an arrangement is more open than the previous ones (Figs. 193 to 196), but with proper care it can be made perfectly satisfactory.

A unique arrangement of bus structures will be occasionally found in large central stations. In this arrangement,

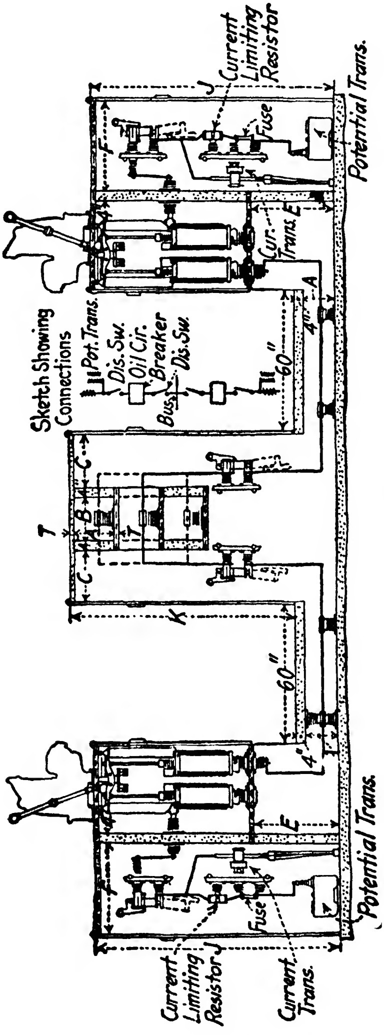


FIG. 196.

generally known as the "isolated-phase arrangement," each phase of the three-phase circuit is entirely isolated from the other two, thus minimizing as far as possible the chances for short circuits.

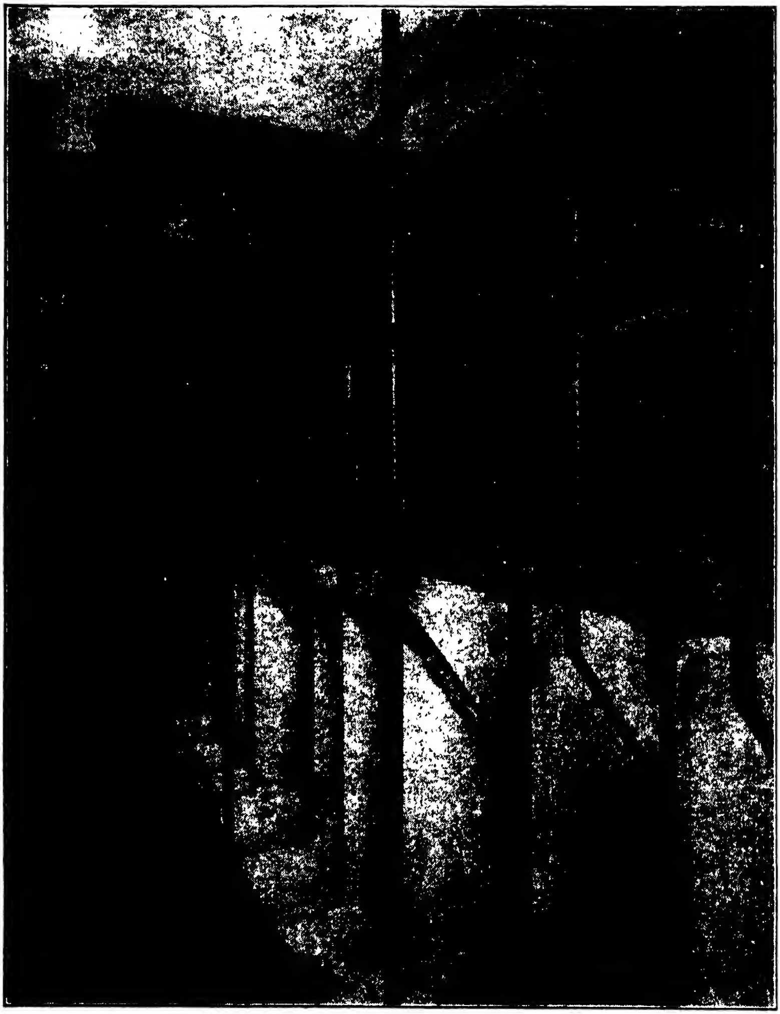


FIG. 197.—Typical method of supporting low-tension bus bars. (*Delta Star Electric Company.*)

One standard arrangement is shown in Fig. 198. Each individual unit of the circuit breakers is mounted in a separate concrete chamber, while the common operating mechanism is mounted on the top of the upper cells. A pipe mechanism passing through the concrete walls connects the units in such a way as to cause simultaneous operation. The disconnecting switches are similarly controlled.

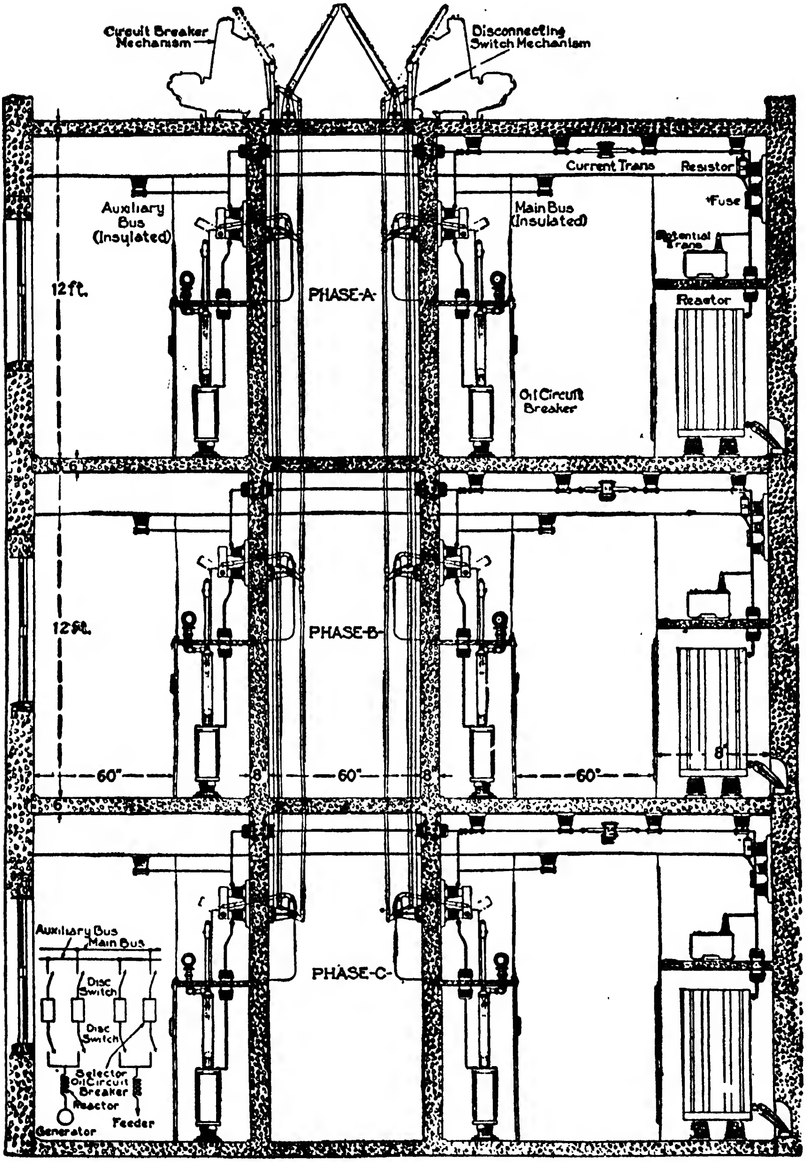


FIG. 198.—Isolated-phase arrangement with vertical separation of phases.

Of late years there seems to be a tendency toward completely enclosed and insulated switchgear. With this in mind, manufacturers have developed the so-called metal-clad switchgear.

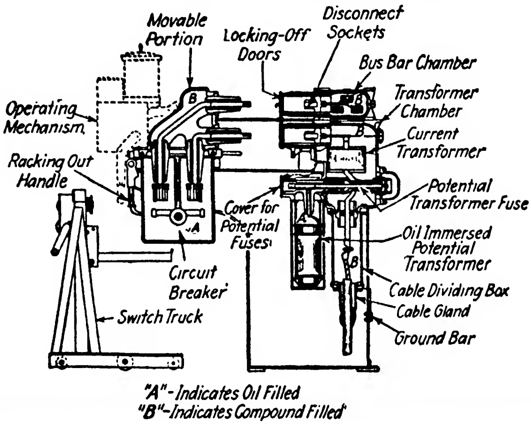


FIG. 199.—Sectional view of Reyrolle switchgear.

FIG. 200.—Installation of Reyrolle switchgear.

A typical example of this equipment is the Reyrolle switchgear as made by the Allis-Chalmers Manufacturing Company, see Figures 199 and 200.

For convenience, the unit is usually divided into two parts, the fixed portion and the movable portion. The fixed portion includes the supporting framework, busbars, disconnect sockets, current transformer chamber, dividing box, and those parts which are fixed in position. The movable portion constitutes a complete assembly supported by the fixed portion and housing the oil circuit breaker with its operating mechanism and disconnect plugs. The sectional view (Fig. 199) is typical of the design for the horizontal drawout switchgear units. In these types all live parts are either embedded in insulating compound or immersed in oil, and the whole is enclosed within grounded metal casings, which form the exterior covering.

**127. High-tension Bus Structures.**—For high-tension voltages the necessary distance between lines becomes so great that it is not economical or practicable to enclose the bus structure in cells or compartments as is the case with low-tension circuits. In Table XI are given the approximate spacings necessary between rigid conductors and between conductors and ground for practically all voltages now in use. The bus structure for high-tension circuits, therefore, is entirely open and, in order to secure safety of operation, must be so arranged that all live parts are well out of reach. A common method used for indoor installations of this nature is to fasten the high-tension busses and disconnecting switches to the ceiling of the high-tension bus room and mount the oil circuit breakers on the floor or on proper framework so that the top of all bushings is well out of reach. The disconnecting switches are generally arranged so that they can be operated from the floor by means of rods and bell cranks. It is evident that the building space necessary to house high-tension equipment is rather large; hence in a good many modern installations all such equipment is placed outdoors.

Since the current is relatively small, the busbars are generally made of copper tubing, but in some cases iron pipe has been used. The bus supports often are composed of standard suspension-unit insulators as used on transmission lines. For cases requiring absolute rigidity high-tension column insulators are used, but as far as possible these should not be subjected to great bending stresses. Flexible cable is sometimes used, particularly as the leads to bushings of circuit breakers or switches. When used for the entire bus structure, a greater number of supporting insulators must be used in order that the entire installation have the proper degree of rigidity.

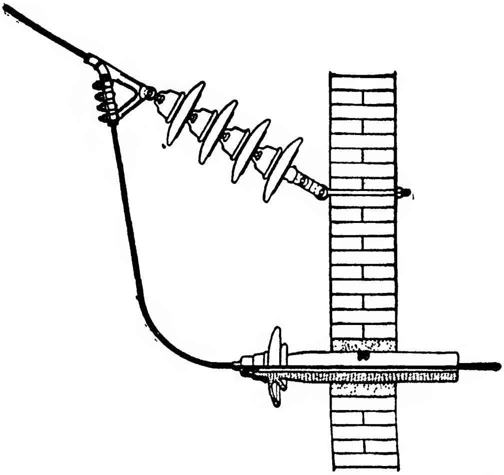


FIG. 201.—Typical wall entrance for high voltage. (*Ohio Brass Company.*)

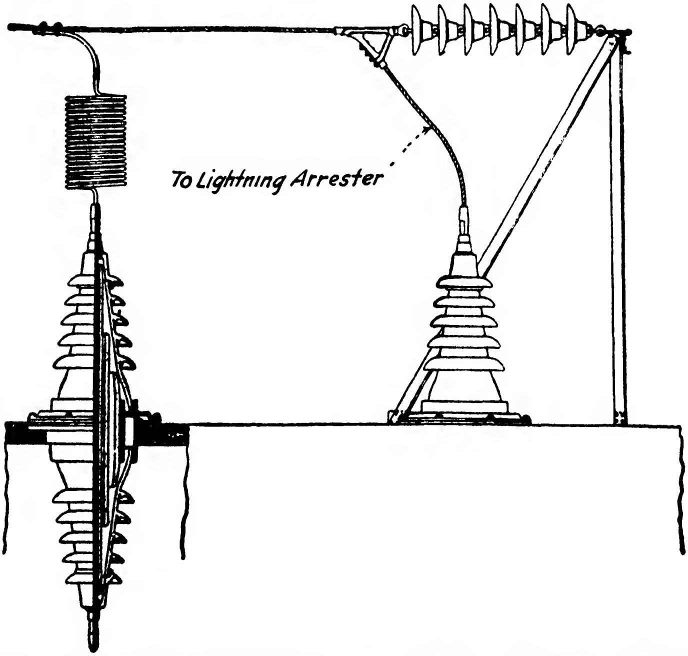


FIG. 202.—Typical roof entrance for high voltage. (*Ohio Brass Company.*)

TABLE XI.[1]—SPACING OF RIGID CONDUCTORS

| Voltage range | Dimensions in inches | | | |
|---|---|---|---|---|
| | Outdoors | | Indoors | |
| | To ground | Between live parts | To ground | Between live parts |
| 2,000 to 3,500 | 3½ | 4 | 3 | 3½ |
| 3,501 to 7,500 | 5½ | 6 | 4½ | 5½ |
| 7,501 to 15,000 | 9 | 10 | 7 | 9 |
| 15,001 to 25,000 | 14 | 15½ | 10½ | 14 |
| 25,001 to 37,000 | 19½ | 22 | 14½ | 19½ |
| 37,001 to 50,000 | 25½ | 29 | 19 | 25½ |
| 50,001 to 73,000 | 36 | 41 | 27 | 36 |
| 73,001 to 95,000 | 47 | 53 | 34½ | 47 |
| 95,001 to 115,000 | 56 | 64 | 41 | 56 |
| 115,001 to 135,000 | 66 | 75 | 48 | 66 |
| 135,001 to 155,000 | 75 | 86 | 55 | 75 |
| 155,001 to 175,000 | 85 | 97 | 62 | 85 |
| 175,001 to 195,000 | 94 | 108 | 69 | 94 |

[1] RUSHMORE and LOF, "Hydroelectric Power Stations."

Corrections for Altitude

| | |
|---|---|
| Sea level to 1,000 ft | Use table |
| 1,000 to 3,000 ft | Add 10 per cent to spacing in table |
| 3,000 to 5,000 ft | Add 20 per cent to spacing in table |
| 5,000 to 7,000 ft | Add 30 per cent to spacing in table |
| 7,000 to 9,000 ft | Add 40 per cent to spacing in table |

The problem of bringing a high-tension wire out of a building must be carefully worked out. Two typical methods of doing this are shown in Figs. 201 and 202. The problem is essentially the same as that found in high-tension transformers and circuit breakers requiring expensive bushings.

### Questions for Class Discussion

**1.** Name some of the factors that must be considered when deciding upon a particular type of switching equipment.

**2.** Name the distinct types of switching equipment and specify the particular field of application for each type.

**3.** What are some of the limitations of "direct-control switchboards"?

**4.** Name a few of the advantages gained by the use of the "remote manual control" over that of the self-contained direct-control boards.

**5.** What are the general limitations of the "remote type of control"?

**6.** Is there any essential difference in switching practice in high- and low-voltage plants? What values would be considered as high voltage, and what as low?

**7.** Compare, for example, (*a*) small isolated plants, (*b*) large hydroelectric developments.

**8.** Why do large modern stations use the more expensive remote electrical control of circuit breakers?

**9.** In some systems the circuit breaker at the powerhouse end of a feeder has remote electrical control while a breaker of the same rating in the substation is manually operated. Justify this practice. What other difference would you expect?

**10.** Give a brief description of the remote manual-control mechanism.

**11.** Give a brief description of the method generally employed in large plants for mounting and enclosing the low-tension busses and switching equipment. Illustrate by a few sketches.

**12.** Enumerate some of the factors that must be carefully considered when designing a system of low-tension bus structures.

**13.** What is meant by the so-called "isolated-phase" arrangement of busses and switch structures? Illustrate by sketches.

**14.** Why are not the high-tension busses and switching equipment enclosed in cells or compartments in a similar manner used for the low-tension bus structures?

**15.** Describe a typical method for supporting the high-tension busses and switching equipment in an indoor installation.

**16.** Discuss the details of the construction and operation of the completely enclosed types of switchgear. What are the advantages of this equipment over the standard forms of open switchgear.

# CHAPTER XI

## SWITCHING AND CONTROL DEVICES[1]

**128. Purpose.**—Under the general head of switching and control devices are included all types of switches, fuses, circuit breakers, and a large number of other devices, the purposes of which are to make, break, or change the connections in an electric circuit, under either normal or abnormal conditions.

**129. Switches.**—The most important types of switches fall in one of the following classes (*a*) knife switches, (*b*) disconnecting switches, (*c*) air-break switches, (*d*) control switches, (*e*) auxiliary switches, (*f*) oil switches.

*a. Knife Switches.*—Such switches are used to open and close circuits of low voltage and current capacity. They are extensively used in lighting and small power circuits as shown in Fig. 183. In order to protect such low-capacity circuits against overloads and short circuits, it is necessary that proper fuses be connected in series with the switch blades.

*b. Disconnecting Switches.*—For power circuits it is necessary to use some type of circuit breaker to open or close the circuit. In order to isolate the circuit breakers, it is generally considered good practice to connect knife switches in series with the circuit breakers. Such knife switches are known as disconnecting switches. They should never be opened until the circuit breaker in the same circuit has been opened, and should always be closed before the circuit breaker is closed. They are not designed to break currents and should, therefore, never be opened while current is flowing in the line. In Fig. 203 is shown a typical indoor heavy-current low-tension disconnecting switch. There is no definitely fixed rule as to where and how such switches must be used, but as a general rule they should be used on both sides of circuit breakers or in such a manner that it may be possible to deaden both sides of the circuit breakers in order that repairs or replacements may be made without any danger.

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[1] Ten Years of Progress in Circuit Interrupters, *Elec. Eng.*, Vol. 60, No. 11, p. 523, November, 1941.

It is also advisable to connect the switches in such a manner that when opened the blade will be dead. A number of diagrams illustrating the application of disconnecting switches are shown in Figs. 96 to 111. Disconnecting switches may be operated by hand, either directly or by means of a wooden pole, or through a set of levers and bell cranks; or in the case of high-voltage

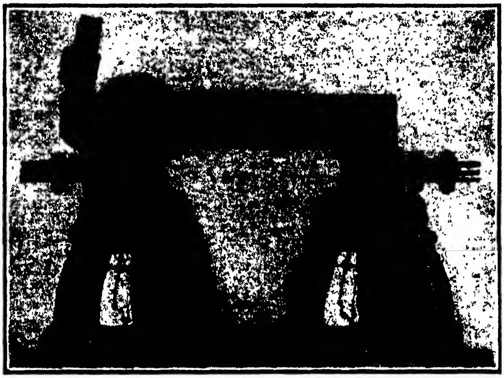


Fig. 203.—Heavy-current disconnecting switch. (*Ohio Brass Company.*)

Fig. 204.—Single-pole 30,000-volt air-break switch. (*Hi-Voltage Equipment Company.*)

switches the control may be done electrically. Disconnecting switches for high-voltage circuits will be discussed more in detail in Chap. XXI.

*c. Air-break Switches.*—By "air-break" switches are meant switches designed to open circuits under load. They are generally used outdoors for circuits of medium capacity, such as lines supplying an industrial load from a main transmission line or feeder. In order to take care of the arc that occurs on opening such a switch, special arcing horns are provided, so that the arc may rise and be ruptured. Air-break switches are built for about 135,000 volts maximum, but their use is in general confined to lower voltages. These switches are not designed to open under abnormal conditions, such as short circuits. Figure 204 shows a typical air-break switch.

*d. Control Switches.*—This class includes all switches that are used to control the operation of other equipment. As a general rule, they are designed for operating voltages less than 250 volts and very small current capacities. The types generally used in power plants are illustrated on the switchboards of Figs. 185 to 187. In addition to these types there are a large number of special types, such as "rotating"- and "plug"-type instrument switches as illustrated in Chap. XII.

*e. Auxiliary Switches.*—In this class are included all switches or contactors that are actuated by some other control switch or device. In the control of power equipment, such as circuit breakers, it is impracticable to handle the operating current through the control switches on the switchboard; hence an auxiliary operating switch is placed near the circuit breaker, this switch being electrically operated by a control switch that may be located at any desired distance from the circuit breaker. Thus the control circuits may be designed for very small currents, while the operating circuits as a general rule must handle much larger currents and very often at higher voltages.

*f. Oil Switches.*—For certain applications at high voltages and large current capacities it is desirable to immerse the switch contacts under oil. The effect of the oil is to cool and quench the arc that tends to form when the circuit is broken.

*g. Magnetic-impulse Switches.*—In this type of switch the arc is extinguished by blowing it magnetically into arc chutes where it is lengthened cooled, and interrupted. The magnetic effect is produced by the circuit current which is passed though suitable coils, setting up a strong magnetic field across the space between the switch contacts as they are opened. The basic principle involved in lengthening the arc is that of the simple motor, in which force is directly proportional to the product of magnetic flux and current.

**130. Fuses.**—Fuses are used to protect circuits of small capacity against abnormal currents such as overloads or short circuits. There is a large variety of fuses on the market, but the most important types that are used for power purpose are (*a*) cartridge fuses, (*b*) transformer fuse blocks, and (*c*) expulsion fuses.

*a. Cartridge Fuses.*—Cartridge fuses are composed of a strong fiber casing inside of which is enclosed a fuse wire, generally an alloy of lead. The fuse wire is fastened to copper caps which are fastened to each end of the casing. Figure 183 shows a lighting switchboard on which are shown a large number of cartridge fuses used in conjunction with knife switches. Fuses of this general type are available for circuits up to about 25,000 volts. There are on the market a large number of fuses of this general type, the particular details of construction being very varied. They are used as a protective device in low-capacity circuits, such as small lighting and power lines, and on the secondary of instrument-potential transformers, when used for metering or relay protection.

*b. Transformer Fuse Block and Cutout.*—The proper protection of distribution circuits has for years been recognized as best fulfilled by means of fuses. Distribution transformers are as a general rule placed on poles, towers, or in manholes and any automatic protection would be entirely too complicated and expensive. Fuses offer a simple and cheap method of protection. It is common practice to place these fuses in the secondary of such transformers, thereby protecting the transformer against short circuits or overloads. There are two types of fuses that are generally used for this purpose.

Both types include a porcelain housing, enclosing the fuse and contact points. In one type the fuse is carried on a plug that is provided with an insulating porcelain knob in order that it may be removed for re-fusing. A second type consists of a rectangular porcelain receptacle with a removable front door that carries the fuse.

*c. Expulsion Fuse.*—For higher voltages such as are found in power circuits or main feeders, there is often a demand for a fuse, on account of its simplicity. The expulsion-type fuse has been developed for such service (see Fig. 205). This device consists of a hollow tube, made of some heat-resisting substance such as fiber with a lining of asbestos or some other material, through which is passed a fuse wire. One end of the tube is closed and connected to the line; the other end is opened and allows the fuse wire to project out and connect to the other terminal. When a short circuit or overload occurs, the fuse is blown and a certain amount of gases form inside the tube. These gases in escaping to the air cause the arc, which is generally produced, to be blown out. Since there is always a tendency for an arc to occur, these fuses are adaptable only to outdoor use. They may be obtained for practically any modern transmission line voltage.

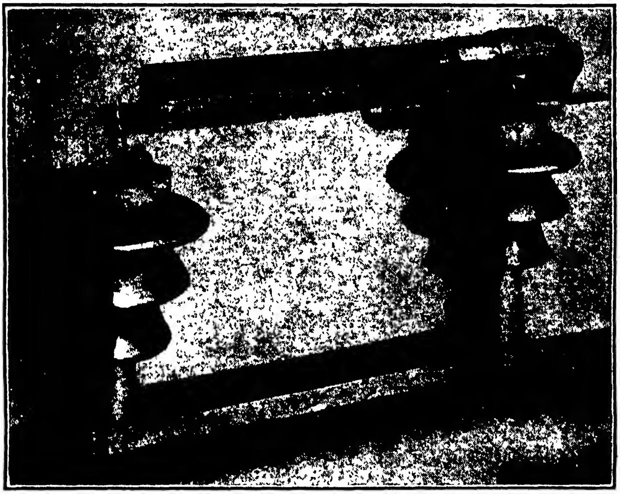


Fig. 205.—Expulsion-type fuse. (*Hi-Voltage Equipment Company.*)

**131. Classification of Circuit Breakers.**—There is probably no other part of a power system that is more important than the equipment that controls the system. All the control devices discussed above are suitable for only relatively small capacities, but for large capacities it is necessary to employ more dependable means of control, such as is obtained by the use of circuit breakers. Circuit breakers must be designed not only to carry the normal current of the circuit, but also to interrupt successfully the maximum current that might flow under abnormal conditions. They may be classified according to:

- Interrupting medium
  - Air
  - Air blast
  - Oil
  - Magnetic blast
- Service
  - Indoor
  - Outdoor
- Operation
  - Gravity opened
  - Gravity closed
  - Horizontal break
- Contacts
  - Butt
  - Wedge
  - Laminated, flat contact
  - Bayonet
  - Explosion chamber
  - Deion grid
- Action
  - Nonautomatic
  - Automatic
- Mode of control
  - Direct control
  - Remote control
    - Manual
    - Electrical
      - Motor
      - Solenoid
    - Pneumatic
- Tank construction
  - All poles in one tank
  - One tank for each pole
- Mounting
  - Panel mounting
  - Rear of panel
  - Remote from panel
    - Framework
    - Cell
    - Floor

**132. Air Circuit Breakers.**—In Fig. 206 is shown a typical carbon or air circuit breaker. As shown in Fig. 207 carbon circuit breakers have two or three contacts. To protect the main contacts against arcing or pitting, secondary copper contacts and also carbon contacts are provided. In low-capacity circuit breakers, the secondary copper contacts are omitted. When the circuit breaker opens, the sequence of operation is as follows: Main contacts open first, then the secondary contacts, and lastly the carbon contacts. In this manner the carbon contacts take most of the arcing, and since carbon is very refractory, the contacts are not damaged very much. In case of damage to either the secondary or carbon contacts, it is possible to replace these easily. Carbon circuit breakers are mostly used for direct-current service and in a few cases on low-voltage alternating-current service.

**133. Circuit Breakers.**—Standard oil circuit breakers may be classified according to their method of operation, as (*a*) gravity opened, (*b*) gravity closed, and (*c*) horizontal break. Several variations of these types are nevertheless found.

FIG. 206.—A 3,000- to 4,000-amp. carbon circuit breaker. (*Westinghouse Electric Corporation.*)

*a. Gravity-opened Type.*—This type, which is by far the most common, is illustrated in Figs. 208, 210, 213, and 214. The contacts are operated by an insulated rod which projects outside the tank (see Fig. 214). It will be noticed from Fig. 214 that the tendency is for the contacts to fall open due to gravity, and therefore they must be raised when it is desired to close the circuit breaker.

*b. Gravity-closed Type.*—Figures 211 and 212 show a typical circuit breaker of this type. An examination of Fig. 212 will

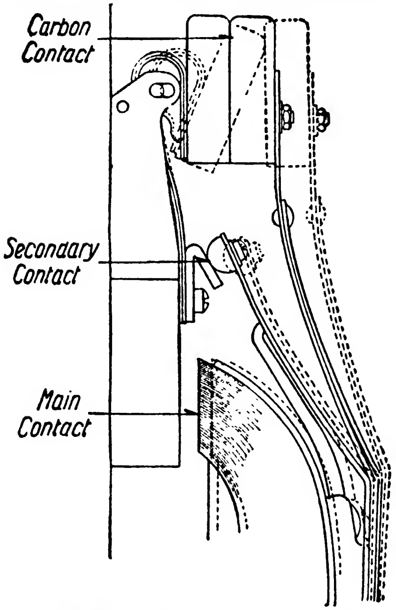


FIG. 207.—Outline showing sequence of operation of carbon circuit-breaker contacts.

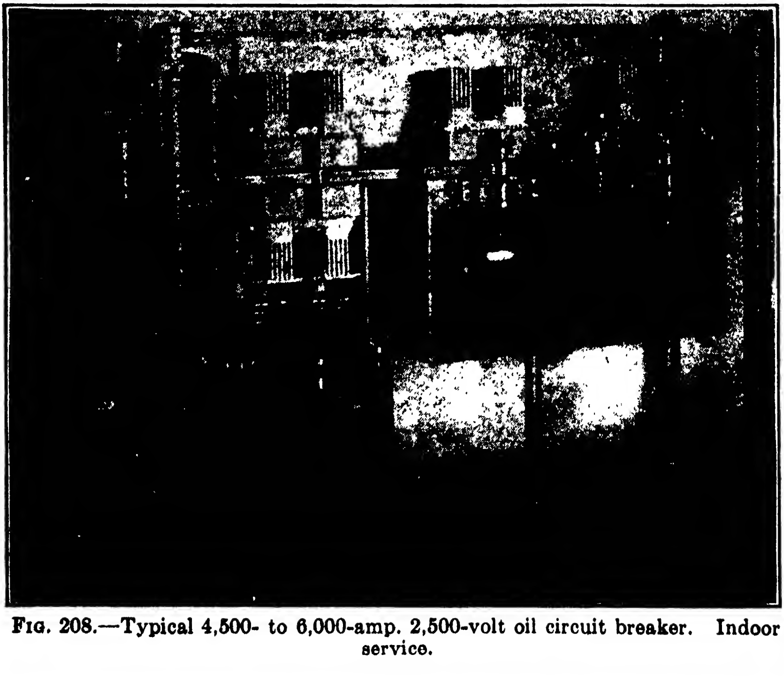


FIG. 208.—Typical 4,500- to 6,000-amp. 2,500-volt oil circuit breaker. Indoor service.

indicate that this circuit breaker will close under the action of gravity. The terminals are at the bottom of the tanks, the circuit being completed through the contact rods. It will be noticed that this circuit breaker is equipped with a set of main contacts located at the top of the tank. These contacts open before the arcing-rod contacts are opened and, hence, are not subjected to arcing and can, therefore, be located outside the tanks. This circuit breaker has two breaking points in series, but this particular type (Figs. 211 and 212) has each arcing contact in a separate oil tank, while the other types have only one tank per pole. In order that the gases formed due to the arcing at the contacts may escape, it is necessary to provide a proper outlet at the top of the tank. This outlet takes the form of a tube which is generally filled with quartz pebbles which help to separate out any oil that might otherwise be carried up by the gases.

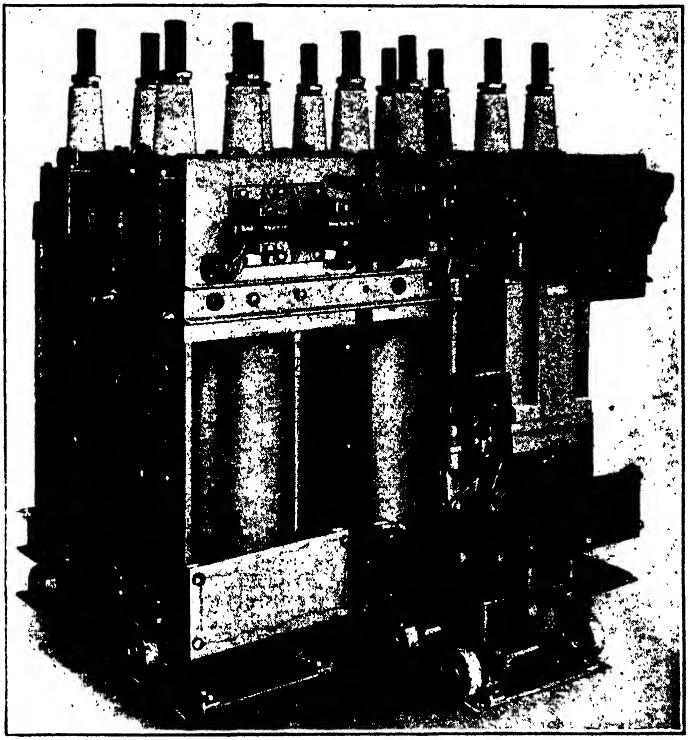


FIG. 209.—Typical indoor oil circuit breaker for about 15,000-volt service.

*c. Horizontal-break Type.*—In both of the types described above, the circuit is broken by contacts moving in a vertical plane; a third type has its contacts arranged for horizontal motion. This type is illustrated in Figs. 215 and 216. From Fig. 216 it is seen that the moving terminals can turn through an angle of 90 deg., thereby obtaining at least two breaking points in series. For high voltages it is possible to use a number of contacts in series, the particular one shown in Fig. 216 having six.

Fig. 210.—Type O. E.-6 oil circuit breaker. (*Westinghouse Electric Corporation.*)

*d. Air-blast Circuit Breakers.*—Air-blast circuit breakers were introduced into United States practice in 1939. Several designs are available, but all are based upon the same general plan, namely, to blow out the arc with a jet of air that is supplied from a pressure tank. To assist in extinguishing the current, the arc is blown into a set of arc chutes, where it is subdivided into several parts, making the task of extinguishing somewhat easier. The details of such a circuit breaker are shown in Figs. 217*a* and *b*.

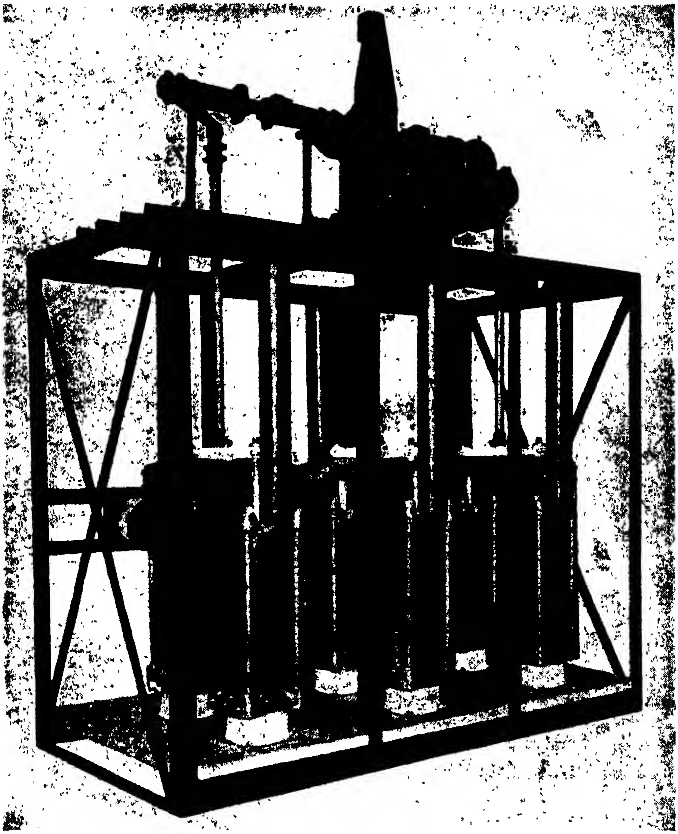


Fig. 211.—Oil circuit breaker, 5,000 amp., 7,500 volts. (*General Electric Company.*)

*e. Magnetic-blast Circuit Breakers.*—In the field of breakers for 5,000 volts and less, several manufacturers have brought out air circuit breakers that extinguish their arcs by blowing them magnetically into arc chutes where they are lengthened, cooled, and interrupted (see Fig. 217*c*).

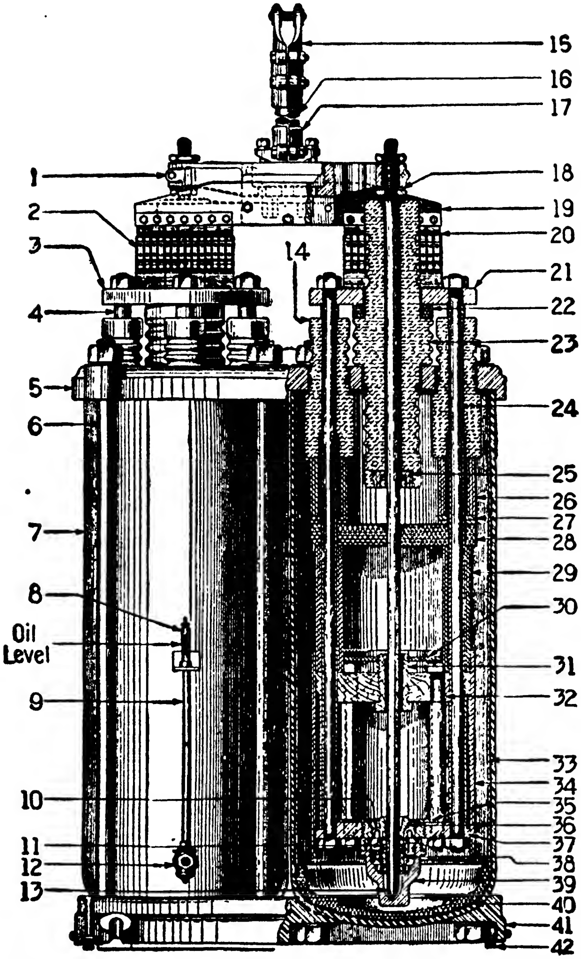


FIG. 212.—Oil circuit breaker. (*General Electric Company.*)

NOMENCLATURE

1. Crosshead.
2. Contact fingers.
3. Contact block.
4. Bushing.
5. Cap.
6. Tie bolt.
7. Oil vessel.
8. Oil gauge.
9. Oil tube.
10. Flexible lead.
11. Spring.
12. Oil drain.
13. Contact rod.
14. Insulator.
15. Operating-rod clamp, upper.
16. Operating rod.
17. Operating-rod clamp, lower.
18. Sleeve for crosshead.
19. Conductor bars.
20. Contact fingers.
21. Contact block.
22. Spacer.
23. Insulator.
24. Supporting rod.
25. Stuffing box.
26. Tube.
27. Spacer.
28. Baffle.
29. Bushing.
30. Insulation.
31. Bushing.
32. Baffle.
33. Lining.
34. Casing.
35. Shim.
36. Arcing tip.
37. Conductor.
38. Secondary contacts.
39. Retainer.
40. Oil deflector.
41. Truck.
42. Roller.

*f. Impulse Oil Circuit Breakers.*—In this breaker (Fig. 217*d*) the arc is extinguished by an oil blast produced by a spring-driven piston. The particular breaker shown is designed to interrupt a 25-cycle 11-kv. railway-trolley circuit in one cycle.

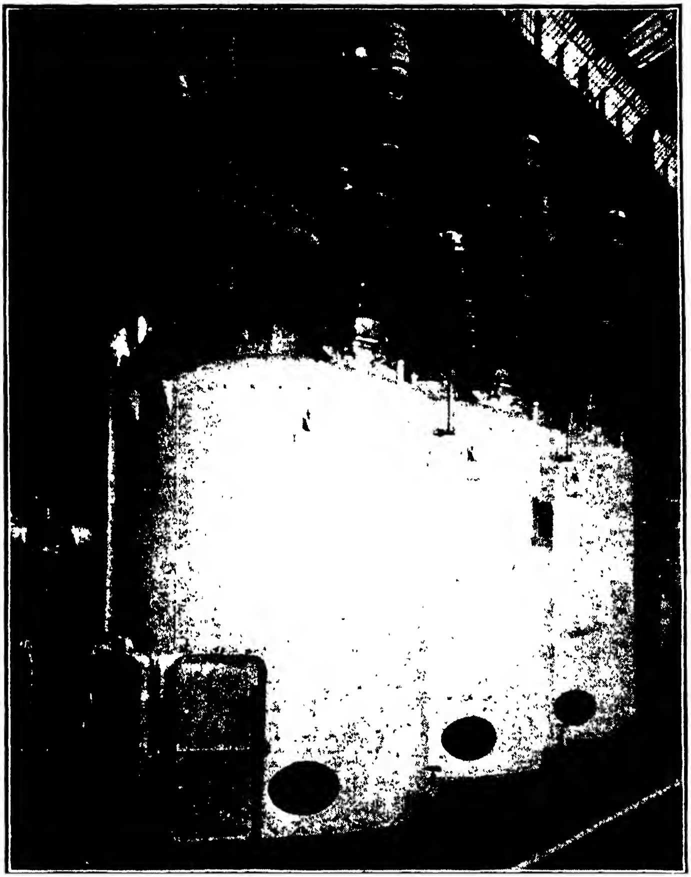


FIG. 213.—A 154-kv. outdoor oil circuit breaker. (*Westinghouse Electric Corporation.*)

A rather unusual impulse type of breaker is used at the two desert switching stations of the 287-kv. Boulder Dam–Los Angeles transmission line. Each of these breakers has eight breaks per pole supplied with oil by a spring-driven piston. The interrupters and the oil exposed to arcing (only a little over

200 gal.) are contained in horizontal Herkolite and porcelain tubes which are supported on vertical columns (Fig. 217*e*).

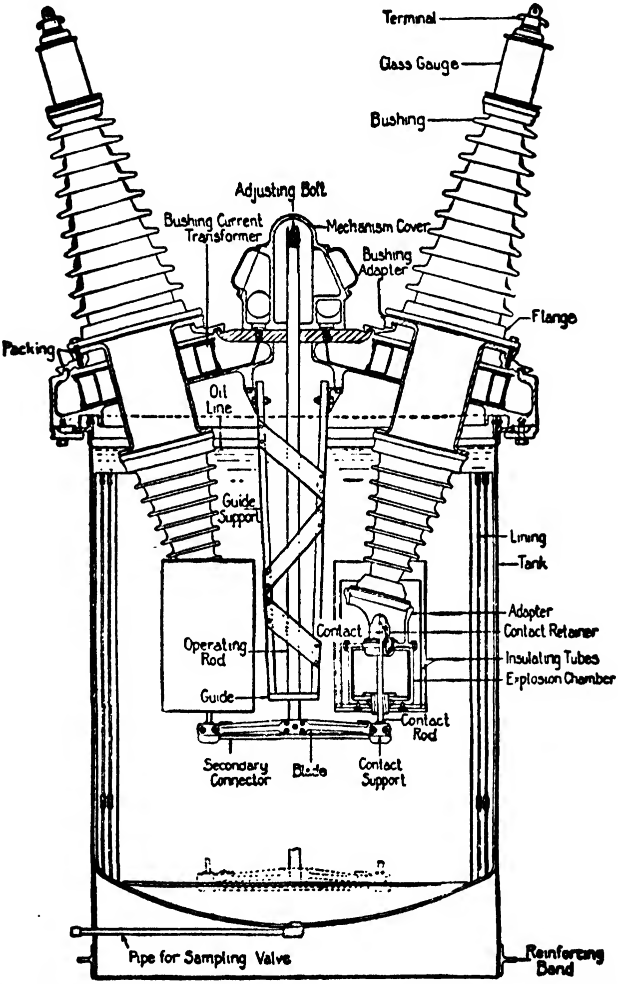


FIG. 214.—Typical outline of single-pole element of an outdoor oil circuit breaker, 110,000 volts above. (*General Electric Company.*)

**134. Contact Details.**—The simplest type of contact is obtained by the use of either flat or curved metal surfaces as the terminals of the circuit breakers. The moving contactors when closed are held firmly against the stationary terminals by means of heavy springs. This type is known as the butt contact. It is satisfactory for low voltages and capacities; however, for higher voltages and large capacities it is generally necessary to go to more complicated designs or to a number of contacts in series or parallel.

The wedge design, as the name implies, involves a wedge-shaped terminal on the moving element, which when in the closed position is forced between spring jaws. In a good many designs this type of contact is used as the current-carrying terminals, and secondary butt-type contacts are made to open later, thereby interrupting the arc. This is done to protect the wedge contacts from burning.

FIG. 215.—Outdoor oil circuit breaker, 70 kv., of the horizontal multibreak type. (*Pacific Electric Manufacturing Company.*)

Some of the lower voltage breakers are equipped with laminated contacts. Examples of this contact are seen in Figs. 207 and 208.

The bayonet or rod type of contact is shown in Figs. 212 and 214. In some of the high-tension breakers it is essential that the contacts be opened at high speed. This is accomplished by having the arcing tips connected to the contact arms through heavy springs. As the breaker starts to open it carries the arcing tips with the moving elements, thereby compressing the springs. By a latch mechanism the arcing tips are opened, allowing the contacts to move at a very high rate of speed.

With the increase of system capacities, engineers have had to resort to a good many improvements in the design of contacts in order to open satisfactorily the heavy currents of these large systems. The explosion chamber as developed by the General Electric Company is one of the designs that are offered for this field of work (see Fig. 218).

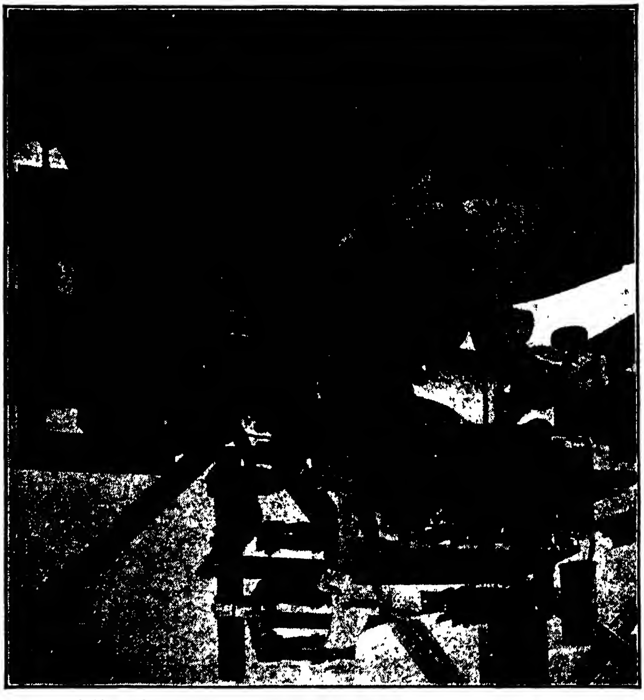


Fig. 216.—Multibreak contacts of oil circuit breaker shown in Fig. 215. (*Pacific Electric Manufacturing Company.*)

The contacts of the oil-blast explosion chamber consist of an upper, an intermediate, and a lower element. In the closed position, these three elements are pressed together.

When the breaker is tripped, the intermediate and lower elements move downward. An arc is drawn between the upper and the intermediate. This arc forms gas and places the oil in the explosion chamber under high pressure. There is little relief for this pressure until the intermediate element reaches its stop. At that point the lower element leaves the intermediate, thus drawing a second arc and venting the established pressure through the hollow lower element. Thus, solid oil is blasted across the second arc. This action forces gas and oil down through the lower element. At a current zero, the arc products are swept away and a solid wall of oil is placed in the arc path.

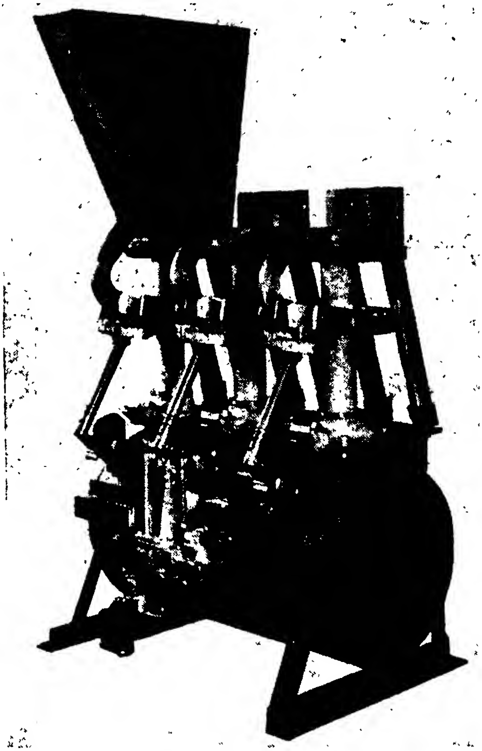


FIG. 217*a*.—Typical air-blast circuit breaker. (*Westinghouse Electric Corporation.*)

The deion circuit-breaker contacts, as developed by the Westinghouse Electric Corporation, are a radical departure from previous methods of design. The details are shown in Figs. 219 to 221. The current-carrying contacts are of the plain-butt type. The arc is drawn in a narrow and long slot which is obtained by the stack of grids as shown in detail in Figs. 220 and 221. These grids are made up of four

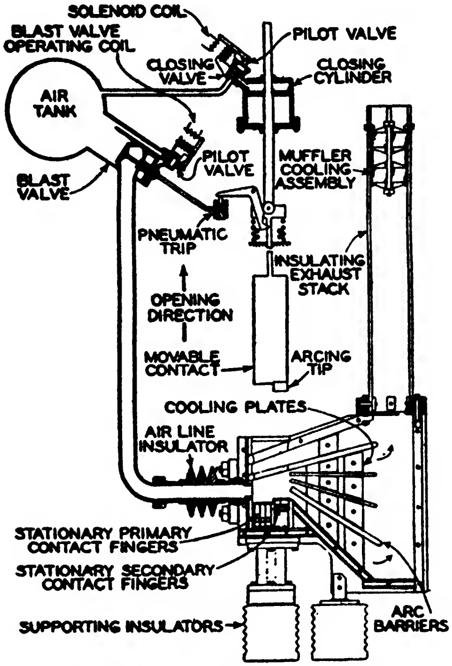


FIG. 217*b*.—Air-blast circuit breaker.

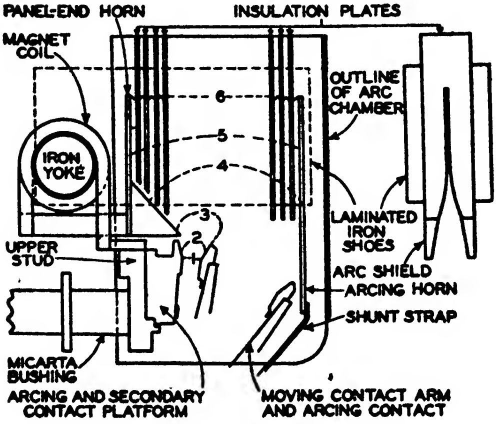


FIG. 217*c*.—Magnetic-blast circuit breaker.

elements, namely, one iron plate of good magnetic qualities and three insulating elements. When an arc is drawn, a strong magnetic field is produced in the iron element. This magnetic field forces the arc toward the closed end of the slots. The

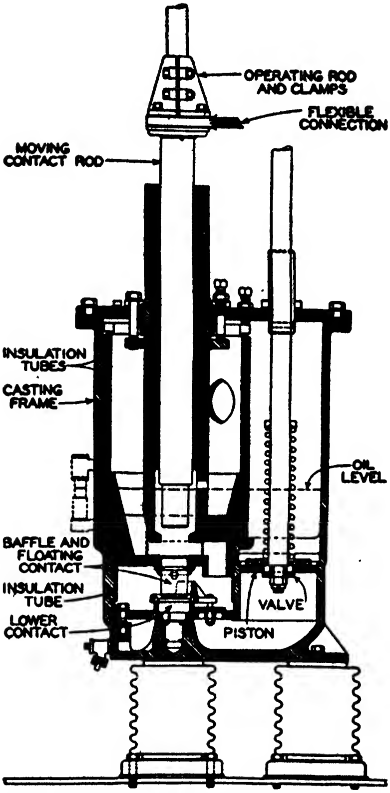


FIG. 217*d*.—Impulse oil circuit breaker.

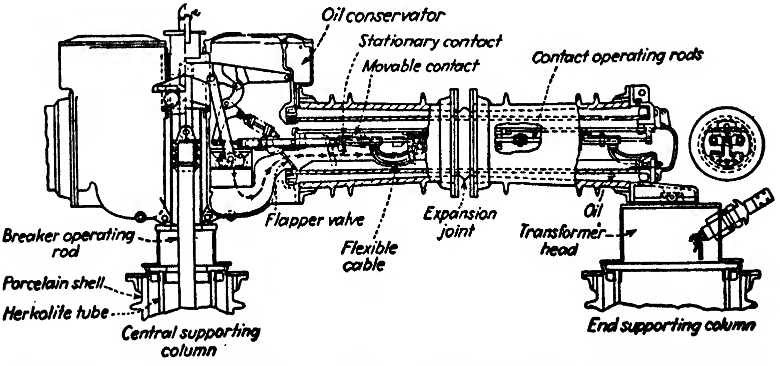


FIG. 217*e*.—Impulse oil circuit breaker for 287 kv. circuits of Boulder Dam-Los Angeles transmission line.

gas produced in the back of the slots can escape only by passing outwardly through the arc. This action causes a stream of gas to be created across the arc, thus cooling and extinguishing it.

**135. Circuit-breaker Construction.**—Mechanical details of circuit breakers vary a great deal, depending on the particular requirements that must be met. A few of the factors of importance are discussed below.

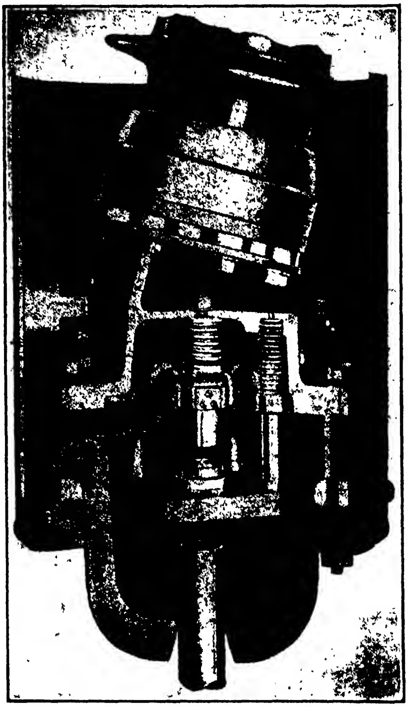


Fig. 218.—Explosion-chamber type of contacts.

Indoor- and outdoor-service circuit breakers, though based on the same principles, are nevertheless quite different in some respects. Typical indoor circuit breakers are shown in Figs. 208 to 212 and typical outdoor units in Figs. 213 and 216. Outdoor circuit breakers must naturally be water- and moisture-proof, the bushings must be designed for all weather conditions and, as a general rule, must be given greater clearance. Indoor-type units are in most cases of lower voltage ratings and therefore

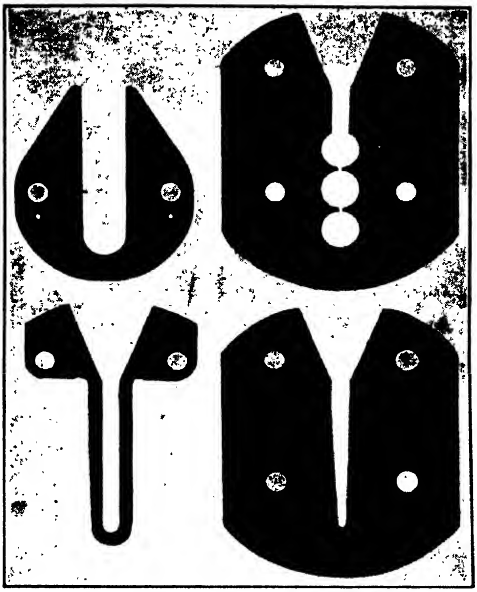


FIG. 219(*a*).—Deion grid elements.

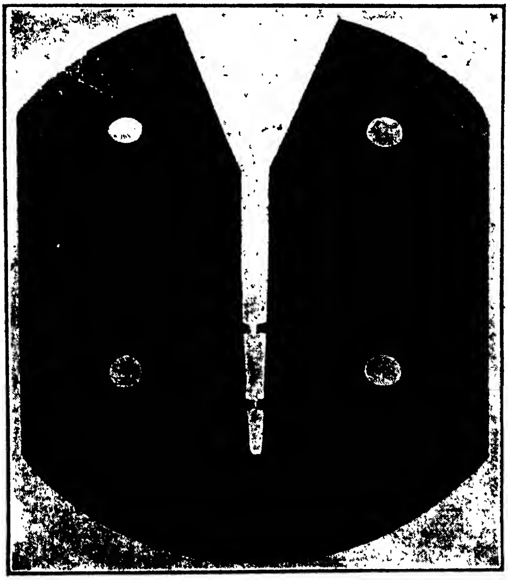


FIG. 219(*b*).—Assembly of Deion grid elements.

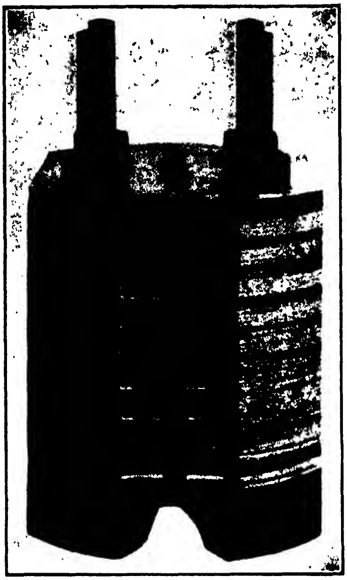


FIG. 220.—Deion grid stack.

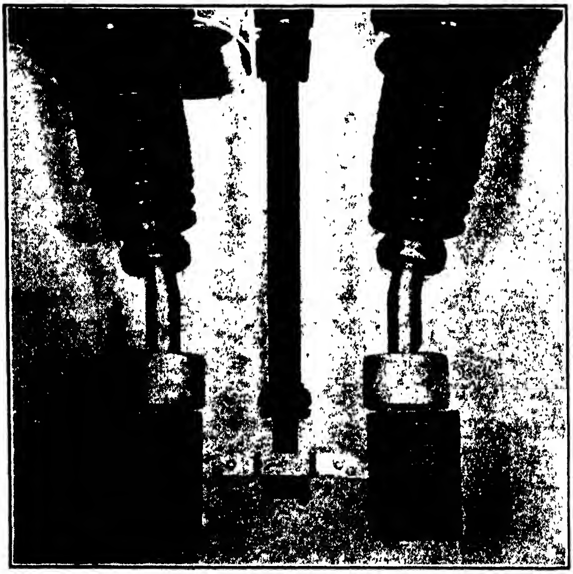


FIG. 221.—Deion grid contacts.

present a different appearance. These units are generally mounted in cells as described in Chap. X (see Figs. 210 and 211). Outdoor oil circuit breakers are either frame mounted (Fig. 215) or floor mounted (Fig. 213). For low-voltage indoor installations the circuit breakers may be mounted on suitable framework in the vicinity of the switchboard or directly upon the switchboard panels.

For very low capacity and voltages all poles of a polyphase circuit breaker are sometimes placed in the same tank, but for medium- and high-capacity units it is necessary to enclose the separate poles in individual tanks. Where all poles are in one tank, there always is the possibility of an arc's being established between phases. Tanks may be of the "box" shape (see Fig. 208) or cylindrical. For small circuit breakers the box shape is satisfactory, but on account of the high internal pressures, which are created when rupturing a heavy current, it is essential that circuit-breaker tanks be cylindrical or at least semicylindrical, with no sharp bends. It has been found that a pressure as high as 150 lb. per sq. in. may occur near the arcing point of oil circuit-breaker contacts, and since all containers, when subjected to internal pressure, tend to assume a spherical shape, it is essential that circuit-breaker tanks be made, as far as possible, without sharp corners.

**136. Circuit-breaker Control.**—The general types of switching have been covered in ~~detail in~~ Chap. X and, therefore, will not be repeated here. A few additional details are, however, important. Remote electrical control may be obtained by means of an operating motor or solenoid. In practically all cases direct current is used, but sometimes alternating-current motors may be preferable. Figures 210 and 211 show examples of solenoid and motor-operated circuit breakers. The operating voltages used are either 125 or 250 volts. The direct current is generally obtained from storage batteries, which give continuous service with the maximum possible reliability.

The pneumatic method of circuit-breaker control is gaining favor, owing to its positive and unusually fast action. In this type of control, compressed air is used to operate the circuit breakers.

In addition to control whereby an operator may close or open a particular circuit breaker, it is also essential that proper relays be placed in the circuit in order that circuit breakers may be opened automatically in case of abnormal conditions. A great number of the troubles that occur on transmission lines and feeders are of a momentary nature, and, therefore, a great saving of time and expense can be made if the circuit breakers of such circuits are arranged so that they will reclose themselves automatically after they have been opened by the action of some relay. Such circuit breakers are said to be automatic. It is essential, however, that some arrangement be provided whereby such a circuit breaker cannot remain in the closed position if the trouble has not been cleared. Automatic breakers of this type are generally arranged to reclose two to four times, after which they will remain open until the trouble is cleared. It is also important that some arrangement be provided whereby it will be impossible for an operator to close a circuit breaker when the trouble is still on the line. In the case of manual-operated units this is accomplished by connecting the contacts to the handle by means of a latch. Normally this latch is closed and the handle is rigidly connected to the contacts, but in case of trouble the latch is opened by the action of the protecting relay, thereby breaking the connection between the handle and the operating rod. Such a mechanism has been called "trip-free from handle."

**137. Application of Circuit Breakers.**—To apply circuit breakers properly it is necessary that the normal current of the circuit, the rated voltage, and the required interrupting capacity in amperes all be known. The first two quantities are generally known without computations or measurements, but the determination of the interrupting capacity presents a more difficult problem. The complete network must be taken into consideration, and the current that might be delivered to the circuit breaker in case of a short circuit in the particular feeder must be accurately determined. From a knowledge of the type and time setting of the relay that will be used in conjunction with the circuit breaker it is possible, by the use of Table XIII, Art. 154, to estimate the necessary interrupting capacity in amperes or kilovolt-amperes.

The interrupting capacity of a particular circuit breaker is also affected by the frequency of the circuit, the power factor prior to the short circuit, the temperature, and also the altitude of the breaker above sea level. The transient that is set up during short circuit is rather complex and hard to analyze, but it has been found that the stored electrostatic and magnetic energy of the system has definite effects upon the transient and therefore upon the interrupting capacity. Like all electrical equipment, the capacity is also limited by the safe operating temperature. As has been stated, the oil quenches the arc by its cooling action and by its pressure. It is, therefore, to be expected that the rating would vary with elevation. Up to an elevation of about 3,300 ft. above sea level there is no perceptible decrease in rating. For other elevations the current and voltage ratings should be multiplied by the following factors:

| Distance above sea level, feet | Current-rating factor | Voltage-rating factor |
|---|---|---|
| 4,000 | 0.99 | 0.98 |
| 5,000 | 0.96 | 0.95 |
| 8,000 | 0.94 | 0.86 |
| 10,000 | 0.91 | 0.80 |
| 12,000 | 0.89 | 0.74 |
| 14,000 | 0.87 | 0.70 |

The rating of a circuit breaker depends also upon the duty cycle that is imposed upon it. In other words, a circuit breaker that is opened several times within specified intervals of time is subjected to a greater burden than a similar unit that is opened only once, assuming that the voltage, current interrupted, and all conditions of operation are the same in both cases. It is important, therefore, that some standard "duty cycle" be employed; otherwise the ratings quoted by manufacturers would be meaningless.

The standard duty cycle of power circuit breakers is as follows: CO—15 sec.—CO. This duty cycle implies that a circuit breaker is closed, then opens due to relay action. It is then reclosed in 15 sec. and again reopens.

There are, however, many applications which require that breakers be subjected to more severe duties; hence when choosing the proper circuit breaker it is essential that allowance be made for the type of service and also for the duty cycle that is likely to be imposed upon the breaker.

### Questions for Class Discussion

**1.** To what field of application are knife switches and fuses suited? What are their limitations?

**2.** What is the purpose of disconnecting switches? Where are they used?

**3.** What is an air-brake switch? What field of application does this device fulfill?

**4.** State the purpose of the following: (*a*) control switches, (*b*) auxiliary switches, (*c*) cartridge fuses, (*d*) transformer fuse block and box, (*e*) expulsion fuses.

**5.** What is an air (or carbon) circuit breaker? State its field of application.

**6.** What is the difference between an oil switch and an oil circuit breaker? State the field of application of each one.

**7.** Why is oil used in oil switches and oil circuit breakers?

**8.** Describe briefly the construction of the following types of oil circuit breakers: (*a*) gravity opened, (*b*) gravity closed, (*c*) horizontal break.

**9.** What methods of oil circuit-breaker control are used in modern power plants?

**10.** What are the relative merits of motor- and solenoid-operated breakers?

**11.** State and briefly describe the common methods used for mounting oil circuit breakers.

**12.** Describe the properties of an ideal fluid to use in place of oil in circuit breakers.

**13.** What effect does the power factor have upon the operation of a breaker? Explain.

**14.** Explain in detail what happens when a circuit is broken under oil?

**15.** About what value of pressure is produced in the oil-breaker tanks? Explain why.

**16.** What is the disadvantage of placing all contactors, say of a three-phase circuit, in one tank?

**17.** What is the average period of time elapsed between a short circuit and the time the circuit breaker starts to open, and completely breaks arc?

**18.** Why are breaker tanks not made square or rectangular in section?

**19.** Why does the rating of a breaker depend on the altitude at which it is operated?

**20.** Can a circuit breaker be selected on the basis of normal rated current-carrying capacity alone? Of what importance is the rupturing capacity of an oil breaker?

**21.** What factors determine the magnitude of the current that will flow through a breaker under conditions of short circuit?

**22.** How does frequency affect the rating of an oil circuit breaker? Why are such breakers seldom used in direct-current circuits?

**23.** What is meant by the duty of a circuit breaker?

**24.** Why do manufacturers specify a 2-min. interval between interruptions and limit the number of successive openings?

**25.** Is the instantaneous short-circuit current furnished by a generator different in magnitude from the continuous short-circuit current? About how long does it take for the current to reach its steady short-circuit value? How does the time element of the relay setting affect the rupturing capacity required of an alternating-current breaker?

**26.** What are the important considerations in the design of an oil circuit breaker for a three-phase 60-cycle alternator, 20,000 kva. at 12,000 volts, leakage reactance 10 per cent, steady short-circuit current 2.5 times full load? Specify the minimum requirements for a breaker in this circuit. What difference would 10 per cent reactors in each phase load make in your specifications?

**27.** How does a circuit breaker for an outdoor substation differ from a similar breaker under cover?

**28.** Explain the action and purpose of a trip-free-from-handle circuit breaker.

**29.** Describe and discuss the advantages and applications of the different types of circuit-breaker contacts.

**30.** What is the method of contactor control used in the pantograph type of breaker?

**31.** Discuss and describe the details of the deion circuit breaker

**32.** Discuss and describe the details of the oil-blast circuit breaker.

# CHAPTER XII

## METERS AND MEASUREMENTS

**138. General Classification.**—There are so many different types of meters that are being used that a complete classification covering all types cannot be given; however, the following classification will cover most of the common power-plant instruments. Meters are therefore classified according to:

| | |
|---|---|
| Principle of operation | Electrostatic |
| | Electrothermal |
| | Electromagnetic |
| Mechanism | Indicating |
| | Integrating |
| | Recording |
| Scale deflection | Uniform |
| | Nonuniform |
| | Double reading |
| Types of construction | Portable |
| | Switchboard |
| Application | Ammeter |
| | Voltmeter |
| | Watt and watt-hour meter |
| | Reactive volt-ampere meter |
| | Kilovolt-ampere meter |
| | Demand meter |
| | Power-factor meter |
| | Frequency meter |
| | Synchroscope |
| | Temperature meters |

**139. Desired Meter Characteristics.**—Some of the most important requirements that commercial meters should possess may be classified as follows:

1. Rugged mechanism.
2. Permanent calibration.
3. Proper damping.
4. Slight sensitivity to stray magnetic fields.

Very accurate meters can be built, but in many cases such meters are fragile and are, therefore, not suitable for commercial work. There are many things that might cause a meter to become inaccurate with age, the most important being ageing of the iron in the magnetic circuits and friction or wear of the moving parts. Meters should be damped properly so that their readings are "dead beat," or, in other words, there should be very little oscillation of the pointer when a reading is desired. A certain amount of stray magnetic field is practically always present in power plants, and unless proper precaution is taken such a stray field will introduce a certain amount of error in the meter readings.

**140. Principle of Operation.** *a. Electrostatic.*—The fundamental principle that charged bodies, if of the same polarity, repel each other and, if of different polarities, attract each other is utilized in the operation of voltmeters for very high voltages. In Fig. 222 is shown the essential parts of a typical instrument of this type. It consists of two circular plates *C* and *D* connected to the conductors *A* and *B* of the high-voltage circuit. The plates *C* and *D* are generally placed off center. The revolving element consists of two hollow cylinders mounted at the ends of a lever which also carries a pointer. When a difference of potential is applied to the two plates *C* and *D*, the cylinders become charged as shown, and an attraction force is set up causing the revolving element to take up a position as indicated. For very high voltages the condensers *E* and *F* are left in the circuit, but for lower voltages they are short-circuited, thereby affording a considerable range of voltages for one meter.

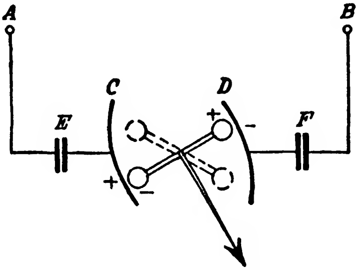


Fig. 222.—Electrostatic voltmeter.

The entire meter is immersed in an oil tank, the oil serving the double purpose of insulator and proper damper, since the cylinders must revolve in an oil bath. The scale of such a meter cannot be uniform on account of the eccentricity of the plates *C* and *D* and also because of the fact that the force is proportional to the voltage squared.

*b. Electrothermal.*—Meters built upon this principle depend upon the expansion and contraction of a wire carrying current to move a pointer over a suitable scale. A typical hot-wire meter is shown in Fig. 223. A current is caused to flow between *A* and *B* through a platinum-iridium-alloy wire. The heat developed in this wire causes it to expand and sag. Attached at *F* is a fine phosphor-bronze wire, which is always kept in tension by the action of the silk thread connected to it at *D*. This silk thread passes around a small pulley on the shaft of the pointer and is kept in tension by the action of a spring. It follows, therefore, that any expansion of the wire between points *A* and *B* will cause motion of the pointer. Since the expansion of the platinum-iridium wire depends on the heat generated, the motion of the pointer will be proportional to the square of the current flowing, and hence the scale of such a meter will not be uniform. Such a meter can be used as either a voltmeter or ammeter for both direct and alternating current.

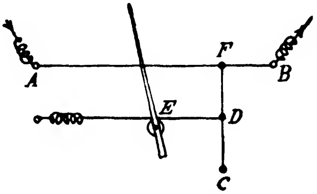


Fig. 223.—Hot-wire meter.

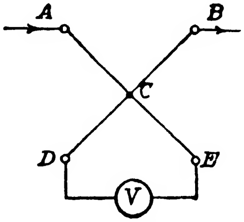


Fig. 224.—High-frequency meter.

Another application of the electrothermal principle is used for measuring high-frequency currents (see Fig. 224). Two wires, one of copper and the other of advance metal (copper and nickel), are stretched between terminals *AE* and *BD*, the two wires being connected at *C*. Current is caused to flow through *ACB*, thereby heating the junction point of the two wires and producing a voltage due to thermocouple action. This voltage is unidirectional since it depends upon the heat produced at *C*. Any accurate direct-current voltmeter or galvanometer can be used to read this voltage, which is proportional to current passing through the junction point *C*.

*c. Electromagnetic.*—The majority of meters used in commercial work fall in this class. As the name indicates, the operation of the meters of this type depends upon the presence of a magnetic field which acts upon a movable element. Electromagnetic meters may be further classified as follows:

1. Permanent-magnet type.
2. Moving-iron type.
3. Dynamometer type.
4. Induction type.

**141. Permanent-magnet Meters.**—The essential parts of such a meter are shown in Fig. 225. A small coil of wire *A* carrying the current to be measured, or a shunted portion of it, is wound on a light cylindrical frame of aluminum. The frame is so pivoted in jeweled bearings as to move freely in a small annular space between a soft-iron core *B* and the pole pieces *N* and *S* of a permanent magnet *P*. Attached to the aluminum frame is a light pointer by which the deflections can be read. Proper damping is obtained by means of eddy currents that are induced in the aluminum frame during the motion of the coil. The revolving element is retarded by means of two spiral springs, generally located at the two ends of the pointer shaft. These springs are also used to lead the current into and out of the moving coil. It is easily seen that such meters are applicable only to direct-current circuits, since no resultant torque can be produced with an alternating current. This meter may be arranged to read current as an ammeter, or if connected in series with a proper resistance, it may be made to read voltage.

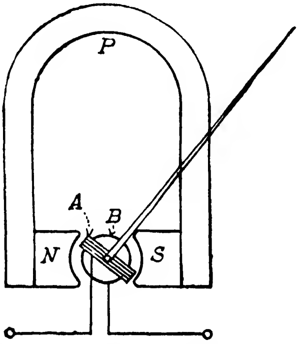


FIG. 225.—Permanent magnet meter.

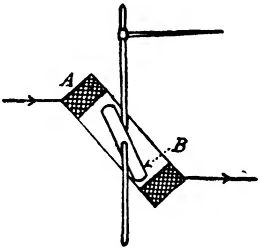


FIG. 226.—Thomson inclined-coil instrument.

**142. Moving Iron Meters.**—There are several meters now in use that are built on this principle, probably the most important being the Thomson inclined-coil instrument (see Fig. 226). This meter is composed of an energizing coil *A*, which is located at about 45 deg. with the horizontal, and a rotating element, which is merely a rectangular piece of thin soft-iron *B* mounted on a shaft. When the coil *A* is energized, the soft-iron vane seeks to place itself parallel with the magnetic flux of the coil; hence the shaft is caused to rotate. The torque thus produced is opposed by the action of a spiral spring. Such a meter can be used as an ammeter or voltmeter for either direct or alternating current, but is mostly used for alternating current. The scale of such a meter varies approximately as the squared power.

**143. Dynamometer-type Meter.**—The dynamometer type of meter is composed of two stationary coils and one movable coil upon which is mounted a pointer (see Fig. 227). When current flows in these two windings, the movable coil tends to place itself parallel to the stationary coils. The motion of the movable coil is opposed by the action of a spiral spring. It is obvious that such a type of meter can be used for alternating-current as well as direct-current measurements. It can be used as an ammeter, voltmeter, wattmeter or reactive volt-ampere meter. In case of ammeters or voltmeters all the coils are connected in series, while as a wattmeter the stationary coils form the current element, and the movable coil forms the potential element.

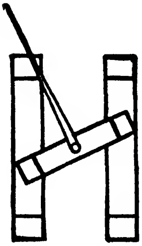


FIG. 227.—Dynamometer type of meter.

**144. Induction-type Meters.**—Induction-type meters operate on the principle of the revolving magnetic field produced by out-of-phase currents that are flowing in separate windings. If an aluminum disk or drum is located between two such windings, there will be eddy currents induced in the disk, and a resultant torque will be produced which will be proportional to the magnetic flux and the eddy currents flowing in the disk.

In Fig. 228 is illustrated a typical induction watt-hour meter. *A* is the potential coil and *B* the current coil. Coil *A* is highly inductive owing to its large number of turns, while coils *B* have only a few turns and hence are practically noninductive; hence the magnetic fluxes of coils *A* and *B* will be out of phase by approximately 90 electrical degrees at unity power factor. The voltages and therefore the eddy currents that are induced in the revolving disk will lag the magnetic fluxes by 90 electrical degrees; hence the eddy currents produced by coil *A* will be a maximum at the same instant that the flux produced by *B* is a maximum, or vice versa. The torque produced, therefore, will be proportional to the power delivered, provided the currents in coils *A* and *B* are exactly 90 electrical degrees out of phase. Owing, however, to the resistance of coil *A*, these currents cannot be 90 electrical degrees apart; hence an error will be introduced in the readings of such a meter. To compensate for this error, a coil *C* is placed on the potential pole *A* and short-circuited through a resistance. The voltage and current in this coil will be 90 electrical degrees behind the flux produced by coil *A*. Coil *C* will, therefore, produce a flux that will lag behind flux *A* by 90 electrical degrees, and by properly adjusting the resistance in coil *C* it is possible to obtain a resultant flux (vector sum of flux *A* and *C*) that will be in phase with the eddy currents produced in the revolving disk.

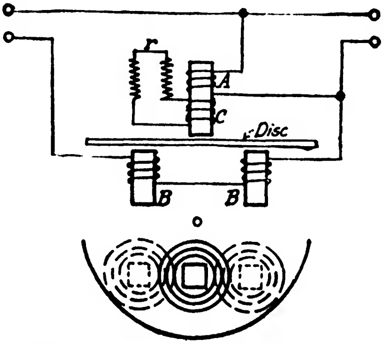


FIG. 228*a*.—Induction-type watt-hour meter.

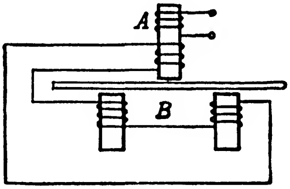


FIG. 228*b*.—Fundamental principle of induction-type voltmeter.

The same general principle can be used for voltmeters or ammeters. In this case, there is only one main pole, as indicated by *A* (Fig. 228*b*). A secondary set of poles *B* is excited from the current induced in a winding placed around the main pole. In this manner the flux produced by poles *B* will be practically in quadrature with the flux produced by pole *A*, and therefore a torque will be produced in the disk, the rotation of which can be opposed by a suitable spiral spring. This type of meter is obviously suitable for use on alternating-current circuits only.

**145. Type of Mechanism.** *a. Indicating Meters.*—This class includes ammeters, voltmeters, wattmeters, power-factor meters, etc., in other words, all such meters as are equipped with a pointer that is caused to move along a proper scale, thereby indicating the conditions existing in the circuit at a particular instant.

*b. Integrating Meters.*—All instruments that measure energy or its equivalent must be provided with a proper mechanism to sum up the energy consumed by the circuit to which the meter

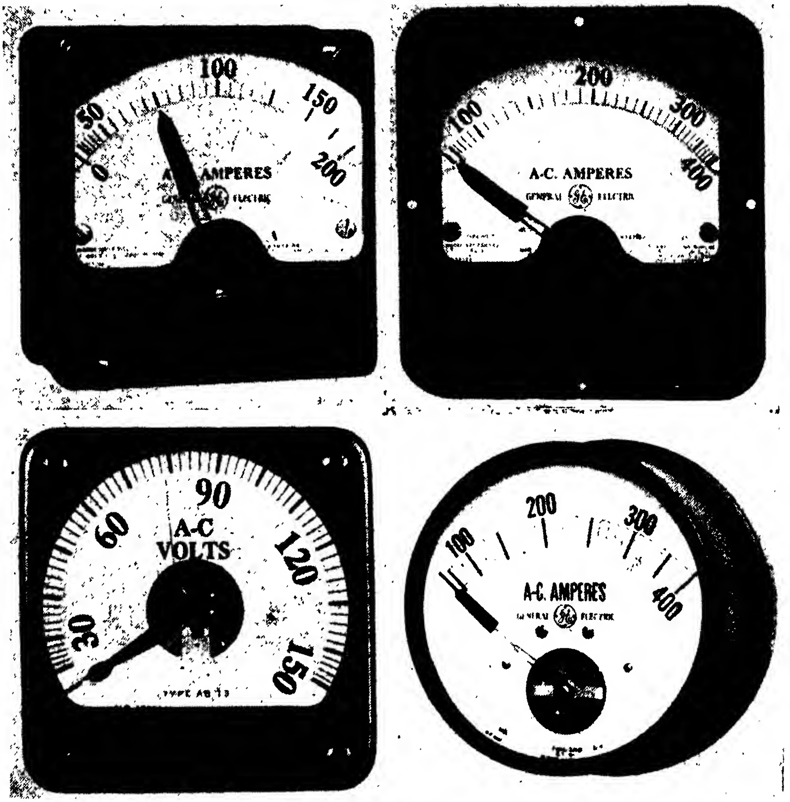


FIG. 229.—Typical types of switchboard instruments. (*General Electric Company.*)

is connected. The most common meter of this type is the watt-hour meter. The revolving disk or armature of such a meter causes a set of gears to rotate, thereby registering the total energy consumption.

*c. Recording Meters.*—A recording instrument is essentially an indicating meter, the pointer being provided with a suitable pen point and the scale being a paper roll or a circular chart. In either case the chart is caused to move by some kind of clock mechanism, the pen point thereby tracing the complete record of conditions existing in the circuit. Recording meters are particularly suitable for certain cases where a record is desired.

**146. Scale Deflections.**—As has been indicated, meters may have uniform or nonuniform scales, the law of the deflection being dependent on the principle underlying the meter. As a general rule, most meters are arranged to show deflection in only one direction, but it is often desirable to have a meter that will show a deflection in two directions, that is, a double-reading meter. A common example of such an instrument is found in ammeters designed to indicate charging and discharging currents. Wattmeters are sometimes designed to read the flow of power in either direction; hence such meters are arranged to deflect in either direction.

**147. Type of Construction.**—Portable and switchboard instruments are built on any of the principles outlined in Arts. 140 to 145. Portable instruments must be very rugged in order to withstand the severe usage to which they are generally subjected. Switchboard instruments are of two general types: rectangular or round for either surface or flush mounting (see Figs. 229*a* to *d*).

**148. Applications.** *a. Ammeters.*—Alternating-current ammeters are generally of the moving-iron type (Fig. 226), the dynamometer type (Fig. 227), or the permanent-magnet type if equipped with a suitable rectifier circuit. The permanent-magnet type of instrument of Fig. 227 is distinctly a direct-current device. The standard rectifier circuit used with this instrument for alternating-current measurements is shown in Fig. 230.

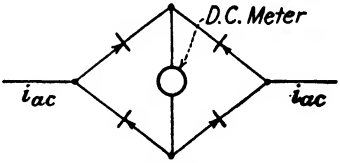


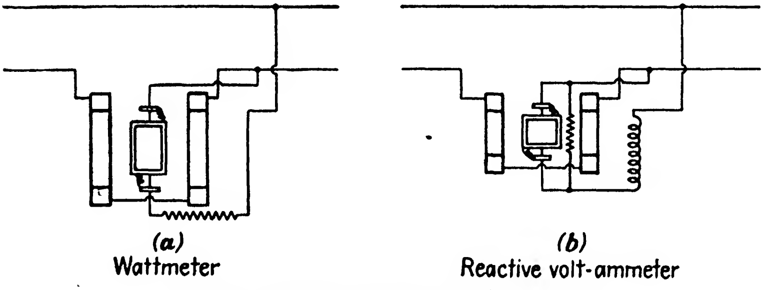
FIG. 230.—Rectifier current used with direct-current instruments.

*b. Voltmeters.*—Alternating-current voltmeters are commonly of the dynamometer type, though the moving-iron and permanent-magnet types are also used for voltmeters. In the case of voltmeters, an appropriate resistance must be used in series with the instrument in order to limit the meter.

*c. Wattmeters.*—The electrodynamometer instrument is generally used for the measurement of power. The stationary coils are connected in series with the line, therefore they carry the current of the circuit. The circuit potential is applied to the moving coil. A suitable resistance must be used in series with the movable coil.

For sinusoidal current and voltage, the dynamometer meter will give a deflection proportional to $VI \cos \theta$, where $V$ is effective voltage, $I$ the effective current, and $\theta$ the phase angle between $V$ and $I$.

*d. Reactive Volt-ampere (Var) Meters.*—The reactive volt-amperes of a circuit is equal to $VI \sin \theta$. In order to make a wattmeter read reactive volt-amperes, it is only necessary to shift the voltage that is applied to the moving coil by 90 deg. so that the wattmeter will read $VI \cos (90 \pm \theta) = VI \sin \theta$. This can be done by substituting an inductive reactance for the resistance of Fig. 231*a*. In addition, the moving coil is shunted with a noninductive resistance as shown in Fig. 231*b*. By suitable design the current through the moving coil can be shifted to a time-phase position of exactly 90 deg. behind $V$.


(*a*)
Wattmeter

(*b*)
Reactive volt-ammeter

FIG. 231.—Electrodynamometer instrument.

*e. Watt-hour Meters and Reactive Volt-ampere Hours (Var-hours).*—These two meters are of the induction type (see Fig. 228*a*). By suitable connections either kilowatt-hours or reactive kilovolt-ampere hours can be obtained. The detail connections are the same as used for wattmeters and reactive voltammeters. The motion of the revolving disk (Fig. 228*a*) is transferred to a set of gears that record kilowatt-hours or reactive kilovolt-ampere-hours.

*f. Kilovolt-ampere Meters.*—Measurement of kilovolt-amperes involves two independent elements: a watt-hour meter and a reactive volt-ampere element as outlined above. The motions of the two independently moving elements are added vectorially by means of a ball-type differential gearing fitted within the register mechanism (see Fig. 232). The resultant motion of the sphere of Fig. 232 is proportional to total kilovolt-amperes, and if properly harnessed it can be used to indicate kilovolt-ampere demand, maximum kilovolt-ampere demand, or power factor.

*g. Three-phase Energy Meters.*—Three-phase metering of real and reactive power and energy are accomplished by two- or three-element meters, depending on whether the system has three or four wires. Induction-type meters are used for this purpose. The individual real power elements are mechanically coupled to drive one common register. The reactive volt-ampere elements are similarly mechanically coupled and drive a second common register. These two registers may act independently or may further be coupled mechanically to a sphere drive to register kilovolt-ampere (see Fig. 232).

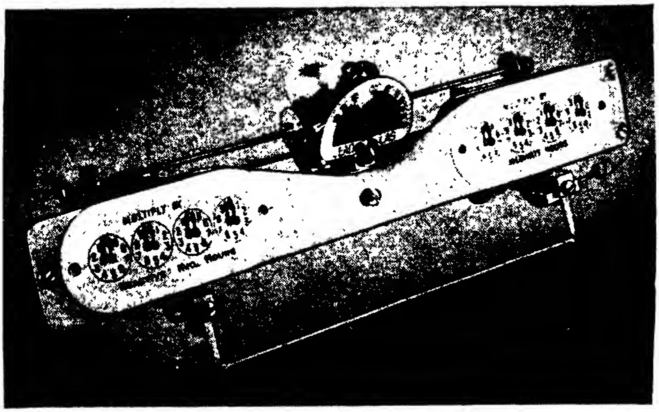


FIG. 232.—Vectorial ball differential mechanism for polyphase kva. meters (*Westinghouse Electric Corporation.*)

*h. Power-factor Meter.*—In Fig. 233 is shown a single-phase power-factor meter of the dynamometer type. The stationary coils $A_1$ and $A_2$ are connected in series and placed directly in the line, while the movable element composed of two coils $B_1$ and $B_2$ is connected across the line. Owing to the inductance $L$ and resistance $R$ in the circuits of the movable element, the currents through coils $B_1$ and $B_2$ are out of phase by about 90 electrical degrees. At unity power factor the current through $A_1$ and $A_2$ will be in phase with the current in $B_2$ but in quadrature with the current in $B_1$; hence the revolving element will rotate until coil $B_2$ is in the plane of coils $A_1$ and $A_2$. Similarly at zero power factor, coil $B_1$ will take up a position parallel to $A_1$ and $A_2$. For intermediate power factors the moving element takes up intermediate positions.

*i. Frequency Meters.*—In Fig. 234 is illustrated one type of frequency meter. A disk carrying a pointer is pivoted between two poles *A* and *B* which are excited with windings connected in such a way that the torques produced in the disk tend to neutralize each other. A resistance *R* and inductance *L* are connected as shown. A change in frequency will cause a change in the current flowing through coil *B*; therefore the torque produced upon the revolving element will change with the frequency.

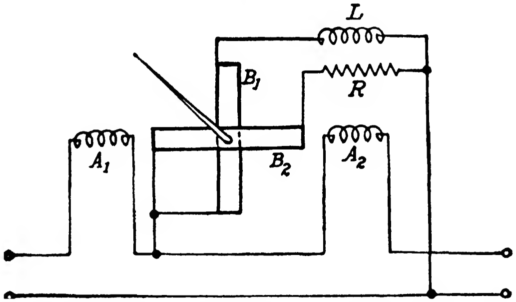
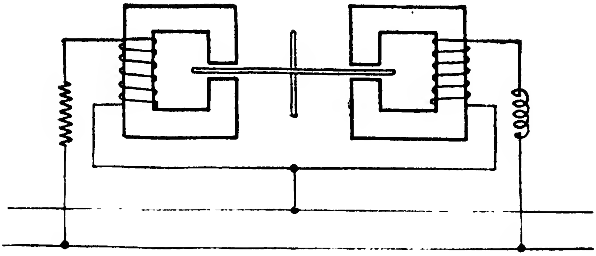


FIG. 233.—Single-phase power-factor meter.

Another type of frequency meter is shown in Fig. 235. *A* and *B* are two stationary coils spaced 90 deg. apart. *C* is a soft-iron core that is free to revolve. The core *C* will therefore take up a position in the resultant field produced by coils *A* and *B*. An investigation of Fig. 235 will show that the currents flowing through *A* and *B* will vary with the frequency, and hence the axis of the resultant field will change, thereby causing the iron core to move with changes of frequency. The reactance $X_s$ is used to damp out higher harmonics.

*j. Synchroscope.*—When synchronizing two generators, it is necessary that the voltages of the two machines be equal and in phase. An instrument that will indicate these conditions is known as a synchroscope. It is essentially a power-factor meter (see Fig. 233). One element composed of coils $A_1$ and $A_2$ is connected across the terminals of one machine, while the other



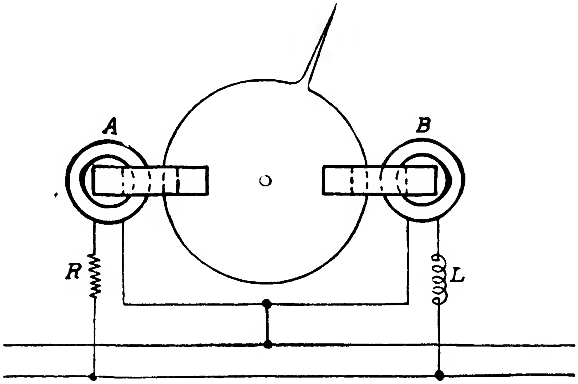


Fig. 234.—Frequency meter.

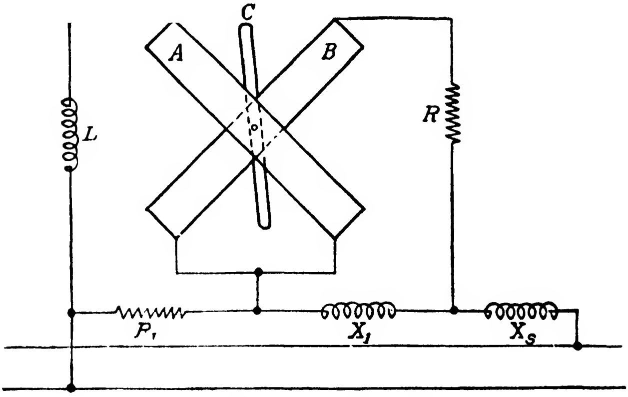


Fig. 235.—Frequency meter.

element, composed of coïls $B_1$ and $B_2$ together with the inductance $L$ and resistance $R$, is connected across the terminals of the second machine.

The pointer of the synchroscope may move in either direction from its zero position, indicating that the machine which is to be connected to the bus is running either fast or slow.

**149. Voltmeter Connections.**—In Fig. 236 are illustrated a few of the standard methods of connecting voltmeters to a circuit. In all the schemes shown one voltmeter with a suitable set of plugging receptacles is used to read all line voltages. The standard rating of the potential element of instruments is 110 volts; hence for higher line voltages it is necessary to use instrument potential transformers between the line and the meters. By means of a four-point plug it is readily seen that all voltages can be read. It is essential that only one plug be provided for the entire plant, because if there were two, inserted by mistake in different receptacles at the same time, they might introduce a short circuit between machines.

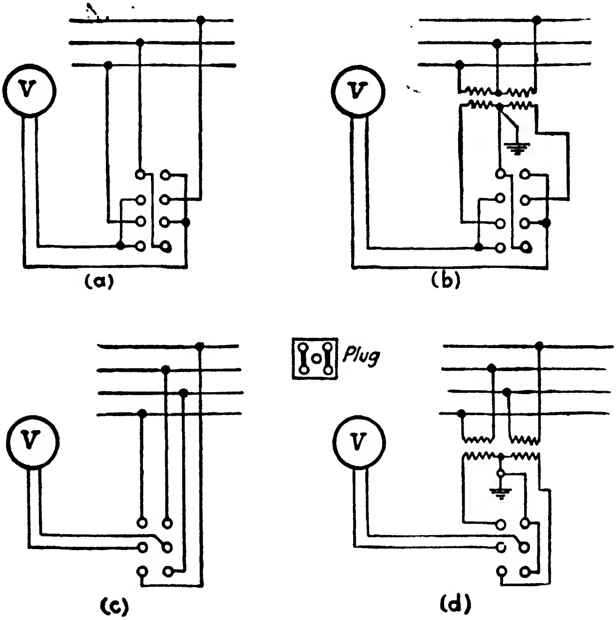


FIG. 236.—Voltmeter receptacles. (*a*) Three-phase alternating-current or single-phase alternating-current and direct-current three-wire circuits. (*b*) Same as (*a*) with potential transformers. (*c*) and (*d*) Two-phase alternating-current circuits.

**150. Ammeter Connections.**—There are two standard methods of indicating the current in a polyphase line, namely, by means of one ammeter and a suitable plugging or switching arrangement or by means of ammeters permanently connected in each line through proper current transformers. Figure 237 illustrates a three-phase circuit, the currents in the three lines being measured by three ammeters and two current transformers. In case of an ungrounded neutral system such a scheme can be used since the current in line *b* is equal to the vector sum of the currents in lines *a* and *c*. In a grounded system, however, it is necessary to use three-current transformers with three ammeters.

Two standard arrangements for reading the three currents of a three-phase circuit with only one ammeter are shown in Fig. 238. Both of these schemes are arranged so that the secondaries of the current transformers are always short-circuited. Both of these arrangements utilize only two current transformers and, hence, are suitable for only ungrounded circuits.

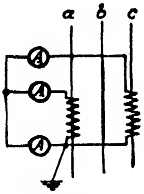


FIG. 237.

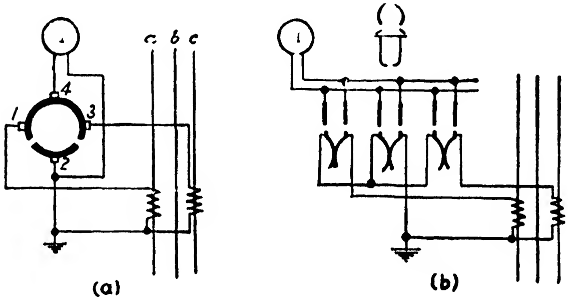


FIG. 238.

FIG. 237.—Ammeter connections for three-phase circuit with neutral not grounded.

FIG. 238.—Ammeter switches.

Since the cost of meters, instrument transformers, and the accompanying wiring needed in a modern power plant is only a small portion of the total plant cost, it is general practice to limit the ammeter plugging or switching devices (Fig. 238) to small-capacity installations and use three ammeters permanently connected in each line of a three-phase circuit for all large installations.

**151. Synchroscope Connections.**—The elementary connections necessary for synchronizing two generators are shown in Fig. 239. Two potential transformers are connected to corresponding terminals of the two generators. The transformers are in turn connected to a synchronizing bus to which is also connected the synchroscope. Synchronizing lamps may also be connected across this bus as shown. It will be noticed that, when the starting and running plugs are inserted in the two receptacles, coil *C* will be connected across the terminals of generator 1 and coils *A* and *B* across the terminals of generator 2. Though the method of connecting lamps in the circuit is shown, they are not relied upon for synchronizing in large plants. Lamps are not sensitive enough and do not give any indication as to which machine is running fast or slow.

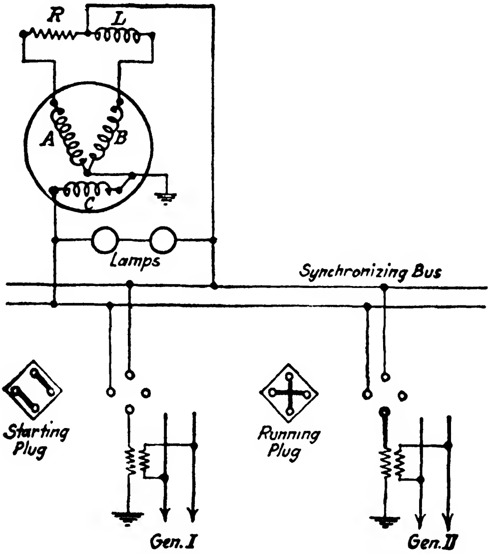


FIG. 239.—Elementary synchroscope connections.

## Questions for Class Discussion

**1.** Name and explain some of the important characteristics that commercial meters should have.

**2.** Name four fundamental principles upon which measuring instruments have been built. Explain each one and state which is most important.

**3.** How was the electrochemical principle applied to instruments? What are some of its advantages?

**4.** Explain the electrostatic type of instrument. To what kind of work is this type of meter adaptable? Name some of its disadvantages.

**5.** Name two different applications of the electrothermal principle to measuring meters. Explain how the measuring is accomplished.

**6.** What is the most important type of instrument? Name four different applications of this principle and state advantages and disadvantages.

**7.** Explain the general details of: (*a*) indicating meters, (*b*) integrating meters, (*c*) recording meters. What are the applications fulfilled by these three types?

**8.** Illustrate by sketches the details of the following types of meters: electrostatic, hot wire, permanent magnet, Thomson inclined coil, dynamometer type, induction type, watt-hour, single-phase power-factor, frequency, synchroscope.

**9.** Draw a diagram of connections for measuring currents in all three phases of a three-phase line, using two current transformers and three ammeters. Will this scheme work on a grounded neutral system?

**10.** Show a diagram of connections for using two potential transformers for measuring the three line voltages of a three-phase line.

**11.** Are two potential transformers sufficient for measuring the three voltages to neutral in an unbalanced three-phase system?

**12.** Illustrate by means of a sketch how the voltage can be measured with only one voltmeter on a three- and a two-phase line.

**13.** Draw diagrams of connections showing two possible ways of measuring the three line currents of a three-phase system with only one ammeter and two current transformers. Is this scheme preferable to that of Question 9?

**14.** Draw a diagram of connections for the synchronizing equipment that is required in a large power station.

**15.** In large power stations, are lamps depended upon for final speed adjustments in synchronizing? Why?

**16.** In a given high-voltage line the current is less than 5 amp. Standard ammeters are built for a 5-amp. range. Would you connect the meter directly into the line?

## CHAPTER XIII

# SHORT-CIRCUIT CURRENTS

**152. Importance of Short-circuit Currents.**—There is probably no other subject of greater importance to the electrical engineer than the question of the short-circuit currents that can be delivered by alternators. The choice of apparatus and the design and arrangement of practically every individual piece of equipment in a system depend upon a proper determination of the short-circuit characteristics of alternators. Under the subject of generators (Chap. IV) a brief description was given, showing in an elementary way what took place in an alternator armature after short circuit, together with a physical conception of the term "synchronous reactance" as applied to alternators. In order to understand fully the method of calculation of short-circuit currents in a generator or network, it is essential that the

Fig. 240.—Burned coils and core after short circuit, in stationary armature of alternating-current generator. (*General Electric Company.*)

student have a more detailed understanding of the transient phenomena in a generator immediately after short circuit. An example of the damage that can be caused by a short circuit is illustrated in Fig. 240.

The treatment given in this text is purposely made as simple as possible. A thorough discussion of this subject would require more space than can be devoted to it in the scope of this book.

**153. Alternator Short-circuit Transient.**[1]—A generator consists essentially of two circuits, an electric and a magnetic circuit which are interconnected as two links of a chain. When the generator is rotated, it corresponds to varying the number of magnetic lines of flux which are interlinking with the electric circuit from a positive maximum to a negative maximum value. In Fig. 241*a* is shown a two-pole alternator of only one coil. This coil is shown in two positions, *A* and *B*. When the coil is in position *A* it encloses the maximum number of magnetic lines of flux, while when it is in the position *B* it encloses zero lines of magnetic flux.

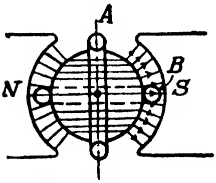


FIG. 241*a*.

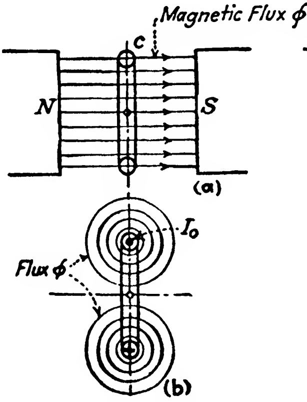


FIG. 241*b*.

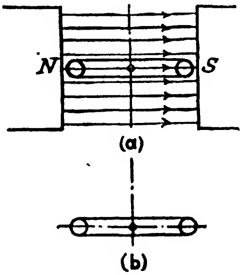


FIG. 241*c*.

In order to understand the phenomena that occur in an alternator under short circuit, it is necessary that the following fundamental principle be understood: *A closed electric circuit, without resistance, must persist magnetically in the same condition as at the instant of closing; that is, it must contain, so long as it*

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[1] See DOHERTY, R. E., and O. E. SHIRLEY, Reactance of Synchronous Machines and Its Applications, *Trans. A.I.E.E.*, p. 1248, June, 1918.

*is closed, the same number of magnetic interlinkages.* The above statement is illustrated by Fig. 241*b*. A ring *C*, of zero resistance, enclosing a constant magnetic flux, is shown at *a*. There cannot be any current through the ring, since the magnetic flux has been assumed constant. Now suppose the ring is moved out of the magnetic field as shown at *b*. In doing this, a voltage is induced in the closed ring which causes a current $I_0$ to flow in such a direction as to maintain the same number of flux interlinkages as when the ring enclosed the main flux as shown at *a*. Since the flux in *a* was assumed constant, it follows that the current established in the ring must be a direct current. In the case of a ring having no resistance, this current $I_0$ will persist indefinitely, but if the ring has a resistance *R* as well as an inductance *L*, the current $I_0$ will not persist but will decrease according to the following well-known law:

$$i = I_0\epsilon^{-\frac{R}{L}t} \qquad (35)$$

where *t* is the time in seconds after the ring has been moved from position *a* to *b* (Fig. 241*b*).

On the other hand, if the ring were located in the magnetic field as shown at *a* in Fig. 241*c* and then removed to *b*, there would be no current flowing, as in this case no attempt has been made to change the number of flux interlinkages.

Consider now the case of the generator illustrated in Fig. 241*a*. If the short circuit occurs when the coil is at position *B* or, in other words, when the coil has zero flux interlinkages, the transient resulting will be symmetrical with respect to the original axis of the voltage wave, the initial effective short-circuit current being determined by the ratio of the effective no-load voltage and the transient reactance of the generator. The amplitude of the successive alternations of this transient will decrease according to an exponential function. After about 2 or 3 sec. the short-circuit current becomes constant, the effective value of which is determined by the ratio of the effective no-load voltage to the synchronous reactance. Such a short-circuit transient is illustrated at *D* and *E* (Fig. 242).

If, however, the short circuit occurs when the coil is in position *A* (Fig. 241*a*) or, in other words, when the coil has a maximum number of flux interlinkages, the transient resulting will be composed of two components, namely, a *direct-current* component which is due to the fact that the armature coil is removed from a position of maximum flux interlinkages to one of zero interlinkages (see Fig. 241*b*), and an *alternating-current* component, the initial effective value of which is equal to the ratio of the effective no-load voltage divided by the transient reactance of the machine.

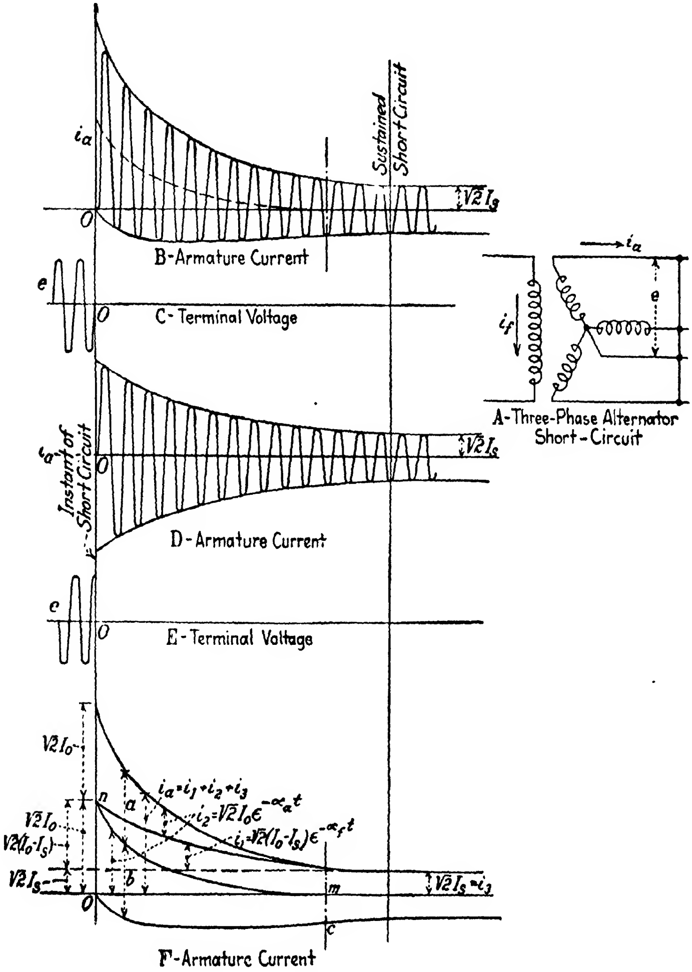

FIG. 242.

Such a transient is shown at $B$ and $C$ and in more detail at $F$ (Fig. 242). The curve drawn through the positive crests of the successive alternations of the transient of $B$ (Fig. 242) can be expressed mathematically as follows:

$$i_a = i_1 + i_2 + i_3 = \sqrt{2}\,(I_0 - I_s)\epsilon^{-\alpha_f t} + \sqrt{2}\,I_0\epsilon^{-\alpha_a t} + \sqrt{2}\,I_s \qquad (36)$$

where $i_1 + i_3 = \sqrt{2}\,(I_0 - I_s)\epsilon^{-\alpha_f t} + \sqrt{2}\,I_s$ = alternating component of the transient.

$i_2 = \sqrt{2}\,I_0\epsilon^{-\alpha_a t}$ = direct component of the transient

$I_0$ = initial effective phase value of the alternating component of short-circuit current $= E/X_t$

$E$ = effective no-load voltage per phase

$X_t$ = transient reactance of alternator, ohms per phase

$I_s$ = effective phase value of the sustained short-circuit current $= E/X_s$

$X_s$ = synchronous reactance of alternator, ohms per phase

$\alpha_f$ = field attenuation factor $= R_f/L_f$

$\mathrm{R}_f$ = effective resistance of the field circuit

$L_f$ = inductance of the field during the transient

$\alpha_a$ = armature attenuation factor $= R_a/L_a$

$R_a$ = effective resistance of the armature per phase

$L_a$ = inductance of the armature per phase

From the preceding discussion it follows that the short-circuit transient of an alternator may be anywhere between the following two limits:

1. A symmetrical transient, obtained if the short circuit occurs when the voltage wave is a maximum (see $D$ and $E$ in Fig. 242). In this case the instantaneous effective current $I_i$ will be equal to $I_0$.

2. An asymmetrical transient, obtained if the short circuit occurs when the voltage wave passes through zero (see $B$ and $C$ in Fig. 242). Since this condition gives the maximum possible short-circuit current of an alternator, its results should be used instead of those of the lower limit.

One may look upon such a transient as symmetrical with respect to an axis $nm$ (see $F$ in Fig. 242), which is determined by the direct-current component $i_2$ of the total short-circuit current

$i_a$. The effective value of the total current immediately after a short circuit must be equal to the square root of the sum of the initial effective direct current squared and the initial effective alternating current squared, or mathematically,

$$I_i = \sqrt{(\sqrt{2}\,I_0)^2 + I_0^2} = \sqrt{3}\,I_0 = 1.73 I_0 \tag{37}$$

Or, expressed in terms of the transient reactance,

$$I_i = \frac{1.73E}{X_t} \tag{38}$$

It is often desirable to express the short-circuit current in terms of the normal full-load current $I_N$ as follows:

$$I_i = \frac{1.73 I_N}{\dfrac{(I_N X_t)}{E}} \tag{39}$$

where $(I_N X_t)100/E$ is termed the per cent transient reactance.

The above theoretical value has been found to differ somewhat from the actual values obtained in practice; hence, in all practical calculations, it is preferable to use certain time decrement curves or tables (see Table XIII), which have been found to check with actual observed values. These tables give the values of short-circuit current in terms of full-load current for different values of leakage reactances.

The transient currents set up in the different phases of a polyphase generator cannot all be alike because of the relative displacement between the phase windings. In other words, a three-phase generator, when short-circuited, will contain three different current transients; the transient of phase $A$ may be symmetrical, that of phase $B$ may be offset above the reference axis, and that of phase $C$ below the reference axis.

Equation (39) can be used for complete short circuits on three-phase generators as well as for short circuits on single-phase generators, but it does not give the correct results for a single-phase short circuit on a three-phase generator.[1] The results for three-phase generators are shown in the following table:

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[1] An analysis of all practical cases of short circuits is given in an article by R. F. Franklin, Short-circuit Currents of Synchronous Machines, *Jour. A.I.E.E.*, August, 1925.

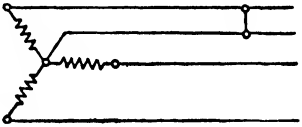
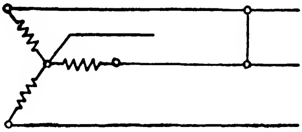
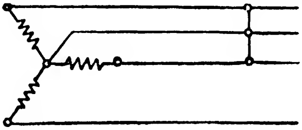
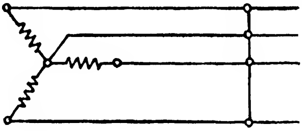
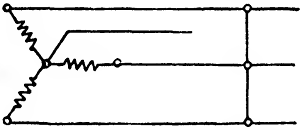
| Kind of short circuit | Three-phase alternator | Maximum peak value of current per phase as a ratio of that obtained in case 4 |
|---|---|---|
| Single-phase, terminal to neutral.......... | case 1  | 1.50 |
| Single-phase, terminal to terminal......... | case 2  | 0.866 |
| Two-phase, terminals to neutral.......... | case 3  | 1.732 |
| Three-phase, terminals to neutral.......... | case 4  | 1.00 |
| Three-phase, terminals to terminals........ | case 5  | 1.00 |

TABLE XII.—ALTERNATOR SHORT-CIRCUIT CURRENT

**154. Per Cent Reactance.**—The per cent reactance of any leg of a circuit is the reactance drop in volts in that leg of the circuit at normal current and frequency expressed as a per cent of the voltage to the neutral of that circuit. In order to distinguish between reactance in ohms and per cent reactance, the following nomenclature is adopted. The reactance in ohms will be designated by $X$ and the per cent reactance by the same letter preceded by the per cent notation, thus $\%X$. Hence, mathematically,

$$\%X = \frac{I_N X}{E} \times 100 \qquad (40)$$

When using the term reactance or per cent reactance it is necessary to specify whether transient or synchronous reactance or per cent reactance is meant, or

$$\%X_t = \frac{I_N X_t}{E} \times 100 = \text{per cent transient reactance*} \quad (41)$$

$$\%X_s = \frac{I_N X_s}{E} \times 100 = \text{per cent synchronous reactance} \quad (42)$$

Referring to Fig. 242 it will be noticed that the sustained value of current is obtained after the transient period has disappeared, and the wave of current becomes symmetrical about the horizontal axis; hence the sustained short-circuit current $I_s$ can be determined as follows:

$$I_s = \frac{E}{X_s} = \frac{I_N}{\%X_s} \times 100 \quad (43)$$

The initial effective short-circuit current or the short-circuit current at any instant of time after short circuit is determined by the use of Table XIII.

**155. Kilovolt-ampere Base of Per Cent Reactance.**—From Eq. (40) it is seen that per cent reactance depends on the current through the circuit, or the kilovolt-ampere rating of the circuit; in other words it is not sufficient to specify only the per cent reactance of a circuit, but in order that the information may be complete, it is necessary that the kilovolt-ampere rating of the circuit be specified in conjunction with the per cent reactance.

**156. Per Cent Reactances in Series.**—Consider the simple circuit of Fig. 243, having a generator of $X_l$ ohms transient reactance and normal current $I_g$, a reactance of $X_2$ ohms and rated current $I_2$, and a reactance of $X_3$ ohms and rated current of $I_3$ amperes. The total reactance of such a circuit is therefore, $X_T = X_l + X_2 + X_3$, and the total voltage drop in the circuit, when current $I_g$ flows, will be $I_gX_T = I_gX_l + I_gX_2 + I_gX_3$.

The total per cent reactance will be

$$\%X_T = \frac{I_gX_T}{E} \times 100 = \frac{I_gX_l + I_gX_2 + I_gX_3}{E} \times 100$$

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*** Transient reactance of alternators is the reactance under fault operation, while leakage reactance applies under running condition. These two reactances are nearly equal, in fact leakage reactance is often used in the calculation of initial current.**

## TABLE XIII.—APPLICABLE TO THREE-PHASE SHORT CIRCUITS ON THREE-PHASE SYSTEMS

(To be used for application of relays)

|  | Method of tripping breaker corresponding to time elapsed | Time in seconds from instant of short circuit[1] | Total r.m.s. current[2] expressed in number of times full-load current for various per cent reactance,[3] in per cent |  |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  | 5 | 8 | 10 | 12 | 15 | 20 | 30 | 40 | 50 | 60 | 75 | 100 |
| No relay | Alternating-current series trip coil. . | 0.00 | 35.00 | 22.00 | 17.75 | 14.90 | 12.00 | 9.01 | 6.00 | 4.52 | 3.55 | 2.94 | 2.36 | 1.74 |
|  | Current transformer. . . . . . . . . . . . . . | 0.05 | 21.18 | 13.60 | 11.10 | 9.40 | 7.74 | 5.89 | 3.98 | 3.04 | 2.41 | 2.03 | 1.64 | 1.23 |
|  | With alternating-current trip coil. | 0.08 | 18.15 | 11.65 | 9.50 | 8.15 | 6.72 | 5.14 | 3.50 | 2.89 | 2.15 | 1.81 | 1.47 | 1.11 |
| Solenoid or motor relay | Current transformer:<br>With alternating-current trip coil. | 0.10 | 16.50 | 10.70 | 8.81 | 7.52 | 6.22 | 4.79 | 3.28 | 2.54 | 2.03 | 1.72 | 1.40 | 1.06 |
|  | With direct-current trip coil. . . . . . | 0.15 | 13.48 | 8.85 | 7.36 | 6.32 | 5.30 | 4.13 | 2.87 | 2.25 | 1.83 | 1.56 | 1.28 | 0.981 |
| Induction relay | Current transformer:<br>With alternating-current trip coil. | 0.20 | 11.90 | 7.86 | 6.56 | 5.66 | 4.82 | 3.74 | 2.67 | 2.11 | 1.72 | 1.48 | 1.22 | 0.943 |
|  | With direct-current trip coil. . . . . . | 0.25 | 10.54 | 7.10 | 6.00 | 5.20 | 4.45 | 3.53 | 2.52 | 2.01 | 1.66 | 1.42 | 1.18 | 0.919 |
|  | Circuit breakers having alternating-current or direct-current trip with definite-time setting | 0.30 | 9.56 | 6.50 | 5.55 | 4.85 | 4.19 | 3.35 | 2.42 | 1.94 | 1.61 | 1.39 | 1.16 | 0.904 |
|  |  | 0.40 | 8.33 | 5.80 | 4.96 | 4.38 | 3.83 | 3.10 | 2.28 | 1.86 | 1.55 | 1.35 | 1.13 | 0.888 |
|  |  | 0.50 | 7.30 | 5.15 | 4.48 | 3.99 | 3.52 | 2.91 | 2.18 | 1.79 | 1.51 | 1.32 | 1.11 | 0.877 |
|  |  | 0.70 | 5.94 | 4.35 | 3.84 | 3.48 | 3.13 | 2.64 | 2.04 | 1.70 | 1.45 | 1.27 | 1.08 | 0.862 |
|  |  | 1.00 | 4.60 | 3.55 | 3.24 | 2.98 | 2.75 | 2.38 | 1.90 | 1.61 | 1.39 | 1.23 | 1.05 | 0.843 |
|  |  | 1.50 | 3.42 | 2.90 | 2.70 | 2.56 | 2.43 | 2.17 | 1.78 | 1.54 | 1.34 | 1.19 | 1.03 | 0.836 |
|  |  | 2.00 | 2.72 | 2.43 | 2.34 | 2.27 | 2.21 | 2.02 | 1.71 | 1.49 | 1.31 | 1.17 | 1.02 | 0.828 |
|  |  | 3.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 1.88 | 1.63 | 1.44 | 1.28 | 1.15 | 1.00 | 0.820 |

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[1] If breakers are equipped with undervoltage release mechanisms, use time value of 0.08 sec. unless such mechanism is provided with a definite-time adjustment that can be set the same as an overload relay.

[2] Rated full-load current based on maximum continuous kilovolt-ampere rating of synchronous machines. When the equivalent reactance of line, reactor, transformer, or combination of these, expressed in per cent based on the total synchronous machine rating, exceeds 150 per cent, the current to be interrupted may be determined directly from that reactance. This is due to the fact that under these conditions the generator reactance and time of opening of the breaker may be neglected.

[3] This includes both internal reactance of machines and reactance of external circuit reduced to the above basis. For reactance values not shown, use the next lower listed reactance.

r

$$\%X_T = \frac{I_g X_l}{E} \times 100 + \frac{I_2 X_2}{E} \times \frac{I_g}{I_2} \times 100 + \frac{I_3 X_3}{E} \times \frac{I_g}{I_3} \times 100$$

$$\%X_T = \%X_l + \%X_2 \frac{I_g}{I_2} + \%X_3 \frac{I_g}{I_3} \qquad (44)$$

Equation (44) indicates that if there are several reactances in eries, the total equivalent per cent reactance is the sum of the individual per cent reactances based on the total rating of the connected generating equipment.[1]

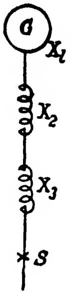

FIG. 243.

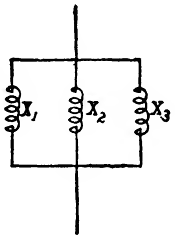

FIG. 244.

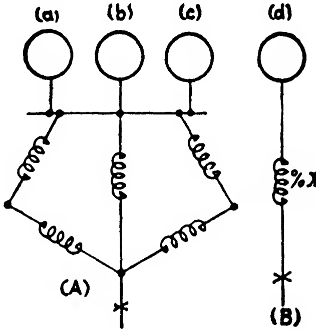

FIG. 245.

In the above the transient reactance of the generator was used; hence the reactance $X_T$ will determine the initial effective current that will flow in case of a short circuit at $S$. If the synchronous reactance of the generator had been used instead of the transient reactance, then the value of $X_T$, which would have been found from Eq. (44), would determine the sustained short-circuit current at $S$.

**157. Per Cent Reactances in Parallel.**—In Fig. 244 is shown a circuit composed of three reactances $X_1$, $X_2$, and $X_3$ connected

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[1] Often the equipment of a power network will be operated at voltages not equal to the name-plate data. In such cases the name-plate data on per cent impedance should be corrected to correspond to the operating voltage: thus,

$$\%Z_0 = \%Z_r \left(\frac{V_r}{V_0}\right)^2$$

where $\%Z_0$ = operating per cent impedance
$\%Z_r$ = name-plate rated per cent impedance
$V_0$ = operating voltage
$V_r$ = rated, name-plate voltage

in parallel, the normal currents of each being $I_1$, $I_2$, and $I_3$, respectively.

The equivalent reactance of the combination is

$$X_T = \frac{1}{\frac{1}{X_1} + \frac{1}{X_2} + \frac{1}{X_3}}$$

The equivalent per cent reactance of the combination is

$$\%X_T = \frac{I_T X_T}{E} \times 100 = \frac{I_T}{E} \cdot \frac{100}{\frac{1}{X_1} + \frac{1}{X_2} + \frac{1}{X_3}}$$

where

$$I_T = I_1 + I_2 + I_3$$

or

$$\%X_T = \frac{100}{\frac{1}{\frac{I_T X_1}{E}} + \frac{1}{\frac{I_T X_2}{E}} + \frac{1}{\frac{I_T X_3}{E}}}$$

$$= \frac{1}{\frac{1}{\%X_1 \cdot \frac{I_T}{I_1}} + \frac{1}{\%X_2 \cdot \frac{I_T}{I_2}} + \frac{1}{\%X_3 \cdot \frac{I_T}{I_3}}} \qquad (45)$$

Equation (45) indicates that the equivalent per cent reactance of a parallel combination is equal to the reciprocal of the sum of the reciprocals of the individual per cent reactances of each circuit of the combination converted to the bases of the total capacity of the entire combination.

**158. Per Cent Reactances in Series Parallel Circuits.**—In order to obtain the equivalent per cent reactance of a series parallel circuit, proceed in the following order:

1. Convert all values of per cent reactances to a common base, which for convenience is generally taken as the sum of the ratings of all the generating equipment connected to the network.
2. Pick out all the series circuits and obtain an equivalent value of per cent reactance for each one.
3. Do the same thing for the parallel circuits within the network.
4. Combine the results of items 2 and 3 until the network has been converted to an equivalent series circuit involving an equiv-

alent generator having a capacity equal to the sum of all the individual generator capacities and one equivalent value of per cent reactance. The problem is illustrated in Fig. 245. The network in part *A* is resolved into an equivalent simple circuit as shown in *B*, where the capacity of generator *d* is equal to the sum of the capacities of generators *a*, *b*, and *c* of network *A*, and the per cent reactance $\%X_B$ is the equivalent of the per cent reactances in the entire network shown in *A*.

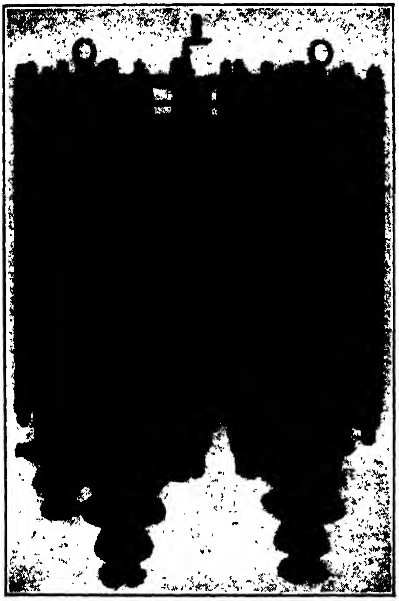

FIG. 246.—Current-limiting reactor. (*Westinghouse Electric Corporation.*)

**159. Current-limiting Reactors.**—It has been shown under the subject of short-circuit currents that the value of current that will flow after a short circuit depends on the amount of reactance in the circuit; hence it is possible to insert into circuits that are subjected to excessive short-circuit currents as much reactance as necessary in the form of a reactance coil or *reactor*. In general it can be stated that reactors perform three definite functions, as follows:

1. Troubles may be localized or isolated at the point where they originate without communicating their disturbing effects to the other parts of the network.

2. They limit the flow of current into a short circuit with the view of protecting the equipment from overheating as well as from failure due to destructive mechanical forces, and also of protecting the system as a whole against shutdown by maintaining the voltage on most of the system while the short circuit is being cleared.

3. They permit the installation of lower capacity circuit breakers.

In Fig. 246 are shown the general details of a current-limiting reactor. It is composed of a winding that is generally made of standard bare copper cable and some type of supporting frame. The winding may be all in series, or in the case of reactors of large current-carrying capacity, it is designed in as many parallel paths as necessary. In the case of a reactor having more than one path, it is necessary so to place the winding that each path will enclose the same amount of flux; otherwise there are apt to be circulating currents among the parallel paths, thereby causing the reactor to heat.

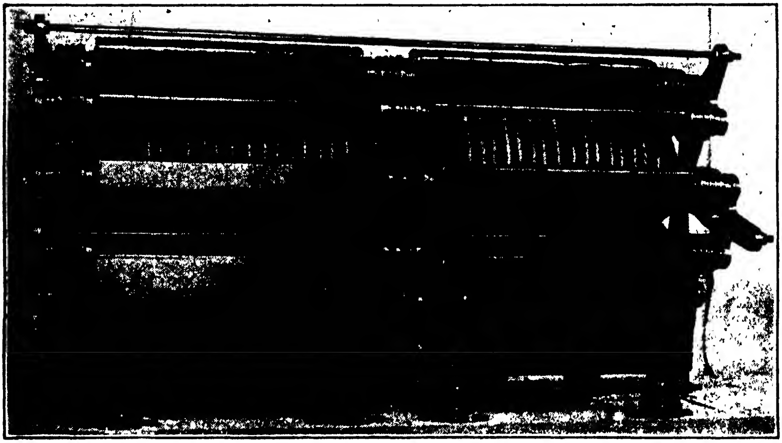

Fig. 247.—Current-limiting reactors. (*General Electric Company.*)

There are two general methods used for supporting the cables:

1. The cables may be wound into grooves in especially prepared, molded, noninflammable supports which are held together by means of heavy nonconducting rods that pass vertically through them. The rods are fastened at the top and bottom to nonmagnetic castings which are arranged for bolting the insulat-

ing supports to them (see Fig. 246). These sectional supports are in some cases made of porcelain, but the main disadvantage of porcelain is the fact that it is not so strong as some other types of supports.

2. A stronger type of construction is shown in Fig. 247, in which case the winding is enclosed in solid-concrete supports which are cast around the cables.

**160. Location of Reactors.**—Reactors may be placed in the generator leads, between bus sections, in the low-tension transformer leads, or in outgoing low-tension feeders. No definite statement can be given as to which one of the above locations is preferable; each installation has its own particular demands which must be carefully considered before a choice of reactor location can be made. A brief description of the most important applications is given below.

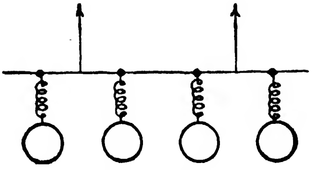
FIG. 248.

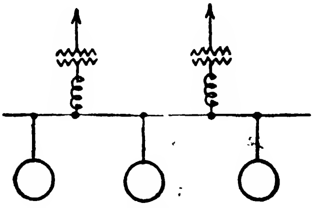
FIG. 249.

**161. Generator Reactors.**—In Fig. 248 is shown the application of reactors in the generator leads. In this case the reactor may be considered as a part of the transient reactance of the generator; hence its effect is to protect the generator in case of any short circuit beyond the reactors. In the case of slow-speed alternators, as for example in some of the hydroelectric units, it is possible to incorporate as much reactance as necessary in the generator itself; hence no reactors are needed. For this reason reactors are rarely used in the generator leads of hydraulic plants. In the case of high-speed turboalternators, it may often be desirable to use reactors in the generator circuit.

**162. Transformer Reactors.**—In a few cases reactors have been installed in the low-tension side of power transformers as shown in Fig. 249, but as a general rule transformers can be designed with enough inherent reactance so that reactors are seldom necessary in the transformer circuits.

**163. Bus Reactors.**—In power plants containing a large number of units it is often desirable to break up the low-tension bus into sections so that troubles can be confined to the section in which they started. These sections can be permanently connected through reactors, thereby obtaining a high degree of flexibility and also obtaining the protection under short-circuit conditions due to the localizing effect of the reactor (Fig. 250).

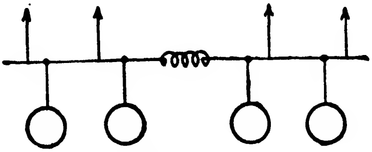

FIG. 250.

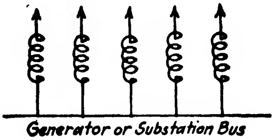

FIG. 251.

**164. Feeder Reactors.**—Most of the disturbances and short circuits occur in the low-tension distribution feeders either feeding from a power plant or distributing substation; hence it is not surprising that a large number of reactors are used for such circuits. In the case of a short circuit in a particular feeder, the reactor prevents the communication of the trouble to the remainder of the system (Fig. 251).

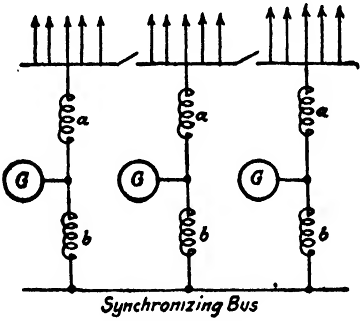

FIG. 252.

**165. Stott System.**—This scheme (Fig. 252) was proposed by the late H. G. Stott, of the Interborough Rapid Transit Company of New York, and is sometimes used in connection with large steam-turbine-driven central stations. The feeder busses are normally operated in sections, but provision is made so that all feeder sections can be connected through switches in the feeder busses. From Fig. 252 it will be noticed that, in case of trouble in any set of feeders, there will be introduced between the fault and any other generator, other than the one feeding that particular set of feeders, a total reactance of $a + 2b$. This scheme provides ample protection for power plants that are located in the load center and therefore distribute the entire output of the plant at comparatively low voltages through a large number of feeders.

Often reactors may be used in more than one of the above applications within one power plant. In the design of power systems, it is important that an accurate determination be made of the abnormal currents that might be flowing in the case of short circuits in order that proper choice of current-limiting reactors may be made.

### Questions for Class Discussion

**1.** Why must the problem of short-circuit currents and stresses be given more careful consideration in the design of large power systems than in small isolated plants?

**2.** In what two ways have designers met this problem?

**3.** Give illustrations of how the mechanical strength of apparatus and networks has been increased.

**4.** How many times normal current will a large alternating-current generator deliver momentarily when its terminals are short-circuited?

**5.** To about how many times normal current should the line current be limited on short circuit?

**6.** Explain what is meant by a symmetrical and an unsymmetrical synchronous-generator short-circuit transient. Under what conditions will these two transients be obtained?

**7.** Prove that the effective value of the total phase current immediately after a short circuit of a synchronous generator may reach the value $I_i = 1.73I_0$; where $I_0$ = initial effective phase value of the alternating component of short-circuit current $= E/X_t$; where $E$ = generator voltage per phase, and $X_t$ = transient reactance in ohms per phase.

**8.** What is meant by the term "per cent reactance"? What is the difference between "per cent transient reactance" and "per cent synchronous reactance"?

**9.** When using the term "per cent reactance," why must a basis of kilovolt-ampere capacity be specified?

**10.** Enumerate in their proper sequence the required steps that are necessary in order to obtain the equivalent per cent reactance of a series parallel circuit.

**11.** What two functions are served by a protective reactance?

**12.** Describe in brief the construction of ordinary current-limiting reactors.

**13.** Why are protective reactors commonly built without an iron core?

**14.** Reactors are rated at so many per cent and a certain number of kilovolt-amperes. Explain the rating.

**15.** Are reactances desirable from the standpoint of voltage regulation in the line? Is the regulation really as bad as might be indicated by the per cent reactance?

**16.** Would a resistance make as desirable a protective device as a reactance coil? Why?

**17.** Give an example of how protective reactances may "localize" trouble.

**18.** In what parts of the circuit may protective reactances be located? Why are they always placed on the low-tension side?

# CHAPTER XIV

## CALCULATION OF SHORT-CIRCUIT CURRENTS

In this chapter a few typical examples of short-circuit-current calculations are carried through for the case of complete three-phase short circuits to neutral.

**166. Example I.**—A three-phase 20,000-kva. generator of 90 per cent synchronous reactance and 15 per cent transient reactance supplies a substation through a single transmission line of 20,000-kva. capacity and 10 per cent reactance. A complete short circuit occurs at $x$ (Fig. 253) on a 5,700-kva. 11-kv. feeder.

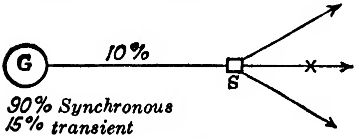

FIG. 253.

Determine:

1. The normal current of the feeder.
2. The initial effective short-circuit current; first, assuming a symmetrical transient and, second, an asymmetrical transient.
3. The sustained short-circuit current.
4. The rating of a reactor, in per cent reactance based on 5,700 kva., to be placed in the feeder in order to limit the sustained short-circuit current to 700 amp.

*Solution.*

$$(1)\qquad I_N = \frac{5{,}700}{\sqrt{3} \times 11} = 300 \text{ amp.}$$

$$(2)\quad I_0 = \frac{20{,}000}{\sqrt{3} \times 11} \times \frac{100}{15 + 10} = 1{,}050 \times \frac{100}{25} = 4{,}200 \text{ amp.}$$

for the case of a symmetrical transient.

From Table XIII, Art. 154, the current multiplier for a total of 25 per cent reactance is found to be approximately 7.5, by interpolating between the figures given for 20 and 30 per cent reactance.

Hence

$$I_t = \frac{20{,}000}{\sqrt{3} \times 11} \times 7.5 = 1{,}050 \times 7.5 = 7{,}875 \text{ amp.}$$

for the case of an asymmetrical transient.

(3) $$I_S = 1{,}050 \times \frac{100}{100} = 1{,}050 \text{ amp.}$$

The total reactance necessary in the circuit

(4) $$\%X_T = \frac{20{,}000}{\sqrt{3} \times 11} \times \frac{100}{700} = \frac{1{,}050 \times 100}{700} = 150 \text{ per cent}$$

based on 20,000 kva.

The rating of the reactor

$$\%X_R \doteq (150 - 100)\frac{5{,}700}{20{,}000} = 14.25 \text{ per cent}$$

on the basis of 5,700 kva.

**167. Example II.**—Given a three-phase system as shown by the single-line diagram of Fig. 254. Synchronous reactance of machine $A$ = 30 per cent and of machine $B$ = 50 per cent, each based on its own capacity. Determine the sustained short-circuit current that will flow into a complete three-phase short circuit at $x$, by the following three methods.

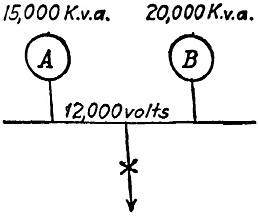

FIG. 254.

1. Component short-circuit currents.
2. Reactances in ohms.
3. Equivalent per cent reactances.

*Solution* 1.—Component short-circuit currents. Sustained short-circuit current delivered by generator $A$:

$$I_{SA} \doteq \frac{15{,}000}{\sqrt{3} \times 12} \times \frac{100}{30} = 720 \times \frac{100}{30} = 2{,}400 \text{ amp.}$$

Sustained short-circuit current delivered by generator $B$:

$$I_{SB} = \frac{20{,}000}{\sqrt{3} \times 12} \times \frac{100}{50} = 964 \times \frac{100}{50} = 1{,}930 \text{ amp.}$$

Therefore, the total sustained short-circuit current delivered will be

$$I_S = I_{SA} + I_{SB} = 2{,}400 + 1{,}930 = 4{,}330 \text{ amp.}$$

*Solution* 2.—Reactance in ohms. Normal current of generator $A$:

$$I_{NA} = \frac{15{,}000}{\sqrt{3} \times 12} = 720 \text{ amp.}$$

Synchronous reactance in ohms of generator $A$:

$$X_A = \frac{\%X_A}{100} \times \frac{E}{\sqrt{3}\, I_{NA}} = \frac{30}{100} \times \frac{12{,}000}{\sqrt{3} \times 720} = 2.88 \text{ ohms}$$

Normal current of generator $B$:

$$I_{NB} = \frac{20{,}000}{\sqrt{3} \times 12} = 964$$

Synchronous reactance in ohms of generator $B$:

$$X_B = \frac{\%X_B}{100} \times \frac{E}{\sqrt{3}\, I_{NB}} = \frac{50}{100} \times \frac{12{,}000}{\sqrt{3} \times 964} = 3.6 \text{ ohms}$$

Therefore,

$$I_{SA} = \frac{E}{\sqrt{3}\, X_A} = \frac{12{,}000}{\sqrt{3} \times 2.88} = 2{,}400 \text{ amp.}$$

$$I_{SB} = \frac{E}{\sqrt{3}\, X_B} = \frac{12{,}000}{\sqrt{3} \times 3.6} = 1{,}930 \text{ amp.}$$

and

$$I_S = 2{,}400 + 1{,}930 = 4{,}330 \text{ amp.}$$

The short-circuit current can also be found from the equivalent reactance in ohms as follows:

$$X_{eq} = \frac{1}{\frac{1}{X_A} + \frac{1}{X_B}} = \frac{1}{\frac{1}{2.88} + \frac{1}{3.6}} = \frac{1}{0.625} = 1.6 \text{ ohms}$$

Therefore,

$$I_S = \frac{12{,}000}{\sqrt{3} \times 1.6} = 4{,}330 \text{ amp.}$$

*Solution* 3.—Equivalent per cent reactances. Total generating capacity = 35,000 kva. Per cent reactances to the basis of 35,000 kva.

$$\%X_A = 30 \times \frac{35}{15} = 70 \text{ per cent}$$

$$\%X_B = 50 \times \frac{35}{20} = 87.5 \text{ per cent}$$

Equivalent per cent reactance

$$\%X_{eq} = \frac{1}{\frac{1}{\%X_A} + \frac{1}{\%X_B}} = \frac{1}{\frac{1}{70} + \frac{1}{87.5}} = \frac{1}{0.0257} = 39 \text{ per cent}$$

Therefore,

$$I_S = \frac{35{,}000}{\sqrt{3} \times 12} \times \frac{100}{39} = 4{,}330 \text{ amp.}$$

NOTE: In a simple problem as Example II any of the three methods can be used with about the same degree of ease, but in complicated network it will be found that the method of equivalent per cent reactances has greater advantage owing to the ease by which the computation can be carried out.

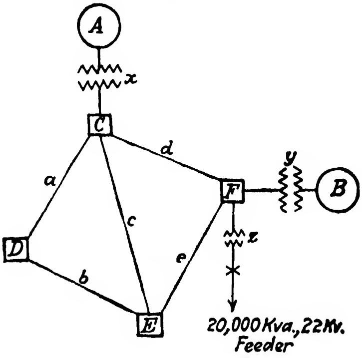

FIG. 255.

**168. Example III.**—Given the following three-phase network (Fig. 255). *A* and *B* are generating plants. *C*, *D*, *E*, and *F* are substations. The per cent reactances tabulated below are based on the rating of the particular parts of the network.

| Circuit | Capacity in kilovolt-amperes | Per cent reactance |
|---|---|---|
| Generating plants: | | |
| *A* | 150,000 | 90 (synchronous)<br>30 (transient) |
| *B* | 50,000 | 50 (synchronous)<br>17.5 (transient) |
| Transformers: | | |
| *x* | 150,000 | 10 |
| *y* | 50,000 | 8 |
| *z* | 20,000 | 5 |
| Transmission lines: | | |
| *a* | 40,000 | 10 |
| *b* | 20,000 | 5 |
| *c* | 50,000 | 20 |
| *d* | 30,000 | 15 |
| *e* | 10,000 | 6 |

Determine:

1. The initial effective short-circuit current at $x$.
2. The sustained short-circuit at $x$.

1. Equivalent per cent reactance of transmission lines $a$ and $b$:

$$\%X_{a+b} = 10 \times \frac{200}{40} + 5 \times \frac{200}{20} = 100 \text{ per cent}$$

Equivalent per cent reactance of transmission line $c$:

$$\%X_c = 20 \times \frac{200}{50} = 80 \text{ per cent}$$

Equivalent per cent reactance between substations $C$ and $E$:

$$\%X_{CE} = \frac{1}{\frac{1}{100} + \frac{1}{80}} = 44.5 \text{ per cent}$$

Equivalent per cent reactance between substations $C$ and $E$ plus transmission line $e$:

$$\%X_{CE+e} = 44.5 + 6 \times \frac{200}{10} = 164.5 \text{ per cent}$$

Equivalent per cent reactance between substations $C$ and $F$:

$$\%X_{CF} = \frac{1}{\frac{1}{164.5} + \frac{1}{15 \times \frac{200}{30}}} = 62 \text{ per cent}$$

Equivalent per cent reactance from generator $A$ to substation $F$ (consider leakage reactance of generator):

$$\%X_{AF} = (30 + 10)\frac{200}{150} + 62 = 115.3 \text{ per cent}$$

Equivalent per cent reactance from generator $B$ to substation $F$ (consider leakage reactance of generator):

$$\%X_{BF} = (17.5 + 8)\frac{200}{50} = 102 \text{ per cent}$$

Equivalent per cent reactance to substation $F$:

$$\%X_F = \frac{1}{\frac{1}{115.3} + \frac{1}{102}} = 54.2 \text{ per cent}$$

Equivalent per cent reactance to point of short circuit $x$:

$$\%X_T = 54.2 + 5 \times \frac{200}{20} = 54.2 + 50 = 104.2 \text{ per cent}$$

Therefore,

$$I_0 = \frac{200{,}000}{\sqrt{3} \times 22} \times \frac{100}{104.2} = 5{,}250 \times \frac{100}{104.2} = 5{,}040 \text{ amp.}$$

for the case of a symmetrical transient, and

$$I_i = 1.73 \times 5{,}040 = 8{,}700 \text{ amp.}$$

for the case of an asymmetrical transient [see Art. 153, Eq. (37)].

2. The equivalent per cent reactance between substations $C$ and $F$ remains the same as obtained in part 1, namely,

$$\%X_{CF} = 62 \text{ per cent}$$

Following the same method as outlined in detail in part 1, except that synchronous instead of transient per cent reactances are used for the generators,

$$\%X_{AF} = (90 + 10)\frac{200}{150} + 62 = 133 + 62 = 195 \text{ per cent}$$

$$\%X_{BF} = (50 + 8)\frac{200}{50} = 232 \text{ per cent}$$

$$\%X_F = \frac{1}{\frac{1}{195} + \frac{1}{232}} = 106 \text{ per cent}$$

$$\%X_T = 106 + 50 = 156 \text{ per cent}$$

Therefore,

$$I_S = 5{,}250 \times \frac{100}{156} = 3{,}365 \text{ amp.}$$

The rated current of the feeder which has the short circuit is

$$I_N = \frac{20{,}000}{\sqrt{3} \times 22} = 525 \text{ amp.}$$

Therefore, the initial effective short-circuit current for the case of asymmetrical transient is

$$I_i = \frac{8{,}700}{525} I_N = 16.6 I_N$$

and the sustained short-circuit current is

$$I_S = \frac{3{,}365}{525} I_N = 6.43 I_N$$

### Questions for Class Discussion

**1.** In the three-phase circuit of Fig. $A$:

$A$ = 25,000-kva. generator. Per cent transient reactance = 10 per cent; per cent synchronous reactance = 37.5 per cent.

$B$ = 75,000-kva. generator. Per cent transient reactance = 15 per cent.

$C$ = reactor of 5 per cent reactance based upon 25,000 kva. Generator line voltage = 13,500 volts.

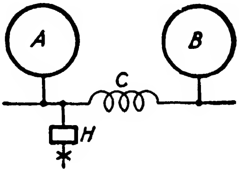

FIG. $A$.

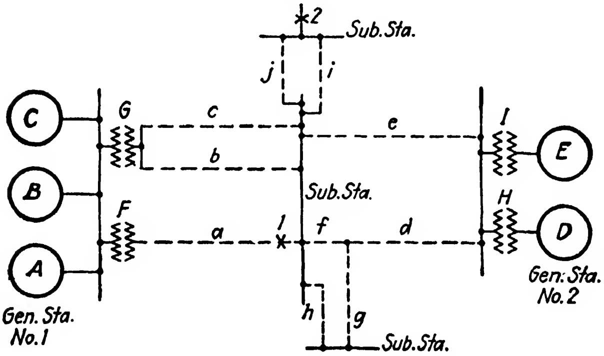

FIG. $B$.

*a*. If the relay-controlling circuit breaker $H$ has a time setting of 0.4 sec., determine the circuit-breaker rating as follows:

1. Interrupting current in amperes.
2. Arc kilovolt-amperes.

*b*. The sustained short-circuit current delivered to a short circuit at $X$ is 5,700 amp. Determine the per cent synchronous reactance of generator $B$ on the basis of 75,000 kva.

**2.** Assume a three-phase power network as given by Fig. $B$. The ratings, voltage, and per cent reactances of each part of the network are as in the table on page 319.

*a*. Determine the sustained short-circuit current that will flow into (*a*) the short circuit at 1; (*b*) the short circuit at 2.

*b*. Determine the initial short-circuit current that will flow into (*a*) the short circuit at 1; (*b*) the short circuit at 2; for both symmetrical and asymmetrical generator transients.

| Circuit generators | Capacity circuit in kva. | Kilovolts | Per cent reactances* | |
|---|---|---|---|---|
| *A* | 20,000 | 12 | 10 | 50 |
| *B* | 30,000 | 12 | 15 | 60 |
| *C* | 50,000 | 12 | 20 | 80 |
| *D* | 45,000 | 12 | 15 | 70 |
| *E* | 55,000 | 12 | 25 | 90 |
| Transformers | | | | |
| *F* | 40,000 | 12/110 | 5.0 | |
| *G* | 50,000 | 12/110 | 7.0 | |
| *H* | 45,000 | 12/110 | 6.0 | |
| *I* | 55,000 | 12/110 | 10.0 | |
| Transmission lines | | | | |
| *a* | 30,000 | 110 | 3.0 | |
| *b* | 20,000 | 110 | 1.0 | |
| *c* | 40,000 | 110 | 4.0 | |
| *d* | 40,000 | 110 | 2.0 | |
| *e* | 40,000 | 110 | 1.5 | |
| *f* | 20,000 | 110 | 0.5 | |
| *g* | 20,000 | 110 | 0.6 | |
| *h* | 10,000 | 110 | 0.25 | |
| *i* | 30,000 | 110 | 1.5 | |
| *j* | 30,000 | 110 | 1.5 | |

* Transient and synchronous reactances are shown for the generators.

# CHAPTER XV

# TRANSMISSION-LINE CALCULATIONS

## ELECTRICAL CHARACTERISTICS[1]

**169. Direct-current Line.**—The design of direct-current lines is rather simple as compared with long-distance alternating-current lines of high voltage. There are three important factors that must be investigated in the direct-current design, namely, (*a*) volts drop in the line, (*b*) the power loss in the line, and (*c*) the safe current-carrying capacity of the conductors.

The voltage drop in the line is limited to a rather low value: for lighting loads it should not exceed more than 2 to 3 per cent of normal receiver voltage at full load; for industrial power loads a voltage drop of 5 per cent or slightly higher is not objectionable. The power loss in the line should be kept down to a reasonable value, in order that the line efficiency may not be poor. For outdoor lines the current-carrying capacity is not so important as the first two items above, but in the case of indoor installations it is important not to exceed the current-carrying capacity limits as fixed by the National Electrical Code, in order to safeguard property against possible destruction due to fire.

**170. Voltage Regulation and Efficiency.**—Voltage regulation of any transmission line, whether direct current or alternating current, is defined as the variation in voltage at the receiver end from full load to no load expressed as a percentage of the normal full-load receiver voltage, or expressed mathematically,

$$\text{V.R.} = \frac{E_0 - E_{\text{F.L.}}}{E_{\text{F.L.}}} \times 100 \qquad (46)$$

The efficiency of a line, as of any other machine, is the ratio of the output power to the input power, or expressed mathematically,

$$\text{Efficiency} = \frac{\text{output}}{\text{input}} \times 100 = \frac{\text{output}}{\text{output} + \text{losses}} \times 100 \qquad (47)$$

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[1] For a more detailed study, of electrical characteristics, see J. G. Tarboux, "Introduction to Electric Power Systems," International Textbook Company, Scranton, Pa.

**171. Economical Size of Conductor.**—The total cost that must be charged against a transmission-line conductor is made up of three separate items: the cost that is independent of the conductor size, the cost that varies with the size of conductor, and the cost of the energy loss in the conductor, or

$$C = K + C_1 + C_2$$

where $C$ = total annual cost
$K$ = constant annual cost
$C_1$ = annual cost proportional to conductor size
$C_2$ = annual cost of power loss

The annual cost proportional to conductor size includes more than the conductor alone, as there are certain items of hardware and tower design that are affected by the cross-sectional area of the conductor. These additional items cannot, however, affect the value of the cost to a great extent; therefore, for simplicity, the item $C_1$ is considered as the cost of the conductor alone. This may be stated as follows:

$$C_1 = wLAC_cF \tag{48}$$

where $w$ = weight of conductor per circular mil-foot = 3.03 $\times 10^{-6}$ for copper
$A$ = area of conductor, circular mils
$L$ = total length of conductor, feet (for three conductors if line is three phase)
$C_c$ = cost of conductor per pound
$F$ = annual fixed charges, including taxes, insurance, interest, and depreciation = 15 per cent (good average)

It is possible to take into account some of the miscellaneous items of cost other than the conductor itself by making proper corrections of the unit cost $C_c$.

The power loss for a line is

$$\frac{I^2R}{1{,}000} = \frac{I^2\rho L}{1{,}000A}\text{ kw} \tag{49}$$

where $\rho$ = ohms per circular mil-foot = 10.6 for annealed copper. The coefficient $L$ has the same meaning as given above.

It has been shown[1] that the yearly energy loss in a line can be expressed as follows:

$$\text{Kilowatt-hour loss} = \text{kw.}_{max} \times C_f = \frac{I_m{}^2\rho L}{1{,}000A} \times C_f \qquad (50)$$

where

$$I_m = \text{maximum demand current}$$

and

$$\sqrt{C_f} = 9 + 0.8459K \qquad (51)$$

where $K$ = yearly load factor in per cent.
Therefore the cost of energy loss per year is

$$C_2 = \frac{I_m{}^2\rho LC_f}{1{,}000A} C_e \qquad (52)$$

where $C_e$ = cost of energy per kilowatt-hour.
There the total is

$$C = K + wLAC_cF + \frac{I_m{}^2LC_fC_e}{1{,}000A} \qquad (53)$$

Differentiating with respect to the area, and setting the first derivative equal to zero,

$$\frac{dC}{dA} = 0 + wLC_cF - \frac{I_m{}^2\rho LC_fC_e}{1{,}000A^2} = 0 \qquad (54)$$

Or the most economical area of conductor in circular units is

$$A = I_m \sqrt{\frac{\rho C_fC_e}{1{,}000wC_cF}} \qquad (55)$$

For annealed copper, Eq. (55) reduces to

$$A = 59I_m \sqrt{\frac{C_fC_e}{C_cF}} \qquad (56)$$

In the case of alternating-current line, the size of conductors cannot be chosen on the basis of power loss alone, but other things must be considered, such as (*a*) mechanical strength, (*b*) required voltage regulation, (*c*) corona, (*d*) cost, and (*e*) current-carrying capacity. In the case of long spans mechanical strength is of great importance; for comparatively low-voltage lines,

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[1] See article by J. G. Tarboux, *Elec. World*, Vol. 93, No. 12, p. 591, Mar. 23, 1929.

power loss, voltage regulation, current-carrying capacity, and cost are important. On high-voltage lines, however, corona (see Art. 182) often demands a conductor size larger than would be necessary on the basis of power loss; and voltage regulation is generally taken care of by means of synchronous condensers, while mechanical strength generally requires either a conductor of large section or else one with a steel core. The solution, therefore, of the most economical conductor for alternating-current service is one involving many factors that cannot be easily taken care of.

The principle set forth in the above solution is however important and helpful, particularly in the design of low-voltage lines. It is seen from Eq. (54) that, for the conductor of lowest total cost, the cost of yearly energy loss in the line must equal the yearly fixed charges on that portion of the conductor cost which is proportional to the area. This law is generally known as Kelvin's law, after Lord Kelvin who first deduced its relations.

For long lines, owing to capacity effects, the current is not the same along the length of the line. This would cause an additional source of error in using the results just obtained, but in the article cited in the footnote (see page 322) a method has been worked out for taking into account this variation of current in long lines.

**172. Alternating-current Line.**—Alternating-current transmission lines involve three circuits which are distinctly different but closely related to each other. These are (*a*) the electric circuit, (*b*) the magnetic circuit, and (*c*) the dielectric circuit. The magnetic circuit consists of lines of magnetic force which encircle the current-carrying conductors, while the dielectric circuit consists of lines of dielectric stress which terminate in the conductors. The presence of the magnetic and dielectric circuits introduces effects upon the line which are measured as inductance $L$ and capacity $C$, respectively. Therefore, alternating-current lines have a resistance $R$, a reactance $X$, and a capacity susceptance $B$. In addition to these three constants, there may often be a leakage current, owing to damaged insulation between conductors and ground, in which case a fourth line constant is present, namely, leakage $G$. Expressing these constants in complex form,

$$Z = \text{total line impedance} = R + jX \qquad (57)$$

$$Y = \text{total line admittance} = G + jB \qquad (58)$$

**173. Skin Effect.**—When an alternating current flows through a conductor, a magnetic flux is set up around that conductor and also in the conductor itself. It follows, therefore, that the center of the conductor is encircled by more lines of force than the outer layers of the conductor; hence a higher voltage of self-induction will be generated in the center than on the outer surface. Because of the unequal e.m.fs. thus induced, the current flowing through the conductor will distribute itself in such a manner that the current density will be less in the interior of the conductor than at the surface. This tendency of alternating current to crowd itself at the surface is known as "skin effect." If $R$ is the direct-current resistance, then the alternating-current resistance

$$R' = KR^* \tag{59}$$

where

$$K = \frac{1 + \sqrt{1 + F^2}}{2} \tag{60}$$

and $F$ is proportional to the product of conductor cross section and frequency. The value of $F$ for copper is

$$F = 0.0105d^2f$$

and for aluminum,

$$F = 0.0063d^2f$$

where $d$ is the diameter of the conductor in inches and $f$ is the frequency in cycles per second.

**174. Reactance of Three-phase Transmission Lines.**—The reactance of transmission lines for each conductor per mile of length is

$$X = 2\pi f\left(80 + 741.1 \log_{10} \frac{S}{r}\right) 10^{-6} \text{ ohms per mile}^\dagger \tag{61}$$

where $S$ is the distance between conductors, and $r$ is the radius of the conductors.

When the three conductors have an unsymmetrical arrangement, it is obvious that the three reactances will be different.[1]

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* Formula by Alfred Still in "Electric Power Transmission."

† See "Standard Handbook for Electrical Engineers."

[1] For a determination of the reactance and capacity of lines having unsymmetrical arrangements of conductors, see J. G. Tarboux, "Introduction to Electric Power Systems," International Textbook Company, Scranton, Pa.

In order to balance up the reactances in the three phases, it is common practice to transpose the conductors. Under these conditions an average reactance is obtained which can be very accurately solved by choosing an equivalent spacing.

$$S' = \sqrt[3]{S_1 S_2 S_3}$$

where $S_1$, $S_2$, and $S_3$ are the distances between the three conductors.

**175. Capacity of Three-phase Transmission Lines.**—When $S$ is greater than $20r$, which is always the case in high-tension transmission lines employing bare conductors, the capacity between any one conductor and the neutral is

$$C = \frac{0.03883}{\log_{10} \frac{S}{r}} \text{ microfarads per mile} \tag{62}$$

The capacity susceptance between one conductor and the neutral will, therefore, be

$$B = 2\pi f C = 2\pi f \left( \frac{0.03883}{\log_{10} \frac{S}{r}} \right) \times 10^{-6} \text{ mho per mile} \tag{63}$$

If the distance $S$ is less than $20r$, Eq. (63) will be in error, and the following exact formula must be used:

$$C = \frac{0.03883}{\log_{10} (a + \sqrt{a^2 - 1})} \tag{64}$$

where

$$a = \frac{S}{2r}$$

The charging current is, therefore,

$$I_c = BE \tag{65}$$

The voltage along the line is, however, variable, depending on the particular constants of the line and also on the load delivered. The term "charging current," however, is generally considered as the current that flows into the line at the supply end with normal voltage held at the receiver end at zero load. It is, therefore, customary to calculate the total charging current of the line by multiplying the total line-capacity susceptance by the normal receiver-end voltage. The error involved in such a method is rather small and for the average transmission line is negligible.

**176. Line Voltages.**—There is no definite rule that can be followed when choosing the proper voltage for a particular line. Attempts have been made to obtain mathematically an expression for the most economical voltage, but these expressions have generally been unsatisfactory. For a first approximation the following empirical formula may be used for lines over 20 miles in length:

$$\text{Line pressure in kilovolts} = 5.5\sqrt{L + \frac{\text{kw.}}{100}}^{*} \qquad (66)$$

where $L$ = distance of transmission in miles, and kw. = estimated maximum kilowatts to be transmitted.

As a check on the above equation, Table XIV may be consulted. These values should not be considered as absolute; often short lines of high kilowatt capacity will necessitate higher voltages than given. The most common power-transmission-line voltages are those listed from 44,000 volts and up.

TABLE XIV.—COMMON TRANSMISSION VOLTAGES

| Length of line, miles | Voltages, volts |
|---|---|
| 1 to 3 | 550 or 2,200 |
| 3 to 5 | 2,200 or 6,600 |
| 5 to 10 | 6,600 or 13,200 |
| 10 to 15 | 13,200 or 22,000 |
| 15 to 20 | 22,000 or 33,000 |
| 20 to 30 | 33,000 or 44,000 |
| 30 to 50 | 44,000 or 66,000 |
| 50 to 75 | 66,000 or 88,000 |
| 75 to 100 | 88,000 or 110,000 |
| 100 to 150 | 110,000 or 132,000 |
| 150 to 250 | 132,000 or 154,000 |
| 250 to 350 | 154,000 or 220,000 |

**177. Spacing of Conductors.**—The most important factors determining the proper spacing between conductors and between conductor and tower are as follows: span, material, and diameter of conductors, voltage, temperature, and climatic conditions,

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* Formula by Alfred Still in "Electric Power Transmission."

type of insulators, and type of tower. The following empirical formula has been developed from an analysis of transmission lines and can therefore be used as a first approximation:

$$S = 10 + 1.28E^{*} \qquad (67)$$

where $S$ = horizontal spacing in inches between conductors, and $E$ = line kilovolts.

**178. Short Transmission Lines, Capacity Neglected.**—For transmission lines up to about 30 miles long the capacity effect is generally negligible, and even up to lengths of 50 miles the effect is small, less than 2 per cent error being involved in the results of a 60 cycle per sec. line. For this reason it is possible to design such transmission lines by taking into account only the resistance and reactance, generally spoken of as the *impedance method.* In Fig. 256 is given the equivalent diagram of such a line, and in Fig. 257 are shown the current and voltage relations of one phase of such a three-phase line. Since the capacity effect of such short lines is negligible, it follows that the current $I_s$ at the supply end must be equal to the current $I$ at the receiver end. From Fig. 257 the following voltage relations can be written:

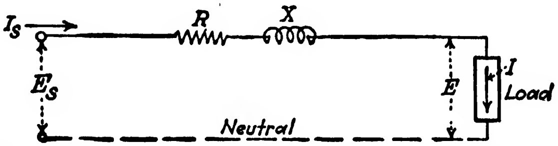

FIG. 256.—Equivalent transmission line to neutral. Capacity neglected.

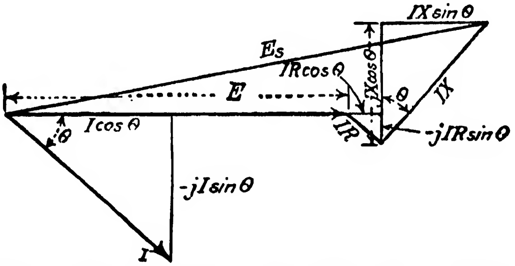

FIG. 257.—Vector diagram of short transmission line. Capacity neglected.

$$E_s = \sqrt{(E \cos \theta + IR)^2 + (E \sin \theta \pm IX)^2} \qquad (68)$$

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* Formula by D. D. Ewing, Analyses of Transmission Lines, *Elec. World,* 1920.

or, expressed in complex quantities,

$$E_s = E + I(\cos\theta \pm j\sin\theta)(R + jX) \qquad (69)$$

The minus sign in Eq. (68) and the plus sign in Eq. (69) are used when the current leads the receiver voltage $E$.

**179. Nominal T Line.**—For lines longer than about 40 miles it is essential that the capacity of the line be taken into effect. One method by which this can be done is illustrated in Fig. 258; the total line capacity being lumped at the center of the transmission line with the resistance and reactance evenly divided between the two ends. The current and voltage relations of one phase of such a circuit are shown in Fig. 259. The solution of Fig. 264 involves three definite steps: (1) determine $E_c$ by Eq. (69) or (70); (2) determine $I_c$ by Eq. (66); and (3) determine $E_s$ by Eq. (69) or (70).

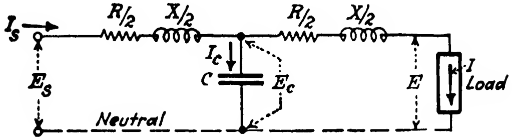

FIG. 258.—Nominal T line.

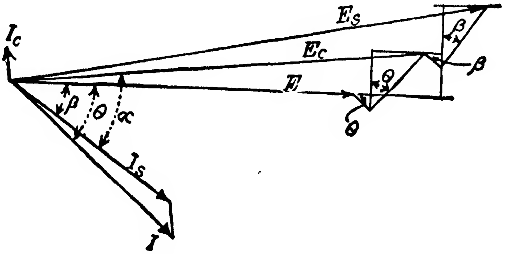

FIG. 259.—Vector diagram of nominal T line.

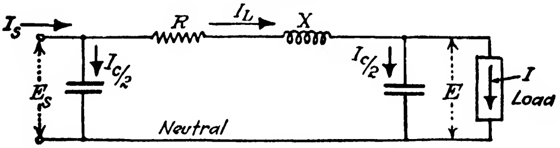

FIG. 260.—Nominal π line.

The receiver voltage at no load can be found from the following relation:

$$E = E_c = \sqrt{E_s^2 - \left(I_c \frac{R}{2}\right)^2} + I_c \frac{X}{2} \qquad (70)$$

**180. Nominal $\pi$ Line.**—Another approximate equivalent circuit is shown in Fig. 260. The capacity is here considered as divided equally between the two ends of the line, with the total resistance and reactances between the two lumped capacities. The vector diagram for such a circuit is shown in Fig. 261, the solution of which is very similar to the previous examples.

**181. Exact Method of Solution.**—The methods of solution given in Arts. 178 to 180 are not satisfactory for long lines, since the constants of a transmission line are distributed along the conductors, and any assumption of lumped constants will introduce errors in the result. One method that might be used to give fairly accurate results would be to divide the constants of the line into a large number of parts, thus approaching a line with distributed constants. The solution of such a problem would be tedious; hence it is better to deduce the exact equations for transmission lines.

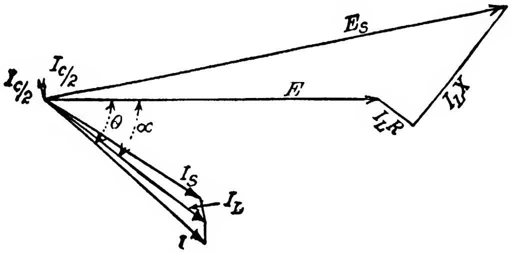

FIG. 261.—Vector diagram of nominal $\pi$ line.

The two conductors of a single-phase line form the two terminals of a peculiar condenser, the area of the terminal plates being equal to the surface area of the conductors, namely, the conductor circumference multiplied by the conductor length. The air between the conductors forms the dielectric of this condenser. The general dielectric field distribution within such a condenser is illustrated in Fig. 262. The capacity therefore extends from the input end to the output end of the line.

Looking at the entire length of the line there will be found a progressive field of capacity current flowing between conductors through the dielectric between wires.

The series current flowing through the two conductors will also set up a magnetic field, also indicated in Fig. 262. This magnetic field also extends from the input to the output of the line.

Because of this magnetic field the circuit will possess an inductance that is fully distributed from end to end of the line.

The resistance of the circuit is also fully distributed from end to end of the line.

Such a problem must be set up by considering a small section of line as the basic element, in fact to be exact the basic element must be an infinitesimally short element of length *dl*.

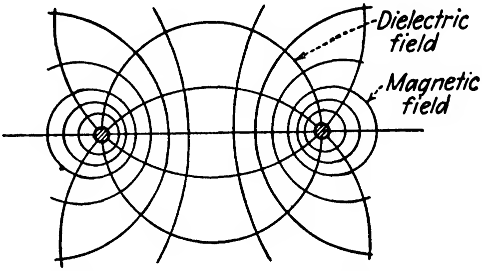

FIG. 262.—Field distribution of a single-phase line.

Consider therefore the circuit of Fig. 263. The potential drop across an element *dl* is indicated as *dE*, while the shunt current within the element *dl* between the two conductors is shown as *dI*.

A perfect transmission line should not possess any leakage resistance path between conductors; however, to make the theoretical results complete it will be assumed that the shunt path between conductors is composed of a resistance in parallel with a capacitor. Thus we define the shunt admittance as $Y = G + jB$ mhos per mile.

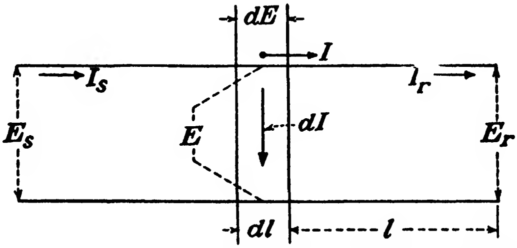

FIG. 263.—Transmission line with distributed constants.

The series impedance is defined as $Z = R + jX$ ohms per mile. Therefore, the series impedance and shunt admittance for the infinitesimal length $dl$ are

$$Zdl \quad \text{and} \quad Ydl$$

With these constants established it now follows that

and
$$\left.\begin{aligned} dE &= IZdl \\ dI &= EYdl \end{aligned}\right\} \tag{71}$$

These two statements form the basis of the long line equations. By simultaneous solution of these two equations we obtain the following:

$$\left.\begin{aligned} \frac{d^2E}{dl} &= ZYE = m^2E \\ \frac{d^2I}{dl} &= ZYI = m^2I \end{aligned}\right\} \tag{72}$$

in which $m = ZY$.

Equations (72) are unique. They indicate that the general solution for $E$ or $I$ must be equal to $1/m^2$ multiplied by the second derivative of such a general solution. It does not require great mathematical acuity to find an expression that satisfies the above demands. From the physical nature of the problem it is natural to expect that the general solution to such equations involve exponential functions.

Thus the general answers to Eqs. (72) are

$$\left.\begin{aligned} E &= K_1\epsilon^{ml} + K_2\epsilon^{-ml} \\ I &= K_3\epsilon^{ml} + K_4\epsilon^{-ml} \end{aligned}\right\} \tag{73}$$

These expressions may be checked by substitution in Eqs. (72).

In Eqs. (73) the constants $K_1$, $K_2$, $K_3$, and $K_4$ must be obtained from the boundary conditions thus:

For $l = 0$, $E = E_r$ = voltage at the receiver end of line, $I = I_r$ = current at receiver end of line. Substituting these boundary conditions in Eqs. (73) results in the following:

$$\left.\begin{aligned} E_r &= K_1 + K_2 \\ I_r &= K_3 + K_4 \end{aligned}\right\} \tag{74}$$

There are four constants in these two equations. To obtain a solution for these four constants, two additional equations are necessary.

It will be recalled that

$$\frac{dE}{dl} = IZ \qquad \text{and} \qquad \frac{dI}{dl} = EY$$

Therefore, from the above derivative forms and Eqs. (71) we have

$$\frac{dE}{dl} = mK_1\epsilon^{ml} - mK_2\epsilon^{-ml} = IZ$$

$$\frac{dI}{dl} = mK_3\epsilon^{ml} = mK_4\epsilon^{-ml} = EY$$

Applying the same receiver end boundary conditions to the above expressions, we obtain the following results:

$$\left.\begin{aligned} I_rZ &= mK_1 - mK_2 \\ E_rY &= mK_3 - mK_4 \end{aligned}\right\} \tag{75}$$

From Eqs. (75) and (74) it is now possible to obtain the solution of the four constants as follows:

$$K_1 = \frac{E_r + I_rZ_0}{2}, \qquad K_2 = \frac{E_r - I_rZ_0}{2}$$

$$K_3 = \frac{I_r + E_rY_0}{2}, \qquad K_4 = \frac{I_r - E_rY_0}{2}$$

where

$$Z_0 = \sqrt{\frac{Z}{Y}} \qquad \text{and} \qquad Y_0 = \frac{1}{Z_0}$$

Substituting the value of these constants into the general solution [see Eqs. (73)] will lead to the following result:

$$\left.\begin{aligned} E &= \frac{E_r + I_rZ_0}{2}\epsilon^{ml} + \frac{E_r - I_rZ_0}{2}\epsilon^{-ml} \\ I &= \frac{I_r + E_rY_0}{2}\epsilon^{ml} + \frac{I_r - E_rY_0}{2}\epsilon^{-ml} \end{aligned}\right\} \tag{76}$$

Finally, it should be noted that the term $m$ is of complex nature, since

$$m = ZY = u + jv$$

Therefore,

$$\epsilon^{\pm ml} = \epsilon^{\pm ul}\epsilon^{\pm jvl}$$

The last two general equations can be simplified as follows:

$$\left.\begin{aligned} E &= E_1\epsilon^{ul}\epsilon^{jvl} + E_2\epsilon^{-ul}\epsilon^{-jvl} \\ I &= I_1\epsilon^{ul}\epsilon^{jvl} - I_2\epsilon^{-ul}\epsilon^{-jvl} \end{aligned}\right\} \qquad (77)$$

where

$$E_1 = \frac{E_r + I_rZ_0}{2}, \qquad E_2 = \frac{E_r - I_rZ_0}{2}$$

$$I_1 = \frac{E_rY_0 + I_r}{2}, \qquad I_2 = \frac{E_rY_0 - I_r}{2}$$

Notice that

$$I_1 = \frac{E_1}{Z_0} \quad \text{and} \quad I_2 = \frac{E_2}{Z_0}$$

Equations (77) indicate very important basic reactions of a transmission line which should be emphasized. In Fig. 264 $E_1$ and $E_2$ may be thought of as the voltages of two generators, one at the sending end and one at the receiver end, the voltage at any point along the line being equal to the vector sum of the voltage effects caused by each generator at the particular point in question.

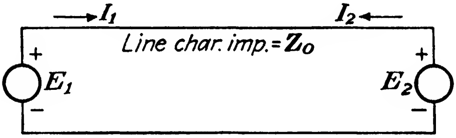

FIG. 264.—Simple transmission-line circuit based upon equations (77).

Similarly, the current at any point in the line is to be thought of as equal to the superposition of two currents, one due to $E_1$ and one due to $E_2$. The resultant current is, however, equal to the vector difference of $I_1$ and $I_2$. One may simplify the picture somewhat by using polarity marks at the two generators, both upper terminals being positive while the lower terminals are negative. It will be noticed that $I_1$ may be considered as positive from left to right while $I_2$ is positive in a right to left direction.

From the point of view of wave motion, $E_1$ represents the sending or generator voltage, while $E_2$ represents the reflected voltage appearing across the receiver end of the line. Similarly, $I_1$ represents the forward or initial current due to the generator, while $I_2$ represents the reflected current due to the load.

Both sets of waves, namely, the forward and reflected waves, experience phase displacement and attenuation as they travel away from the initiating point.

In telephone circuits it is desirable to avoid reflection; hence the design is developed so that

$$Z_0 = \frac{E_r}{I_r} = \text{load impedance}$$

That is, the load impedance is designed to match absolutely the value of line surge impedance. With this feature the reflected waves will disappear and the general equations become

$$E = E_1\epsilon^{ul}\epsilon^{jvl} \quad \text{and} \quad I = I_1\epsilon^{ul}\epsilon^{jvl}$$

Reverting back to the power transmission line point of view, it will be found convenient to change Eqs. (77) in to another form, as follows:

$$E = \left(\frac{\epsilon^{ml} + \epsilon^{-ml}}{2}\right) E_r + \left(\frac{\epsilon^{ml} - \epsilon^{-ml}}{2}\right) Z_0 I_r$$

$$I = \left(\frac{\epsilon^{ml} - \epsilon^{-ml}}{2}\right) Y_0 E_r + \left(\frac{\epsilon^{ml} + \epsilon^{-ml}}{2}\right) I_r$$

Or finally, in the very common form in terms of generalized constants

$$\left.\begin{aligned} E &= AE_r + BI_r \\ I &= CE_r + DI_r \end{aligned}\right\} \qquad (78)$$

where

$$A = \frac{\epsilon^{ml} + \epsilon^{-ml}}{2} = \cosh ml$$

$$B = Z_0\left(\frac{\epsilon^{ml} - \epsilon^{-ml}}{2}\right) = Z_0 \sinh ml$$

$$C = Y_0\left(\frac{\epsilon^{ml} - \epsilon^{-ml}}{2}\right) = Y_0 \sinh ml$$

$$D = A$$

The generalized constants $A$, $B$, $C$, and $D$ are exponentials of complex numbers, which include the proper phase rotation and attentuation. For completeness sake it is indicated that such constants can also be expressed in terms of hyperbolic functions of complex numbers. The identity indicated can be checked by consulting any volume dealing with transmission lines or from suitable mathematical sources.

**182. Corona.**[1]—When the voltage of a conductor in air is raised to a point above the dielectric strength of the surrounding air, the air will break down and become ionized. The ionized air becomes a conductor and therefore an additional source of power loss. Corona manifests itself by an electrostatic glow or luminous discharge accompanied by a hissing sound. In high-voltage transmission lines it is corona that determines to a great extent the size and kind of conductor used.

Several investigators have developed empirical formulas for the computation of corona voltage and corona loss, the ones given below being known as Peterson's equations. These results, particularly the equation for power loss, seem to check test results quite closely.

1. Disruptive critical voltage $E_0$ for smooth round conductors:

$$E_0 = 123.4m\delta^{2/3}\, r \log_{10} \frac{s}{r} \text{ kv. to neutral} \tag{79}$$

where $E_0$ = r.m.s. kilovolts to neutral
$m$ = surface factor
= 0.87 to 0.90 for general design
= 0.92 weathered, low humidity, day
= 0.78 weathered, low humidity, night
$\delta$ = air density factor = $\frac{17.9b}{459 + °\text{F.}}$
$b$ = barometric pressure, inches of mercury
°F. = conductor temperature, degrees Fahrenheit
$r$ = conductor radius, inches
$s$ = equivalent spacing, inches

2. For stranded cables having 12 or more strands in outside layer:

$$E_0 = \frac{123.4\delta^{2/3}m \log_{10} \frac{s}{cr_i} + (n-1)\log_{10} \frac{s}{r - cr_i}}{\frac{1}{cr_i} + \frac{(n-1)}{2(r - cr_i)}} \tag{80}$$

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[1] "Electrical Transmission and Distribution," by Central Station Engineers of the Westinghouse Electric and Manufacturing Company, p. 40.

where $n$ = number of strands in outside layer
$r_i$ = radius, inches, of an individual strand

$$c = 1 - \frac{\sin\left(\frac{\pi}{2} + \frac{\pi}{n}\right)}{\frac{\pi}{2} + \frac{\pi}{n}} = 0.473 \text{ when } n = 12$$

3. For a conductor having six outside strands:

$$E_0 = \frac{123.4\delta^{2/3} rm \left(\log_{10} \frac{s}{r} + 0.0677\right)}{1.37} \qquad (81)$$

4. Corona loss in fair weather in kilowatts per mile per conductor:

$$P = \frac{(33.7fE^2F)10^{-6}}{\left(\log_{10} \frac{s}{r}\right)^2} \qquad (82)$$

where $f$ = frequency, cycles per second, 25 cycles and up
$F$ = Peterson's empirical corona-loss function (see Fig. 265)
$E$ = operating r.m.s. kilovolt to neutral

The above equations for corona apply only for two-wire single-phase and three-wire equilateral three-phase circuits. The solution of the corona loss for unsymmetrical and double-circuit three-phase lines necessitates a determination of the potential gradient at the surface of each conductor.[1] Transposition does not equalize the charges of the three wires at any given point; hence an equivalent spacing ($\sqrt[3]{S_1S_2S_3}$) cannot be used in Eqs. (79), to (81) such as is used for computing inductance and capacity of transposed unsymmetrical three-phase circuits. When the three conductors are placed symmetrically in a plane, as is often the case in practice, corona will start at a lower voltage on the center conductor, where the stress is greatest, than on the outside conductor. The actual critical voltage for the center conductor will be approximately 4 per cent lower, and for the two outer conductors 6 per cent higher than the value for the same minimum spacing in the equilateral arrangement.

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[1] See TARBOUX, J. G., "Introduction to Electric Power Systems," International Textbook Company, Scranton, Pa.

**183. Transposition of Conductors.**—By transposition of the conductors of an overhead transmission line is meant the changing of the relative positions of the wires. This may be necessary on account of any one or all of the following reasons:

1. To eliminate electrostatic and electromagnetic unbalancing of the various phases (see Art. 174).
2. To eliminate mutual induction between parallel lines.

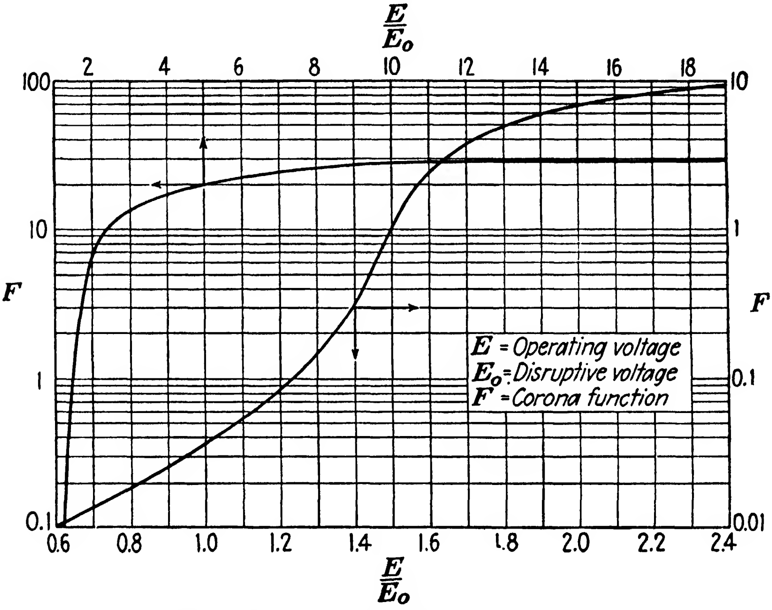

FIG. 265.—Peterson's empirical corona-loss function.

3. To prevent disturbances in neighboring telephone and telegraph circuits.

The number of transpositions depends on the particular conditions desired, but as a general rule, when used to prevent disturbances in parallel telephone and telegraph lines, the conductors may be transposed every mile. For balancing the capacity and reactance of the different phases transpositions may be made anywhere between 2 and 40 miles apart, depending on the type and length of the line.

**184. Transmission-line Steady-state Stability.**[1]—The characteristics of a transmission line, as an electric circuit, are closely

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[1] Below are listed only a few of the many articles that have been published on the topic of transmission stability: GRISCOM, S. B., A Mechanical Analogue

similar to those of a synchronous machine, the main differences being the effect of the magnetic saturation in the latter and the much greater magnitude of the distributed capacity effect in the former. When a synchronous motor is loaded, its rotor drops back in phase position by an angle governed by the synchronous impedance of the machine. As the rotor drops back in phase position, the torque is increased until the pull-out point is reached, after which any further increase in phase angle will be accompanied by a corresponding decrease in torque, and instability occurs. Similarly, as the load on a transmission line is increased, there will be an increase in the phase angle between the sending and receiving voltages. The load cannot, however, be increased indefinitely because any increase in phase angle between the receiving and sending voltages beyond the pull-out point will correspond to a decrease in power delivered, and the line, therefore, will be unstable.

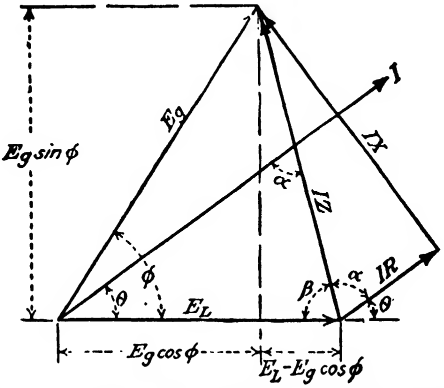

FIG. 266.—Transmission-line vector diagram. Capacity effect neglected.

For the sake of explanation, assume a single-phase line, the capacity effect being neglected. It will also be assumed that the terminal voltages at the sending and receiving ends are kept constant but not necessarily equal in magnitude. The complete

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to the Problem of Transmission Stability, *Elec. Jour.*, May, 1926; FORTESCUE, C. L., and C. F. WAGNER, Some Theoretical Considerations of Power Transmission, *Jour. A.I.E.E.*, February, 1924; CLARKE, EDITH, Steady-state Stability in Transmission Systems, *Jour. A.I.E.E.*, April, 1926; EVANS, R. D., and C. F. WAGNER, Studies of Transmission Stability, *Jour. A.I.E.E.*, April, 1926; SHAND, E. B., The Limitations of Output of a Power System, *Jour. A.I.E.E.*, March, 1924.

current and voltage relations of such a line are shown in Fig. 266. From Fig. 266, the power delivered to the load is

$$P = E_L I \cos \theta = \frac{E_L}{Z} \cdot IZ[-\cos (\beta + \alpha)]$$
$$= \frac{E_L}{Z} \cdot IZ(\sin \beta \sin \alpha - \cos \beta \cos \alpha) \qquad (83)$$

Also, from Fig. 266 the following relations are seen to be true:

$$\sin \beta = \frac{E_g \sin \phi}{IZ}, \qquad \cos \beta = \frac{E_L - E_g \cos \phi}{IZ}$$
$$\sin \alpha = \frac{X}{Z}, \qquad \text{and} \qquad \cos \alpha = \frac{R}{Z}$$

Substituting these values into Eq. (83) and simplifying,

$$P = \frac{E_L}{Z^2} (XE_g \sin \phi - RE_L + RE_g \cos \phi) \qquad (84)$$

Differentiating with respect to the angle $\phi$ and setting the first derivative equal to zero,

$$\frac{dP}{d\phi} = \frac{E_L}{Z^2} (XE_g \cos \phi - RE_g \sin \phi) = 0$$

and, therefore, the phase angle between the sending and receiving voltages corresponding to maximum power delivered is such that

$$\frac{\sin \phi}{\cos \phi} = \tan \phi = \frac{X}{R}$$

or

$$\phi = \tan^{-1} \frac{X}{R} \qquad (85)$$

In a transmission line of negligible resistance, Eq. (85) becomes

$$\phi = \tan^{-1} \infty = 90 \text{ deg.} \qquad (86)$$

The results of Eqs. (85) and (86) indicate the state of the line for its "theoretical static-stability limit." In actual practice, however, this limit can never be reached on account of the sudden changes in the system which are brought about due to switching, short circuits, and other disturbances.

From the above results it is evident that the power limit of a transmission line can be increased by (*a*) decreasing the line impedance, (*b*) using lower frequencies, (*c*) using generators and transformers of low impedance, and (*d*) using generators equipped with quick-acting voltage regulators, so that the generator voltage may be increased as the load is increased.

## MECHANICAL CHARACTERISTICS

**185. General Nature of Transmission-line Sag.**—If a uniform perfectly flexible cable or wire hangs in space between two fixed supports $P_1$ and $P_2$ (Fig. 267), which are at the same elevation, there will be a certain sag in the cable or wire, and the curve thus formed will be a catenary. Since the amount of sag is very small for the average transmission-line span, the actual length of the conductor between points $P_1$ and $P_2$ is nearly equal to the distance between supports. Hence for a good many cases it is sufficiently accurate to assume that the weight of the cable is distributed along the horizontal line $P_1P_2$, thereby making the curve $P_1OP_2$ parabola. The equations of the curve $P_1OP_2$ are therefore as follows:

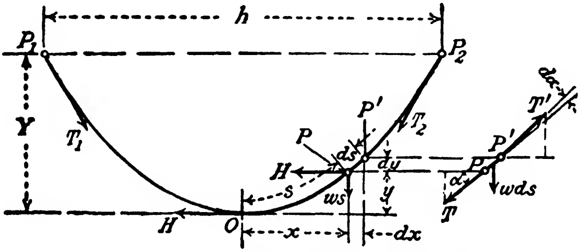

FIG. 267.—Diagram of forces. Wire suspended between supports at same elevation.

Catenary

$$y = c\left(\cosh \frac{x}{c} - 1\right) = \frac{c}{2}\left(\epsilon^{\frac{x}{c}} + \epsilon^{-\frac{x}{c}}\right) - c \qquad (87)$$

Parabola

$$y = \frac{x^2}{2c} \qquad (88)$$

Up to spans of 1,000 ft. it is in most cases sufficiently accurate to consider the curve formed by the conductor as a parabola, thus somewhat simplifying the computations.

**186. Transmission-line Loadings.**—There are three normal loadings that may act upon the conductors of a transmission line, namely, the dead weight of the conductor, additional dead weight caused by accumulation of ice or sleet on the conductor, and wind pressure which, in general, acts at 90 deg. to the dead weight. The resultant loading must be taken as the vector sum of the total vertical loading (dead weight plus ice or sleet) and the wind pressure. The sag, as computed under these conditions (see Art. 187), is not in a vertical plane, but in the plane of the resultant force acting on the cable.

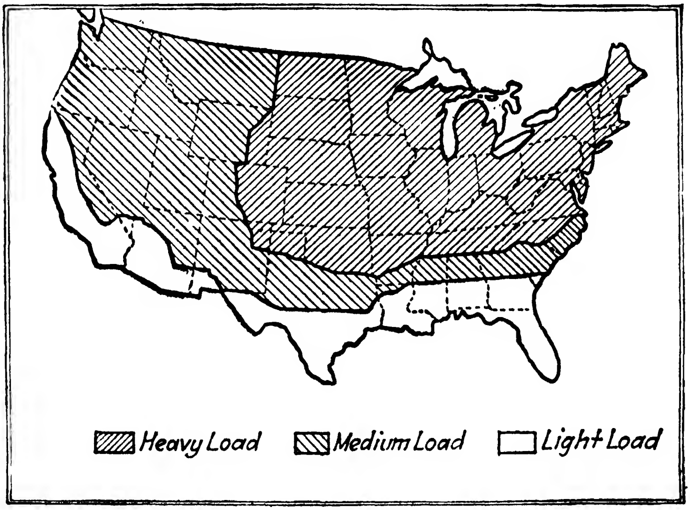

Fig. 268.—Wind loadings on overhead lines.

For the sake of uniformity, there are three classes of loadings which are generally recognized: class *A*, which includes the dead weight of the cable and 15 lb. per sq. ft. wind pressure in a horizontal plane at right angles to the direction of the line; class *B*, which includes the dead weight of the cable, ½ in. of ice surrounding the cable, and 8 lb. per sq. ft. of wind pressure; and class *C*, which includes the dead weight, ¾ in. of ice, and 11 lb. per sq. ft. wind pressure. In Fig. 268 is shown a map of the United States, the different-shaded sections indicating the approximate loadings that may be expected. The entire loading of the cables is transmitted to the poles or towers supporting the line; hence it is important that the poles and towers be properly designed. This is a problem of stresses in beams which will not be dealt with in the scope of this text.

**187. Fundamental Sag and Tension Formulas, Supports at the Same Elevation.**—In Fig. 267, let

$Y$ = sag at the center of span, feet
$H$ = horizontal component of tension = constant
$l$ = length of cable between supports, feet
$s$ = length of cable from point $O$ to point $P$, feet
$T$ = tension in cable at point $P$
$w$ = cable loading per unit of length
$h$ = distance between supports

Below are given the general formulas for the approximate solution based on the equation of a parabola, and also the correct solution based upon the equation of the catenary.

*a. Approximate Solution.*—From Fig. 267 it is evident that

$$\frac{dy}{dx} = \tan \alpha = \frac{ws}{H}$$

For short spans the length of cable $s$ can be taken as equal to the horizontal distance $x$ (see Art. 185); hence

$$\frac{dy}{dx} = \frac{wx}{H}$$

from which

$$y = \int_0^x dy = \int_0^x \frac{wx}{H}\,dx = \frac{wx^2}{2H}$$

and therefore the maximum sag is

$$Y = \frac{wh^2}{8H} \tag{89}$$

The length in feet of the parabolic curve $P_1OP_2$ is

$$l = h\left(1 + \frac{8Y^2}{3h^2} - \frac{32Y^4}{5h^4} + \text{etc.}\right)$$

but for all practical purposes it is sufficiently accurate to consider only the first two terms; or

$$l = h + \frac{8Y^2}{3h} \tag{90}$$

or solving for $Y$,

$$Y = \frac{1}{2}\sqrt{\frac{3h(l - h)}{2}} \tag{91}$$

The following equations are also true:

$$e = \frac{tl}{MA} \tag{92}$$

$$l_u = l - \frac{tl}{MA} \tag{93}$$

$$l_t = l_u(1 + ad) \tag{94}$$

where $e$ = elongation of cable due to stress
$t$ = average tension applied to cable
$M$ = modulus of elasticity
$A$ = cross-sectional area of cable
$l_u$ = unstressed length of cable at reference temperature
$l_t$ = unstressed length of cable at any other temperature
$a$ = coefficient of linear expansion per degree Fahrenheit
$d$ = change in temperature, degrees Fahrenheit

*b. Accurate Solution.*—The tension at the point $P$ (Fig. 267) is the resultant of the horizontal and vertical components; or

$$T = \sqrt{H^2 + w^2s^2} = w\sqrt{c^2 + s^2} \tag{95}$$

where

$$c = \frac{H}{w}$$

For equilibrium between points $P$ and $P_1$, the sum of the horizontal components of force must be equal to zero; or

$$T \cos \alpha = T' \cos (\alpha + d\alpha) \tag{96}$$

The sum of the vertical components of force must also be equal to zero; hence

$$T \sin \alpha + wds = T' \sin (\alpha + d\alpha) \tag{97}$$

Also,

$$T' = \sqrt{H^2 + w^2(s + ds)^2} = w\sqrt{c^2 + (s + ds)^2} \tag{98}$$

From Fig. 267 the following relations are seen to be true:

$$\cos \alpha = \frac{H}{T} = \frac{cw}{T}; \qquad \sin \alpha = \frac{ws}{T}; \qquad \cos (\alpha + d\alpha) = \frac{dx}{ds}$$

$$\sin (\alpha + d\alpha) = \frac{dy}{ds} \tag{99}$$

Substituting Eqs. (98) and (99) into Eq. (96) and simplifying,

$$\frac{dx}{ds} = \frac{c}{\sqrt{c^2 + (s + ds)^2}}$$

But as $ds$ approaches zero as a limit, $s + ds$ also approaches $s$ as a limit; hence

$$\frac{dx}{ds} = \frac{c}{\sqrt{c^2 + s^2}}$$

and

$$x = \int_0^s dx = c\left[\ln(s + \sqrt{c^2 + s^2})\right]_0^s = c \ln \frac{s + \sqrt{c^2 + s^2}}{c}$$

from which

$$s = \frac{c}{2}\left(\epsilon^{\frac{x}{c}} - \epsilon^{-\frac{x}{c}}\right) = c \sinh \frac{x}{c} \tag{100}$$

or the length of cable in one-half span,

$$S = c \sinh \frac{h}{2c} \tag{101}$$

Substituting Eqs. (97) and (98) into Eq. (99),

$$\frac{dy}{ds} = \frac{s + ds}{\sqrt{c^2 + (s + ds)^2}}$$

or as $ds$ approaches zero as a limit,

$$\frac{dy}{ds} = \frac{s}{\sqrt{c^2 + s^2}}$$

and

$$y = \int_0^s dy = \int_0^s \frac{sds}{\sqrt{c^2 + s^2}} = \sqrt{c^2 + s^2} - c \tag{102}$$

Substituting Eq. (100) into Eq. (102),

$$y = \frac{c}{2}\left(\epsilon^{\frac{x}{c}} + \epsilon^{-\frac{x}{c}}\right) - c = c\left[\left(\cosh \frac{x}{c}\right) - 1\right] \tag{103}$$

or the maximum sag,

$$Y = c\left[\left(\cosh \frac{h}{2c}\right) - 1\right] \tag{104}$$

Substituting Eq. (102) into Eq. (95),

$$T = wc \cosh \frac{x}{c} \tag{105}$$

or the tension at the supports,

$$T_{\text{max.}} = w \cosh \frac{h}{2c} \tag{106}$$

It can also be shown that the average tension along the cable is

$$t = \frac{wc}{2}\left(\cosh \frac{h}{2c} + \frac{\frac{h}{2c}}{\sinh \frac{h}{2c}}\right) \tag{107}$$

The three basic catenary formulas are given by Eqs. (100), (103), and (105).

**188. Determination of Sag and Tension Curves.**—The variations of sag and tension of a transmission-line conductor for variations in temperature can be very accurately predicted by means of a set of curves, such as shown in Fig. 269. These curves are based upon the approximate parabolic solution, but similar curves can be determined on the basis of the exact catenary equations. Though the complete catenary solution does not involve very difficult mathematics, it is somewhat longer; hence only the fundamental relations have been given in this text.

The method of the solution of the parabolic equations is illustrated with the following example:

Transmission-line span, 1,000 ft.; conductor size, 666,000 cir. mil, A.C.S.R.; sectional area, 0.5911 sq. in.; weight of conductor, 0.858 lb. per ft.; diameter of cable, 1 in.; wind pressure, 15 lb. per sq. ft.; resultant dead weight and wind pressure, 1.52 lb. per ft.; modulus of elasticity, 11,415,000 lb. per sq. in.; coefficient of expansion, 0.00001086. (This solution does not take into account ice loading, as the design was for a line in a southern climate.)

For dead weight of cable only, Eq. (89) becomes

$$Y = \frac{0.858 \times \overline{1{,}000}^2}{8H} = \frac{107{,}250}{H}$$

and therefore, for different assumed values of $H$, the corresponding sags $Y$ can be found. These values are plotted as curve $A$ (Fig. 269). In the parabolic solution the cable tension is considered as constant throughout the entire span.

For dead weight of cable and wind pressure, Eq. (89) becomes

$$Y = \frac{1.52 \times \overline{1,000}^2}{8H} = \frac{190,000}{H}$$

and therefore, for different assumed values of $H$, the corresponding sags $Y$ can be found. These values are plotted as curve $B$ (Fig. 269).

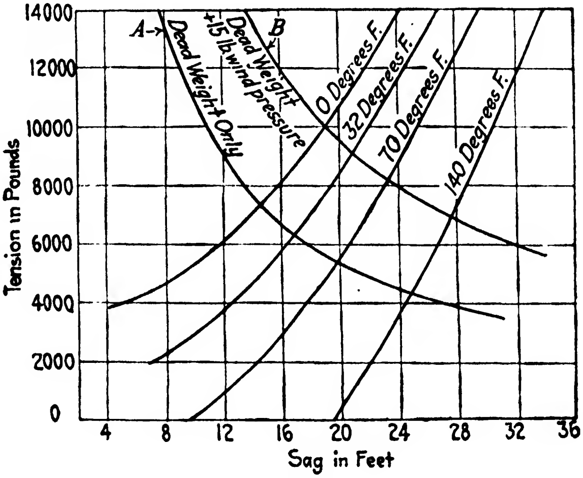

FIG. 269.

The maximum allowable working tension for this cable is taken as 10,000 lb. It is assumed that this tension will occur at 0°F. The sag corresponding to this tension, with 15 lb. per sq. ft. wind pressure acting on the conductor, is therefore 19 ft. The corresponding length of conductor between supports is, by Eq. (90),

$$l = 1,000 + \frac{8 \times \overline{19}^2}{3 \times 1,000} = 1,000.96 \text{ ft.}$$

The unstressed length of such a conductor would upon the removal of the tension become equal to

$$l_u = 1,000.96 - \frac{10,000 \times 1,000.96}{11,415,000 \times 0.5911} = 999.48 \text{ ft.}$$

The unstressed length at 32°F. is found by Eq. (94); or

$$l_{32} = 999.48(1 + 0.00001086 \times 32) = 999.73 \text{ ft.}$$

Similarly the unstressed lengths at 70 and 140°F. are $l_{70} =$ 1,000.24 and $l_{140} =$ 1,001 ft.

If small increments of tension are applied to the respective unstressed lengths of cables, elongations will take place according to Eq. (92). By adding the increments of elongation to the unstressed lengths for the corresponding temperatures, the resultant cable lengths for different values of tension for each temperature are obtained. If these particular lengths of cable could be strung from their supports, neglecting their own dead weight or any other loading, there would be produced a sag, the value of which can be determined by Eq. (91), which in this case may be written in the following form

$$Y = \frac{1}{2}\sqrt{\frac{3h(l_t + e - h)}{2}} \qquad (108)$$

At 0°F. the elongation for an increment of 4,000-lb. tension will be

$$e = \frac{4{,}000 \times 999.48}{11{,}415{,}000 \times 0.5911} = 0.593 \text{ ft.}$$

The remainder of the work for the condition of 0°F. is carried out in the following table.

| Tension, pounds | Length of cable $(l_t + e)$ | Sag-feet, Eq. (90) |
|---|---|---|
| 0 | 999.48 | |
| 4,000 | 1,000.073 | 5.25 |
| 8,000 | 1,000.666 | 15.80 |
| 12,000 | 1,001.259 | 21.75 |

These values are plotted superimposed upon the curves *A* and *B* (Fig. 269). Similar curves for 32, 70, and 140°F. are also shown.

These curves can be interpreted in the following manner: Suppose such a conductor were strung into place with a tension slightly in excess of 8,000 lb., the temperature being about 70°F.

and the cable being subjected to the loading corresponding to curve $B$; then, according to Fig. 269 the sag in the plane of the resultant loading would be about 23.25 ft. With the conductor strung under these conditions, suppose the temperature increased to 140°F.; then the tension would drop to about 7,000 lb. and the sag would increase to about 27.5 ft. Suppose, now, that the wind were to cease; hence the loading would be reduced to that of dead weight of cable only, and from Fig. 269 the tension would be reduced to about 4,300 lb. and the sag to 24.8 ft. By means of such a set of curves the sag and tension conditions of a particular line can be estimated at any temperature and loading. Also, from a knowledge of the climatic conditions of the particular territory covered, it is possible to estimate the maximum sag at the center of the span, from which the required height of towers may be obtained.

## Questions for Class Discussion

### ELECTRICAL CHARACTERISTICS

**1.** Discuss briefly the relative merits of alternating and direct current for the transmission of electrical energy.

**2.** Name and explain the important factors that must be investigated when designing a direct-current line, such as a feeder supplying a direct-current network.

**3.** Define voltage regulation and efficiency of a transmission line.

**4.** Develop an equation for the most economical size of conductor that should be used for a given installation, considering the cost of conductor in place and also the cost of power loss in the conductor. Briefly discuss the limitations of such an equation.

**5.** Name and explain the factors that must be considered when determining the size of conductors for an alternating-current transmission line. Which one is generally the determining factor for a very high voltage line?

**6.** Explain what is meant by the term "skin effect" as used in connection with conductors carrying alternating current. Of what importance is skin effect?

**7.** What is meant by the equivalent spacing between conductors of a three-phase line, the conductors having an unsymmetrical arrangement? Of what importance is this value of "equivalent spacing"?

**8.** Indicate, with the help of a vector diagram, the current and voltage relations at the load and generator ends of a transmission line, the capacity effect being neglected.

**9.** Explain what is meant by the terms "nominal T" and "nominal $\pi$" lines. What are the relative merits of these two circuits as representing the true conditions of a transmission line?

**10.** Develop the exact equations of the solution of a long transmission line, taking into account the distributed capacity of the line.

**11.** Explain clearly what is meant by the following terms: (*a*) corona, (*b*) disruptive critical voltage, (*c*) visual critical voltage, (*d*) corona power loss.

**12.** What effect do weather conditions have upon the disruptive critical voltage and on the corona power loss?

**13.** Why are the positions of the three wires of a three-phase line sometimes interchanged? Explain.

### MECHANICAL CHARACTERISTICS

**14.** What is the equation of the curve formed by a perfectly uniform and flexible cable that hangs still in space between two supports? Give also an approximate but simpler equation that can be applied to such a curve. State the approximate maximum span to which this approximate equation can be applied.

**15.** Name and explain the three general classes of mechanical loadings that may occur upon conductors of a transmission line.

**16.** What is the purpose of "sag and tension curves" of a transmission line? What do these curves show?

## CHAPTER XVI

## TRANSMISSION-LINE INSTALLATION

**189. Location.**—When a transmission line is contemplated, the first thing that should receive careful thought is the question of the best location of the line. In many cases the immediate requirement of a transmission line is merely to supply a particular load from a particular plant. The particular route that the line should follow will depend on the following:

1. Possible future markets for power.
2. Suitable and economic right of way.
3. Favorable climatic conditions.

In many cases it will be profitable to outline a longer route for the line, so as to take in a few towns or localities where future demands for power can easily be met. This requires a careful study of the business trend of the towns or cities and also a study of the natural resources of the neighboring country, etc. The most suitable and economic right of way is dependent on a very large number of items, a few of which are named below:

1. Topography.
2. Accessibility.
3. Cost of right of way.

It is often necessary to take a round-about route in order to avoid swamps or hilly country. Construction through swamps is not only difficult but also costly. Handling of construction materials is a serious problem in very hilly country. As a general rule very long spans are objectionable, because they involve special towers, cables, and fittings, but in many cases it becomes necessary to use them, as in crossing a river, a body of water, or a deep valley.

Accessibility of the line is very important, not only during construction but also for possible repairs or patrolling. For this reason it is advantageous that the line run adjacent to highways or railroads; and, when necessary to pass over private property, it is best to follow the division lines. Sharp curves should always be avoided, since these require especially built towers and foundations. When going through wooded sections it is important that the land be cleared on both sides of the line to a safe distance, so that any falling tree will not hit the line. Right of way may be acquired either by purchase or by easement. For high-voltage transmission lines it is best to purchase the right of way, particularly through congested sections. Easements or contracts of any nature should be made for a long term of years and with the right of renewal.

Certain sections that are known to be subject to a great number of lightning storms should be avoided. Information of this nature can generally be obtained from the U. S. Weather Bureau. Transmission lines in such territory must be adequately protected against disturbance due to lightning (see Chap. XVIII).

When planning a transmission line, the first step is to secure topographical maps from the U. S. Geological Survey, and after the general location of the line has been determined, a special surveying party should be sent over the route for the final profile measurements.

**190. Systems of Transmission.**—Because of economical reasons, three-phase circuits are generally used for transmission of electrical power; hence the treatment given in this chapter, as well as that given in Chap. XV, refers to three-phase lines. Transmission lines may conveniently be classified in the following manner:

1. Single line.
2. Parallel lines.
3. Radial lines.
4. Ring system.
5. Network.

The simplest form is the single line, such as obtained from a power plant supplying its entire output to one load center over a single-circuit line. Such a system has the disadvantage that in case of damage to the line the service is interrupted. Its use is more or less confined to small power systems and is therefore becoming more and more uncommon. Where continuity of service is necessary, it is best to use at least two circuits in parallel, placed either on the same supports or on separate supports. Separate supports afford greater safety against both lines being damaged at the same time, but the cost is much higher than when two circuits are placed on one support. In some cases, where very large quantities of power must be handled, more than two circuits may be run in parallel. Invariably a power plant or substation supplies power to the neighboring territory by means of radial lines. These radial lines may be either single circuit for the less important loads or double circuit for the more important loads. For systems covering a large territory the ring system of transmission is very important. With this system the main high-voltage power line makes a closed ring, taps being taken off at any advantageous point of the ring, thus supplying a large territory. In case of damage to any section of the ring, that section may be disconnected for repairs, and power will be supplied from both ends of the rings, thereby maintaining continuity of service.

A single-line diagram of a ring system, consisting of one generating station supplying four substations, is shown in Fig. 320 (Chap. XVII). In many cases there may be more than one power plant supplying the ring, as for example one side of the ring may be supplied from a hydro-station, while the opposite side may be supplied by a steam station. Furthermore, the ring may be composed of two or more circuits in parallel, or heavily loaded sections may have double circuits while other lightly loaded sections may have only one circuit. The last type, which is a combination of all others, is the most common in large systems. A network often constitutes several ring systems with sections of single, parallel, or radial lines.

**191. Line Supports.**—Electrical power may be transmitted by overhead or underground conductors. Underground transmission, with the exception of a few notable cases, is limited to voltages less than 45,000 volts and, hence, will be considered under the general subject of Distribution in Chap. XX. The supports for overhead transmission lines may be of any one of the following class:

| | |
|---|---|
| Poles | Wood<br>Steel |
| Towers | Flexible<br>Suspension<br>Dead end |

Wood poles are used extensively for comparatively low voltages, though in some cases they have been successfully applied to very high voltages. The kinds of wood used for poles in the

United States are cedar, chestnut, cypress, juniper, and pine, the cypress poles being the best, with an average life (untreated) of about 15 years, while the others are less desirable, pine having an average life of about 5 years. The life of wooden poles can be greatly increased when treated with some type of preservative, such as creosote, zinc chloride, or copper sulphate. Creosote is the best preservative but is more expensive than the two others.

There are a number of ways in which wood poles are used, the simplest being a single pole with crossarms carrying the insulators (Figs. 270 and 271); for two circuits it is often necessary to use two or three crossarms. A large number of bracing methods are used to strengthen pole-lines, particularly at corners or bends, or when under dead-end stress; one common method, known as the A frame, is shown in Fig. 272. Another method, known as the H-frame, is sometimes used, particularly with suspension insulators. It consists of two poles placed vertically with one long crossarm connecting the two, the insulators being hung from the crossarm.

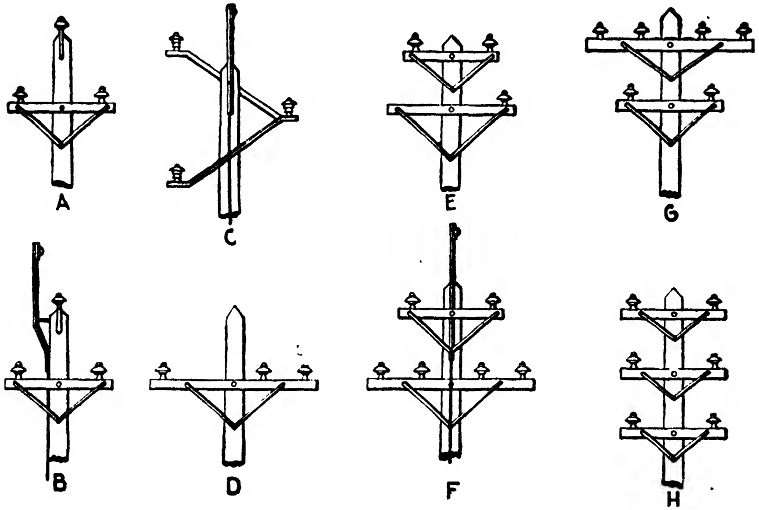

Fig. 270.—Typical arrangements of conductors on low-voltage wooden-pole line.

There is a great variety of steel poles on the market from which a proper choice for a particular installation can be made. They may be made of tubular iron, latticed steel construction, or expanded H sections, the latticed type and expanded H sections being the most common (see Figs. 273, 274, and 275).

Steel towers are invariably necessary for high-voltage transmission of any considerable length. There is no standard for tower transmission, each installation being more or less a problem of its own, but in general three classes may be recognized. In Figs. 276 and 277 are shown two typical four-legged dead-end towers, which must be designed to carry the combined pull of all the wires on one side only, without the foundations yielding or the structure being stressed beyond its elastic limit. Such towers are used at corners or bends in the line where there is

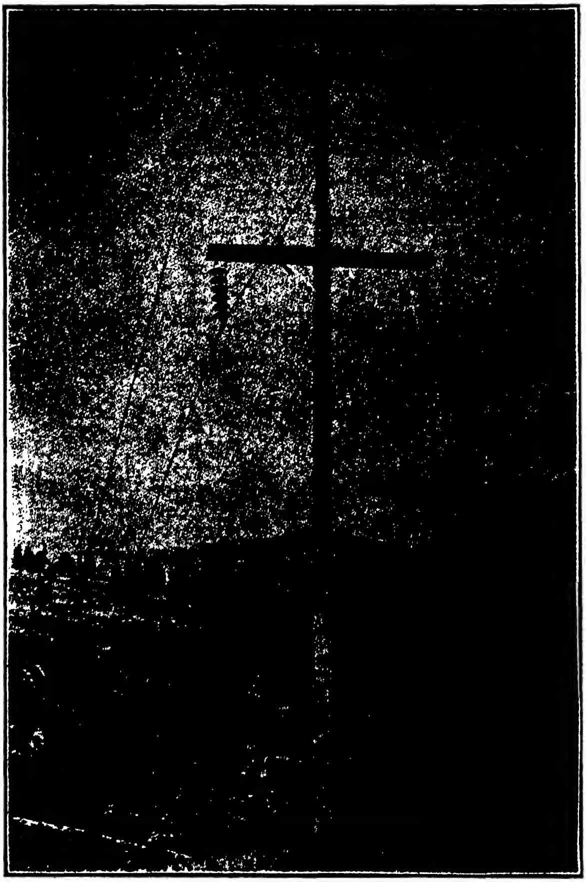

FIG. 271.—Typical 110-kv. wood-pole line. (*Ohio Brass Company.*)

always present a tilting force that tends to upset the tower. They are also used in a straight section of line to carry the tension stresses set up by several spans.

In Figs. 278 and 279 are shown two typical four-legged suspension towers, similar in appearance to the dead-end towers of Figs. 276 and 277 but carrying only a vertical component of force. A very economical line can often be built with a combination of dead-end towers and flexible towers such as shown in Fig. 280. Several flexible towers are placed between dead-end towers, the flexible towers being designed to carry no horizontal force of any kind.

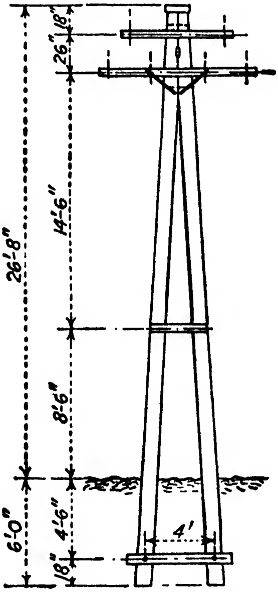

Fig. 272.—Typical A-frame construction for two three-phase 11,000-volt circuits.

Fig. 273.—Steel-pole line. (*Truscon Steel Company.*)

In many cases the topography of the section has dictated what type of tower should be used. The problem of economic erection and transportation is one that must receive careful consideration. A type of tower well suited to hilly country is shown in Figs. 281 and 282, this type being well adapted to this kind of service on account of its ease in erection (see Fig. 283). This type is also well adapted to country subjected to heavy snow and sleet, since any break in a particular conductor would not endanger any other cable. In flat country the towers shown in Figs. 278 and 279 are generally economical; they can be completely assembled with the insulator strings in place and then

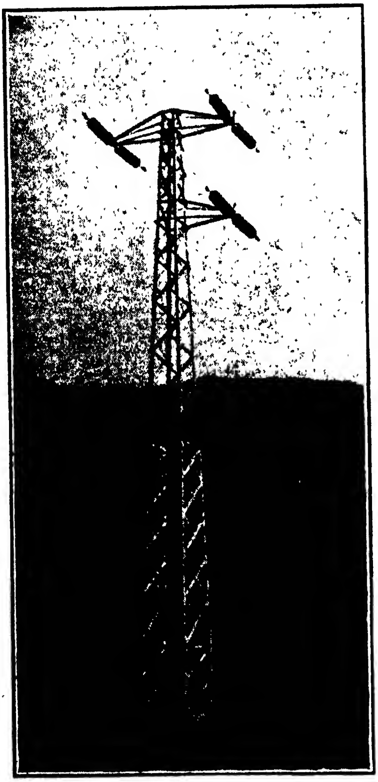

Fig. 274.—A 60-kv. steel-pole line, Southern California Edison Company. (*Pacific Coast Steel Company.*)

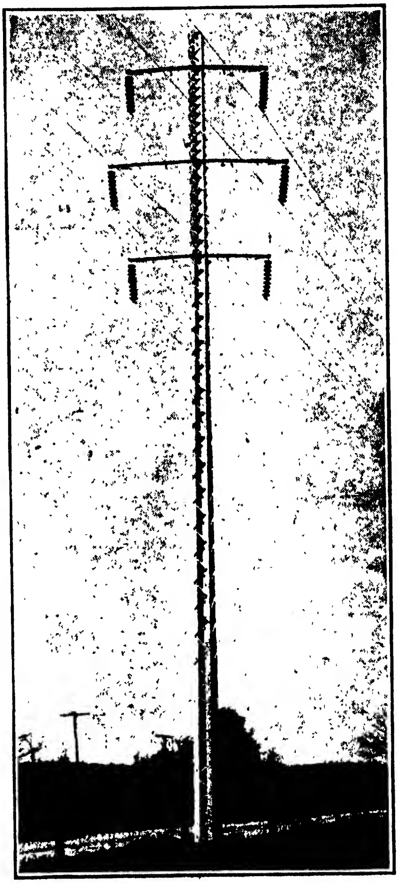

Fig. 275.—A 120-kv. double-circuit pole line, Detroit Edison Company. (*American Bridge Company.*)

raised on their foundations (Fig. 284) with comparative ease. In some cases it is impractical to raise the completely assembled towers, in which cases erection must be done as illustrated in Fig. 285. Other special types of towers are shown in Figs. 286 to 291. Figures 289 to 291 illustrate typical transposition towers (see Art. 183).

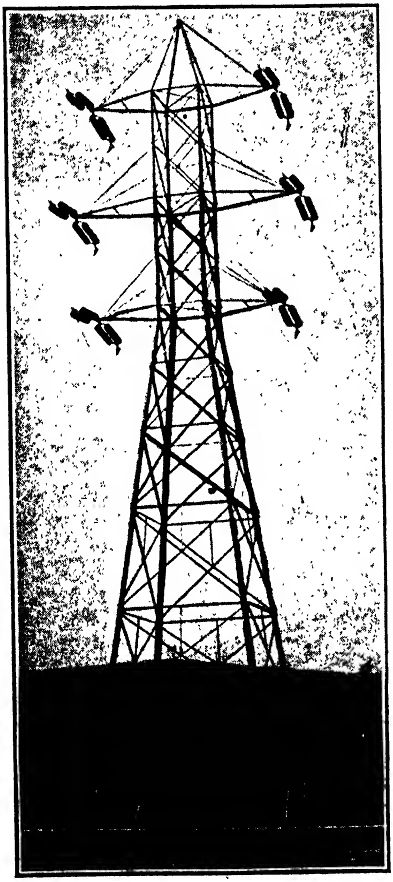

Fig. 276.—A 132-kv. double-circuit strain tower, Ohio Power Company. (*American Bridge Company.*)

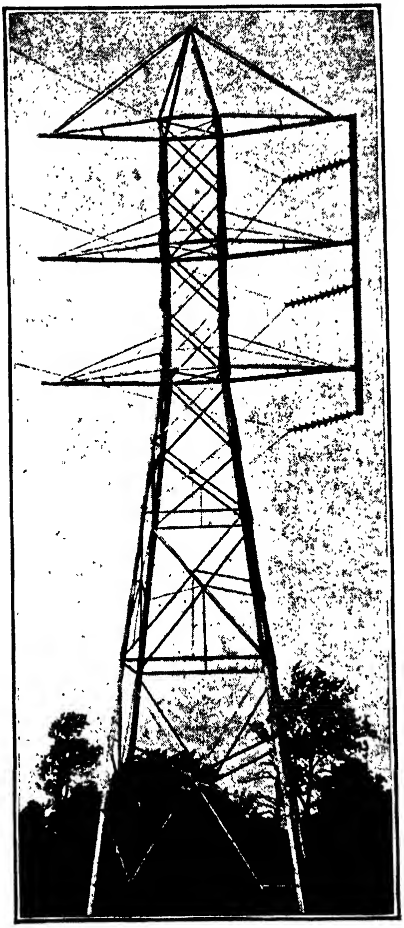

Fig. 277.—Angle tower on 132-kv. line, Ohio Public Service Company (*Ohio Brass Company.*)

All towers should be mounted on concrete foundations in order to avoid trouble. It is important that the foundation be large enough, particularly for four-legged towers, to avoid any settling which will introduce a considerable amount of stress in the tower. In some cases three-legged towers have been used in order to avoid such additional stresses in the tower framework, but they are not very common.

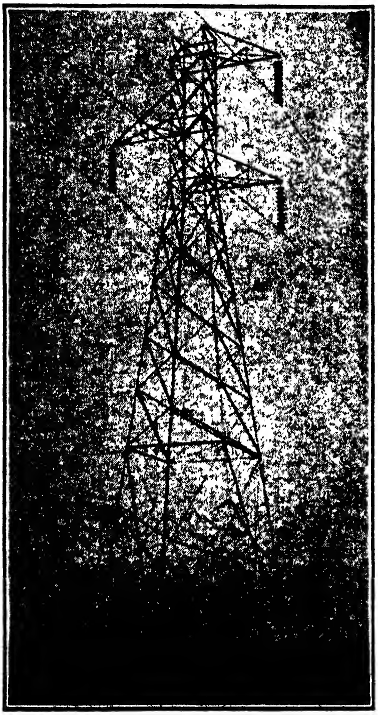

FIG. 278.—A 165,000-volt single-circuit line, Great Western Power Company. (*Pacific Coast Steel Company.*)

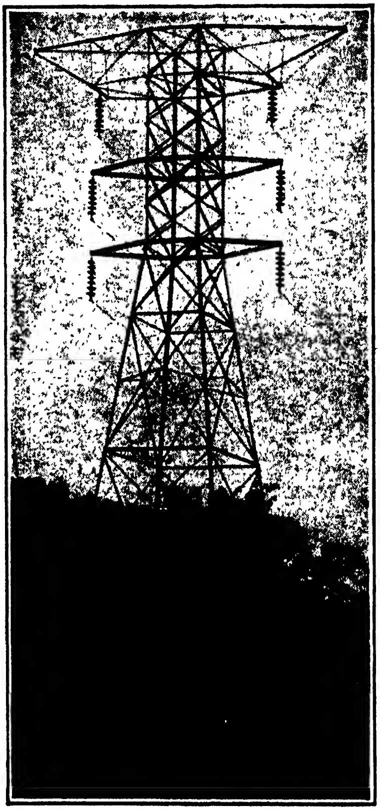

FIG. 279.—Double-circuit suspension tower.

**192. Length of Span.**—The proper length of span to be used cannot be determined easily, since it depends on such a large number of factors. It is mainly an economic problem which cannot be solved except by trial solution together with a great deal of experience. Some of the items that must be considered are the following:

1. Cost of tower and its erection.
2. Cost of lease or purchase of tower site.
3. Cost of foundations installed.
4. Cost of inspection of line and its repairs.
5. Cost of insulators placed on supports.
6. Cost of placing conductors.

As a general rule, wood-pole lines have spans between 100 to 200 ft., and steel-pole and tower lines from 200 ft. up. Steel tower lines of 800 ft. between supports are very common, while under extreme conditions spans of several thousand feet have been used. It must be remembered that as the span is increased it becomes necessary to increase the height of towers and use stronger insulator strings; hence the cost per tower may go up so rapidly that no saving is obtained by using too long a span. On the other hand it should be remembered that the weakest electrical part of a line is found in its insulators; hence too many points of support are undesirable from the electrical standpoint.

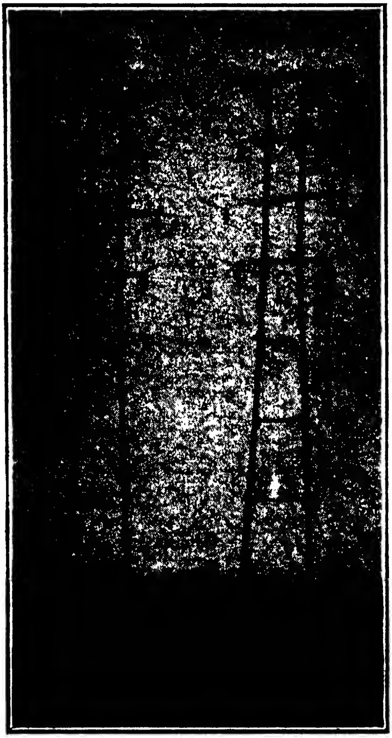

Fig. 280.—Typical flexible towers.

**193. Number of Circuits per Support.**—As indicated in Art. 190, in order to obtain continuity of service it is essential that at least two circuits be run in parallel. These may be placed on separate supports or on the same support. The general tendency in this country is to use the same support for two circuits, but not over two circuits on one tower, except in a few cases where the right-of-way restrictions have demanded otherwise (see Fig. 286). Examples of single-circuit lines are shown in Figs. 271, 274, 278, 281, and 287 and double-circuit lines in Figs. 275, 276,

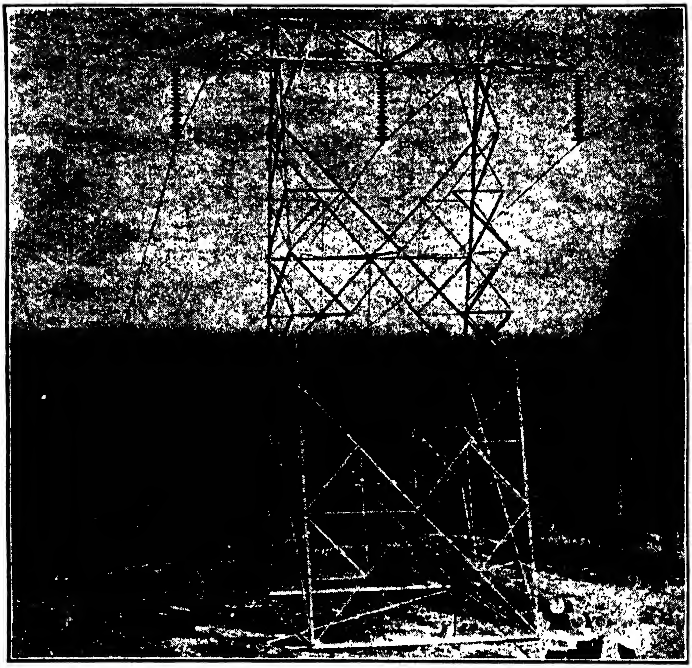

FIG. 281.—A 220-kv. single-circuit line, Pacific Gas and Electric Company. (*Ohio Brass Company.*)

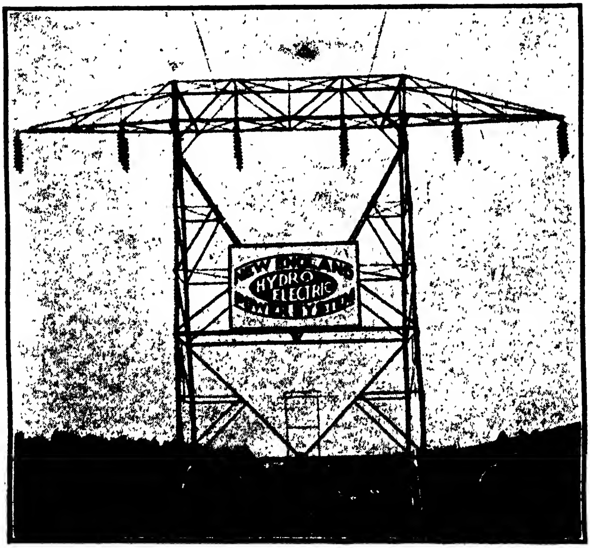

FIG. 282.—A 110-kv. double-circuit line, New England Power Company.

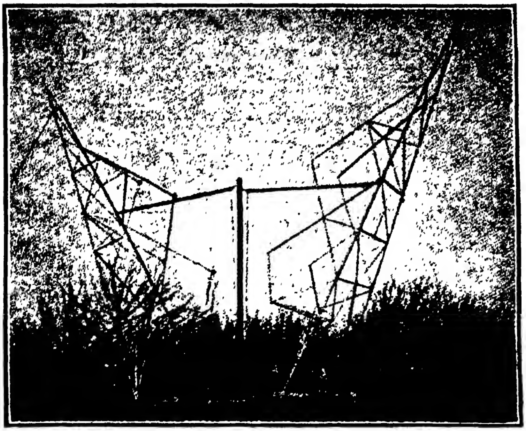

**Fig. 283.**—Erecting a tower in halves. (*Pacific Coast Steel Company.*)

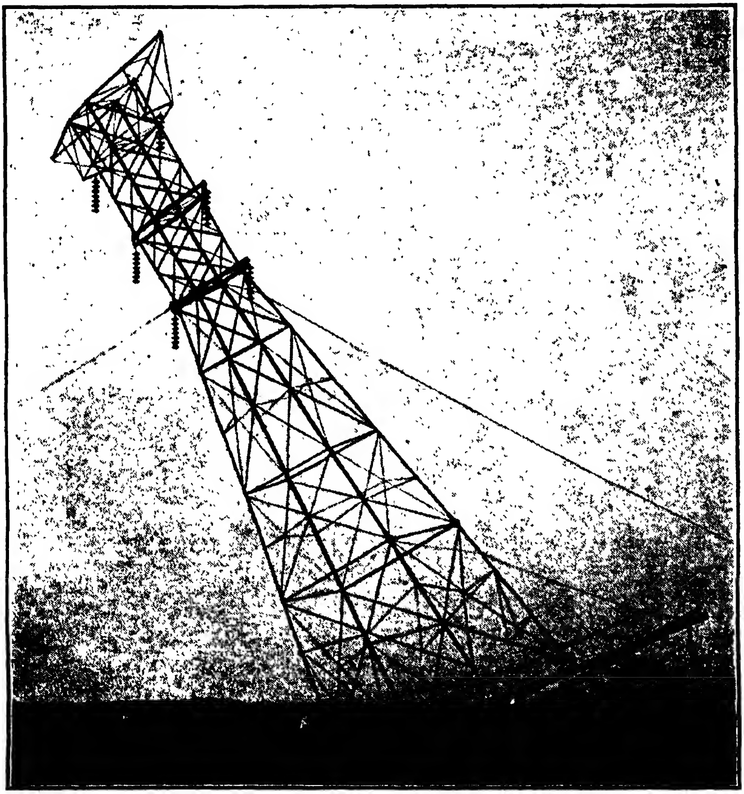

**Fig. 284.**—Raising a double-circuit tower.

279, 280, and 282. When two circuits are placed on one support, it is essential that the conductors be arranged so that repairs may be safely carried out on one circuit when the other is alive.

**194. Relative Location of Conductors.**—There are a good many satisfactory ways of placing conductors on their supports. Only a few, however, can be illustrated in this text. Figure 270 illustrates several methods used for low-voltage wood-pole lines, *A* to *E* being for single-circuit lines, and *F* to *H* for double-circuit lines. The advantage of the equilateral triangle arrangement of *A*, *B*, or *C* is that the reactance and capacity effects of the three phases are alike; in the case of two-circuit lines, however, an equilateral triangle arrangement is not always possible; *F* and *G* being very near to equilateral triangle arrangement. *C* shows the insulators mounted on an angle-iron frame which has been bent into the shape of a "wishbone"; hence this type of mounting is generally known as the wishbone crossarm.

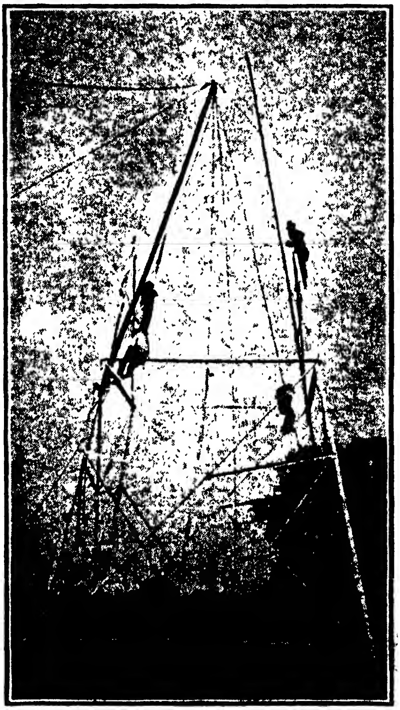

FIG. 285.—Method of erecting steel towers. (*Pacific Coast Steel Company.*)

In order to protect the line against lightning disturbances (see Chap. XVIII), ground wires are often used. Such a wire may be attached to an iron arm at the top of the pole as in *B*, *C*, or *F* (Fig. 270); or in the case of a single-circuit two-crossarm arrangement, it may be attached to one end of the upper crossarm, as for example in *E*, the upper left insulator being placed on the lower crossarm, thus permitting the ground wire to be placed on the left end of the upper crossarm. The ground wires must be solidly grounded at every pole by means of a metal conductor connecting the ground wire to the ground.

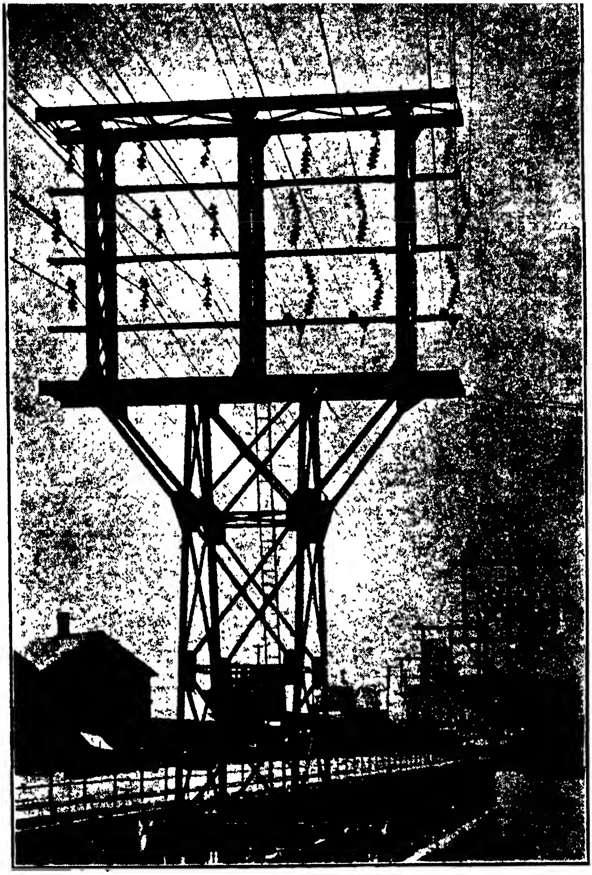

Fig. 286.—Transmission line at 12,000 and 66,000 volts on same towers. (On account of right-of-way restrictions it was necessary to place these towers on cantilever arms over the canal.) (*Niagara Falls Power Company.*)

The arrangement of $G$ is obviously superior to that of $F$, owing to the better accessibility to all conductors. In the case of two-circuit lines, it is important that the two circuits be kept apart; hence each circuit is confined to one side of the pole. For high-voltage lines the general arrangements are about the same as for low-voltage installations. For single-circuit lines a triangular arrangement is preferred (see Fig. 278), though in some cases a horizontal arrangement is used (see Figs. 281 and 287). For double-circuit lines either horizontal or vertical arrangements are used (see Figs. 279 and 282).

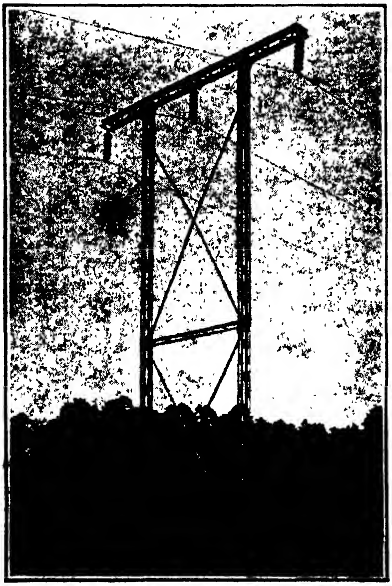

FIG. 287.—Flexible H-frame towers, 110 kv., Georgia Railway and Power Company. (*Tuscon Steel Company.*)

**195. Conductor Material.**—Electric power conductors are generally of the following materials: copper, aluminum, and steel or some combination of these three metals. In some cases special alloys have been used. From a conductivity point of view, copper is the best conductor material, aluminum being second, and steel last.

Commercial conductors are made in several forms, namely:

1. Solid hard-drawn copper.
2. Stranded copper.

3. Hollow copper conductor, stranded.
4. Hollow copper conductor, segmental.
5. Copperweld copper.
6. Aluminum stranded, steel cored.

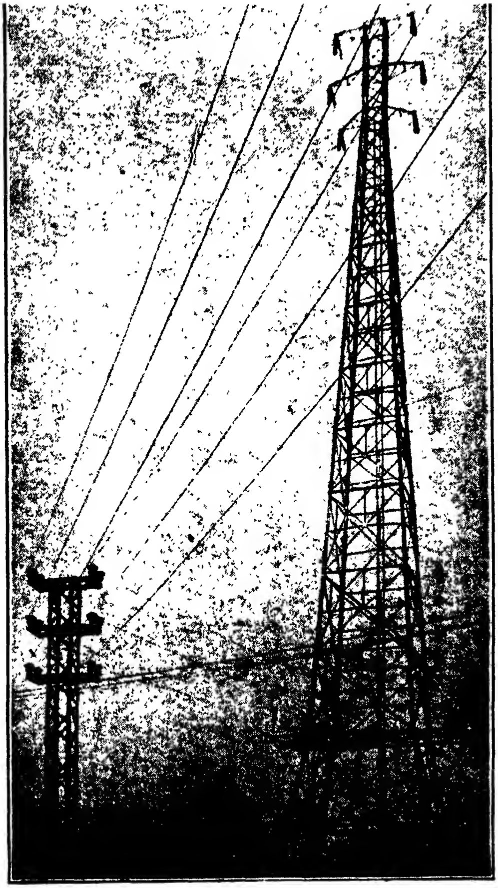

Fig. 288.—Towers for Providence River Crossing, Narragansett Electric Lighting Company. (*American Bridge Company.*)

For distribution lines of low-voltage, solid single-strand copper conductors may be obtained in sizes as large as A.W.G. No. 2 (66,370 cir. mils).

Standard stranded copper conductors are of 3, 7, 12, 19, and 37 strands, which include conductors of 26,250 cir. mils (A.W.G. No. 6) to 1,000,000 cir. mils.

Hollow copper conductors are made up of strands of copper wire wound on a twisted copper I beam as a core, the I beam being twisted in a direction opposite to that of the inner layer of strands. Such conductors range about 119,400 to 750,000 cir. mils, with 12 to 50 strands, outside cable diameters ranging from 0.47 to 1.155 in.

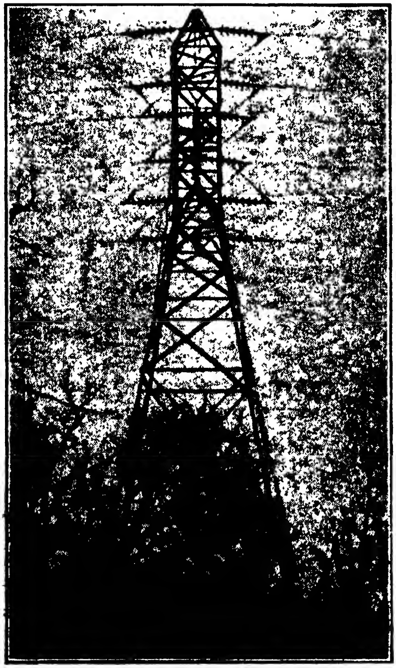

Fig. 289.—Transposition tower, Central Illinois Public Service Company. (*Ohio Brass Company.*)

Another form of hollow copper conductor is made up of segmental sections of copper, mortised into each other to form a self-supporting hollow cylinder. Standard segmental hollow conductors run in sizes from 133,100 to 1,000,000 cir. mils, with outside diameters ranging from 0.5 to 2.103 in.

Two types of copperweld cables are common, namely, copperweld-copper and straight copper-weld. The first type is made up of a number of copper-coated steel strands in conjunction with a number of copper strands. The copperweld strands provide the mechanical strength, while the copper strands improve the conductivity of the resultant cable. For applications requiring high tensile strength, all strands are of copper-coated steel.

Aluminum cables (A.C.S.R.) are made up of aluminum strands wound about a core of stranded steel. The steel cores are made up of 1 to 19 strands of steel, while the surrounding strands may range from 6 to 54 aluminum wires, the larger wires involving as many as three layers of aluminum strands. Cables ranging from No. 6 A.W.G. to 1,590,000 cir. mils are standard, the tensile strength and current-carrying capacity being controlled by suitable proportions of steel and aluminum.

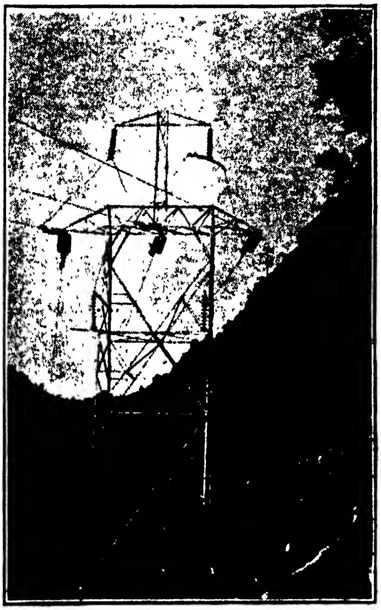

Fig. 290.—Transposition on 165-kv. single-circuit line, Great Western Power Company. (*Pacific Coast Steel Company.*)

Fig. 291.—Transposition tower for double-circuit, 220-kv. line, Pacific Gas and Electric Company. (*Ohio Brass Company.*)

**196. Line Insulators.**—The insulators of a transmission line are its most important item, since the operation of a line cannot be any better than the insulators that support the conductors. Transmission-line insulators must possess good mechanical strength and good insulating qualities under all conditions of weather and temperature and must not deteriorate fast. Insulators are made of glass, porcelain, and patented compounds. Glass is the cheapest material and when properly made will produce satisfactory insulators for low-voltage work, such as telephone and telegraph, and under favorable conditions may be used up to 25,000 volts. Pyrex glass is quite suitable to insulators of the types shown in Figs. 292 and 293. Though there are a number of patented compounds on the market, these do not seem to offer much competition with porcelain, since porcelain has very good electrical characteristics as well as high mechanical strength. Transmission-line insulators may be classified as follows:

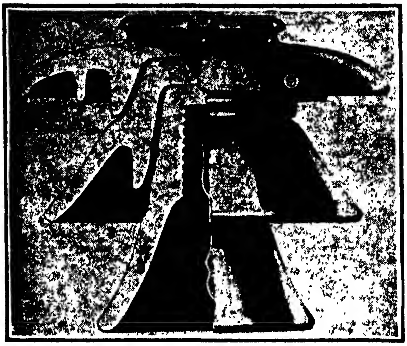

Fig. 292.—A 66,000-pin-type insulator. (*Ohio Brass Company.*)

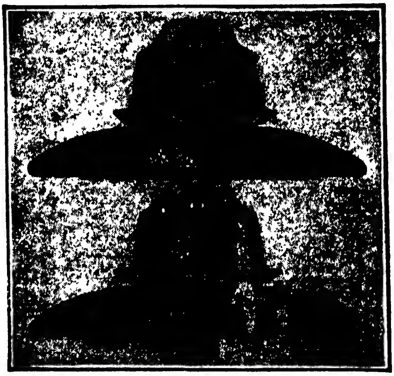

Fig. 293.—Ten-inch suspension insulator units. (*Ohio Brass Company.*)

1. Pin type.
2. Suspension type.
3. Strain type.

For low voltages, pin-type insulators made of glass are generally used. Pin-type insulators made of porcelain are designed for voltages up to about 90,000 volts but are seldon used on lines above 66,000 volts. A typical porcelain pin-type insulator is shown in Fig. 292. For voltages above 66,000 volts it is generally desirable to use suspension insulators as shown in Figs. 293 and 294. It would, at first sight, appear that for higher voltages it would merely be necessary to add more insulators to the string, on the assumption that each insulator took an equal

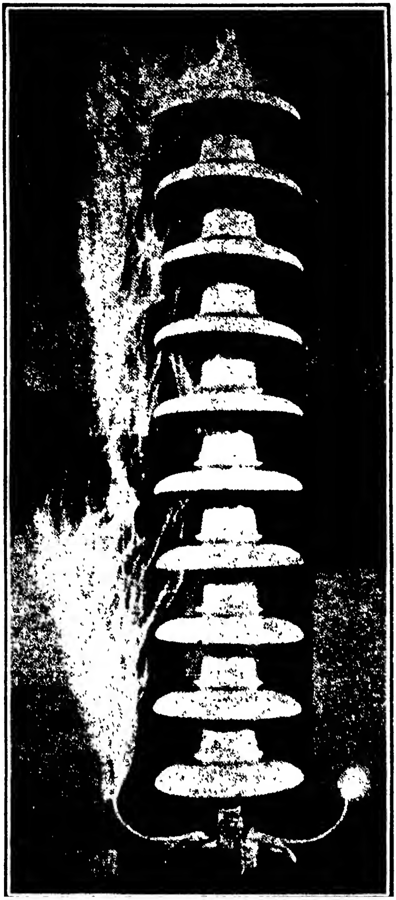

Fig. 294.—Ten units of suspension-type insulators flashing over at 500,000 volts. Note that the arc is kept away from the insulators. (*Ohio Brass Company.*)

share of the potential between the conductor and the ground. The voltages across units of a string do not, however, divide uniformly, the reason being as follows: Each insulator is in reality a condenser, and the air between the units and the supporting tower can also be considered as condensers, the equivalent electric circuit being illustrated by Fig. 295. Such an electric circuit must obey Kirchhoff's laws and therefore is easily solved. The leakage currents through the individual insulators and from insulator connecting links to ground are shown on Fig. 295; and from Kirchhoff's law of currents flowing from a point, it is apparent that

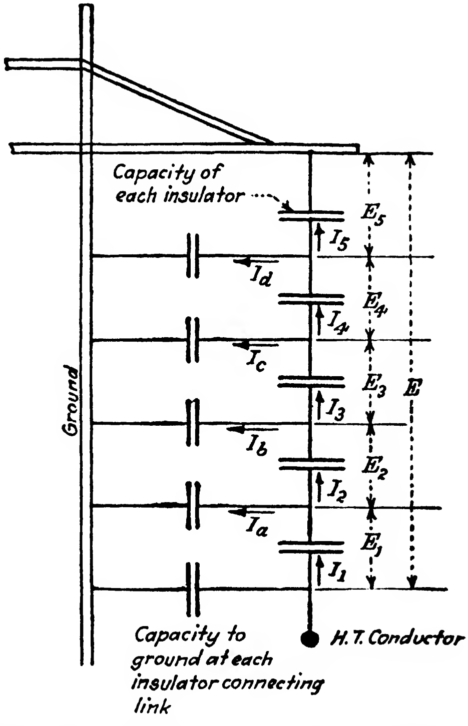

FIG. 295.—Diagrammatic representation of a 5-unit suspension-type insulator.

$$I_1 > I_2 > I_3 > I_4 > I_5 > \text{etc.},$$

and, therefore, the following may be written for the potentials across the respective insulators:

$$E_1 > E_2 > E_3 > E_4 > E_5 > \text{etc.}$$

It follows, therefore, that the voltage stress is greatest across the insulator unit nearest the conductor; hence in a few installations it has been found advisable to use a larger unit next to the conductor. The term "string efficiency" as originally applied by F. W. Peek, Jr., which is the ratio

$$\frac{\text{Arc-over voltage of a string of } n \text{ insulators}}{n \times \text{arc-over voltage of a single insulator}} \qquad (109)$$

shows very clearly that the voltages across individual units are not equal. In the application of string efficiency it is assumed that all units are alike and of the same size. In Table XV is given an example of approximate arc-over voltages and string efficiencies for different number of units.

TABLE XV.*—TYPICAL ARC-OVER VOLTAGES AND STRING EFFICIENCIES OF STANDARD 10-IN. SUSPENSION INSULATORS

| Number of units in series | Flash-over, dry | String efficiency dry, per cent | Flash-over, wet | String efficiency, wet, per cent |
|---|---|---|---|---|
| 1 | 85,000 | 100.0 | 50,000 | 100 |
| 2 | 150,000 | 88.5 | 80,000 | Approximately 80 per cent for any number of units except one |
| 3 | 200,000 | 78.5 | 120,000 | |
| 4 | 250,000 | 73.5 | 160,000 | |
| 5 | 300,000 | 70.0 | 200,000 | |
| 6 | 350,000 | 68.5 | 240,000 | |
| 7 | 385,000 | 65.0 | 280,000 | |
| 8 | 420,000 | 62.0 | 320,000 | |
| 9 | 450,000 | 59.0 | 360,000 | |
| 10 | 480,000 | 56.5 | 400,000 | |
| 11 | 500,000 | 53.5 | 440,000 | |
| 12 | 520,000 | 51.0 | 480,000 | |

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* See PEEK, F. W., JR., Electrical Characteristics of the Suspension Insulator, *Trans. A.I.E.E.*, p. 907, 1912.

It will be noticed from Table XV that the string efficiency under wet test seems to be constant for all numbers of units above two. One possible explanation is that when the insulators are wet their surfaces become conductive, and under these conditions the effect of the capacity current is reduced.

Strain insulators may be of the pin or suspension type. Up to about 30,000 volts pin-type insulators are satisfactory, but for higher voltages the suspension type is generally used. Strain insulators are used on dead-end towers at bends or corners of transmission lines, or when making very long spans. Extra heavy suspension units are made for such service, but often standard units may be used. On ordinary straight-line dead-end towers a single string is often sufficient, but for severe service two or more strings may be connected in parallel. In Table XVI is given the approximate number of units recommended for straight-line suspension or strain service.

Table XVI.—Number of Suspension-type Insulator Units for Different Line Voltages

| Line voltage | Units in suspension | Units in strain |
|---|---|---|
| 33,000 | 2 | 3 |
| 44,000 | 3 | 4 |
| 66,000 | 5 | 6 |
| 88,000 | 6 | 7 |
| 110,000 | 8 | 9 |
| 132,000 | 9 | 10 |
| 154,000 | 10 | 11 |
| 165,000 | 11 | 12 |
| 220,000 | 14 | 15 |

The values of Table XVI should not be taken as definite, for more or less units may be used under certain conditions; however, the values given will serve as a general guide.

### Questions for Class Discussion

**1.** What factors determine the location of a transmission line?

**2.** Name several systems of transmissions, and discuss briefly the field of application for each one.

**3.** Name three main types of line construction, and give advantages and disadvantages of each.

**4.** What is the general spacing used between wood poles? What is the disadvantage of using too many poles?

**5.** What factors determine the maximum span between towers?

**6.** Indicate by sketches four possible ways of placing conductors on a double line system.

**7.** Name several types of conductors as used for alternating-current transmission lines, and state the field of application of each type.

**8.** Name two distinct types of transmission-line insulators. What is the difference between suspension and strain insulators?

**9.** What is meant by the term "string efficiency" of insulators? Explain clearly.

# CHAPTER XVII

# PROTECTION OF ELECTRICAL SYSTEMS

**197. General Requirements.**—A typical power system is shown in Fig. 296. The function of relays and circuit breakers in such a power system is to prevent or limit damage to the system due to faults or overloads and to isolate the faulty section from the remainder of the system. Common types of system faults and their prevalence have been estimated as follows:

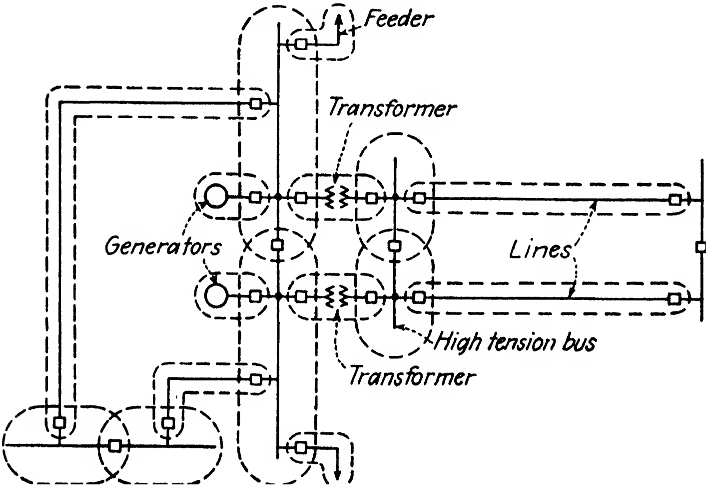


FIG. 296.—Typical system showing zones of protection.

| Faults | Per Cent |
|---|---|
| Three-phase | 5 |
| Two-line-to-ground | 10 |
| Line-to-line | 15 |
| Line-to-ground | 70 |
| Total | 100 |

The function of the relay system is to recognize the fault and to initiate the operation of devices or circuit breakers to isolate the defective element with the minimum disturbance to the service. Typical system protective zones are shown in Fig. 296. These zones might be classified as (1) generators, (2) low-tension busses, (3) transformers, (4) high-tension busses, (5) high-tension transmission lines, and (6) feeders. A certain amount of overlap is bound to be present between two adjacent zones since a circuit breaker forms the connecting link between zones. For this reason a certain circuit breaker may be equipped with more than one type of protection.

The speed with which relays and circuit breakers operate has a direct bearing on (*a*) the quality of service to consumers, (*b*) the stability of the system, (*c*) the amount of power that may be transmitted without exceeding the stability limit, (*d*) the damage done by a short circuit and consequently the cost and delay in making repairs, and (5) safety to life and property. The successful operation of the modern power system is to a great extent due to the modern high-speed circuit breakers.

Relays have been developed for practically all types of system disorders, which may be listed as follows:

*a. Rotating Machines.*—(1) Short circuits in machine, (2) open circuits in machine, (3) overcurrent, (4) overheating, (5) motoring of generator, (6) loss of field, (7) overspeed, (8) bearing overheating, (9) single-phase and unbalanced current operation, (10) stator overvoltage, (11) undervoltage, (12) underspeed, (13) loss of synchronism, and (14) single and reverse phase starting. This list covers possible faults in generators and motors, not all being applicable to generators.

*b. Transformers.*—(1) Short circuits, (2) open circuits, and (3) overloads.

*c. Busses.*—Bus failures are somewhat remote compared with failures in other parts of a system. An insulator support may fail, producing a line-to-ground fault, or in remote cases a bus-to-bus short circuit may occur.

*d. Transmission Lines.*—Transmission and distribution lines, because of their length and exposed nature, are the source of most trouble. Several causes may initiate trouble, such as (1) overloads and (2) any type of short circuit, caused by the breaking of the conductors or falling trees, etc.

The relaying used should be designed to protect the immediate system zone and also give "back-up" protection to all circuits and equipment. This "back-up" protection is generally obtained by having the relay system respond quickly for faults close by and after a longer time for the more remote faults.

Every scheme of protection can be divided into two parts, according to their particular function:

1. That part of the protective circuit which recognizes any abnormal condition in the power circuit. In practically all alternating-current installations such a function is best performed by either a current- or potential-instrument transformer. For alternating-current circuits of very low capacity and voltage, and also for direct-current circuits, an actuating coil may be connected either in series or across the line as the particular conditions may demand.

2. The other part of the protective circuit is any device that is actuated by the instrument transformer or actuating coil, thereby closing the tripping circuit of the oil circuit breaker in the damaged section of the system, or performing any other desired function that would restore the equipment to normal conditions. Such a device is known as a "relay."

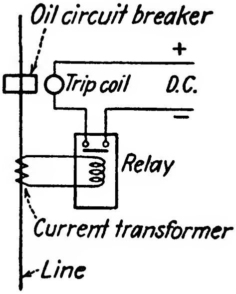


FIG. 297.—Elementary relay connections.

In Fig. 297 are shown the fundamental elements of a relay system. An excess current through the line is recognized by the current transformer, which in turn energizes the relay. The contacts of the relay will then close, causing the circuit breaker to open.

Before going into some of the actual applications of relay systems to electrical equipment and circuits, it is best to become familiar with the most important types of relays.

**198. Basic Relays.**—All relays are essentially composed of three elements: an actuating element, a movable element, and a set of contacts. Relays may be classified in the following three ways: (*a*) according to their time action; (*b*) according to their mechanical details or principle of operation; and (*c*) according to their application.

*a. Time Action.*—By time action is meant the length of time from the instant when the actuating element is energized to the instant when the relay contacts are closed. This time action may be:

(1) Instantaneous.—In this case the contacts are closed imme-

diately after current in the actuating coil exceeds its minimum calibrated value.

(2) Definite Time Limit.—In this case there is a definite time elapsed between the instant when the current in the actuating coil exceeds its minimum calibrated value and the instant when the relay contacts are operated. This particular time setting should be independent of the amount of current through the actuating coil, being the same for all values of current in excess of the minimum calibrated value of the relay.

(3) Inverse Time.—In this case the time delay is inversely proportional to the amount of overload; that is, the greater the overload, the less the time delay. Practically all inverse-time relays are also provided with a definite minimum time feature, in order that the relay may never become instantaneous in its action for very large overloads. There will be found demands for all three of the above types together with a large number of special designs, but in this text only the fundamental principles and applications can be covered.

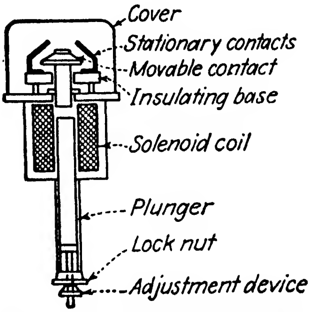


Fig. 298.—Plunger-type relay.

*b. Mechanical Details or Principles of Operation.*—The most important types of relays can be divided into two general classes according to their mechanical details or principles of operation.

(1) Plunger Type.—This type consists of a core or plunger which is movable within a solenoid. When a sufficient amount of current is passed through the winding, the core is pulled up, thus causing the cone-shaped disk at the top to bridge the gap between the stationary contacts. The position of the plunger with respect to the coil is adjustable; the lower its position, the more current is required to pull it into the closing position, and by adjusting its position it may be set to take any predetermined value of current within the range of the coil. Such a relay is illustrated by Fig. 298.

In Fig. 298 has been shown a plunger relay equipped with only one set of stationary contacts. There are many installations in which it is desirable to perform simultaneously several different functions, or to control simultaneously several different kinds of apparatus. For such purposes plunger-type relays have been developed with a very large number of sets of contacts.

(2) Induction Type.—Many types of relays are designed along the principle of the split-phase or shaded-pole induction motor. This basic principle is the same as used for induction-type meters that are discussed in Art. 144. A typical application is shown in Fig. 299 of a General Electric Company induction-type overcurrent relay. The rotating element is composed of an aluminum disk that receives its driving torque from a U-shaped magnet provided with shaded rings. The shading rings act to produce a split-phase field. Damping is provided by two permanent horseshoe magnets. Time delay is obtained by means of the permanent damping magnets and the amount of disk travel before contracts close. A time lever, movable over a scale plate, varies the travel of the disk. For instantaneous protection in case of heavy overcurrent above its setting, the induction unit may be equipped with an instantaneous plunger-type attachment, (see Fig. 299).

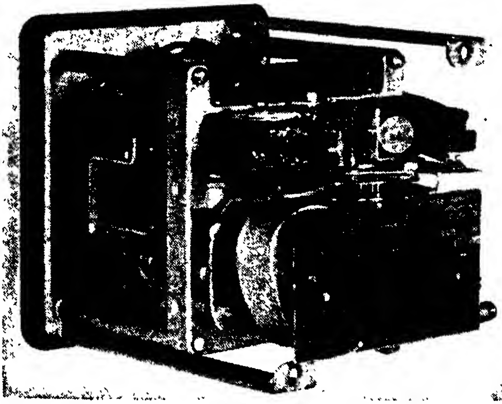


Fig. 299.—Single-phase overcurrent induction-type relay, equipped with instantaneous attachment. (*General Electric Company.*)

Another application of the induction principle of a percentage differential relay is shown in Fig. 300. This unit is equipped with two shaded-pole U-magnet driving elements acting on opposite sides of a single disk. One of these (the operating element) drives the disk in the contact-closing direction, and the other (the restraining element) drives the disk in the contact-opening direction. A contact mechanism is geared to the disk shaft. The circuit contacts close when the operating magnet overcomes the restraining magnet. This type of relay is used in many cases in which differential currents are involved (see Art. 200).

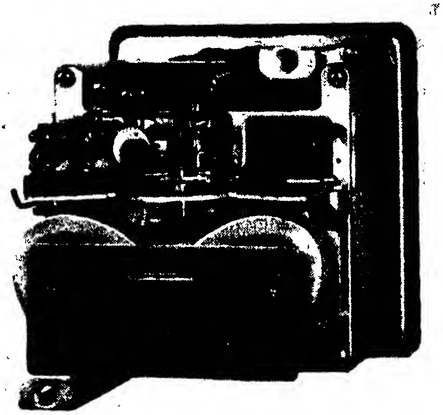


FIG. 300.—Single-phase percentage differential induction relay. (*General Electric Company.*)

**199. Applications of Relays.**—The applications of relays are numerous, but the most important can be classified as follows:

| | |
|---|---|
| *a.* Current relays... .. .. ............ | Overload<br>Underload |
| *b.* Directional relays... ................. | Reverse current<br>Reverse power<br>Reverse phase<br>Reverse polarity |
| *c.* Voltage relays...... ................ | Undervoltage<br>Overvoltage |
| *d.* Auxiliary relays...................... | Control<br>Signal |
| *e.* Differential relays | |
| *f.* Distance or impedance relays | |

*a. Current Relays.*—The plunger and induction-type relays are both adaptable to overload duty. By far the greater application of these relays is for overload protection, but in many industrial control systems it is desirable to open a circuit in case the load falls below a minimum value. Underload relays are generally of the instantaneous plunger type. Under normal conditions the plunger is held up, causing the contacts to remain open. When the load falls below a predetermined value, the plunger is released and the control circuit is closed.

*b. Directional Relays.*—Reverse current and reverse polarity are essentially relays for direct current. They are used to protect direct-current generators, storage batteries, synchronous converters, or other apparatus from damage due to reversal of current in case of short circuits or grounding of machines or connections.

Reverse-phase relays are used in connection with motor installations for elevators, hoists, conveyors, cranes, machine tools, and textile machinery. These relays guard against injury to the operator or damage to machinery or manufactured products, which might occur owing to a reversal of motor rotation in case of an accidental interchange of motor leads. These relays operate on the induction principle.

Reverse-power relays are of the induction type. They are essentially induction watt-hour meters and are similar in principle of operation to the overload-induction relay. The driving torque of the rotating disk is obtained from two independent windings, namely, a current coil and a potential coil. In the case of polyphase reverse-power relays, one common rotating element is used with as many driving coils as necessary acting on the same shaft. Reverse-power relays, in order to be effective, must be very sensitive; hence they are generally instantaneous in their time action and therefore are invariably used in conjunction with some type of overload relay, either definite or inverse time.

*c. Voltage Relays.*—Low-voltage relays are of the plunger type provided with a potential winding regularly wound for 110 volts. In operation, so long as the potential is about normal, the plunger is held up, causing the contacts to remain open. When the potential falls below some adjustable percentage of normal, the plunger is released and the control circuit is closed. Overvoltage relays may be either instantaneous or time limit and are similar in construction to overload plunger-type relays, differing only in that potential windings are substituted for current coils. They may be used to protect any apparatus against damage due to abnormal voltages.

*d. Auxiliary Relays.*—In many cases the particular apparatus controlled by a relay requires too much current to be handled by the relay contacts; hence an auxiliary control relay is used to handle the large operating current. The control relay is, in turn, operated by the main relay. There are also times when a certain number of operations should be performed in a definite sequence, as for example, the starting up of an automatic substation. The operation of one relay performs a certain duty; as soon as this operation has been completed, another relay is energized, thereby performing another task, and so on until the complete substation is in operation. Again, there are applications where certain operations must be produced simultaneously at different places, as, for example, the tripping of several oil circuit breakers that are located at different points. It is a general policy in large stations to place an alarm or signal that will operate and thereby call the operator's attention in case of any trouble. This can be done by placing the actuating coil of an auxiliary relay in series with the contacts of the protective relay. The auxiliary-relay contacts can then control a bell or other alarm. In case the protective relay contacts close, the auxiliary relay is energized and hence the alarm given.

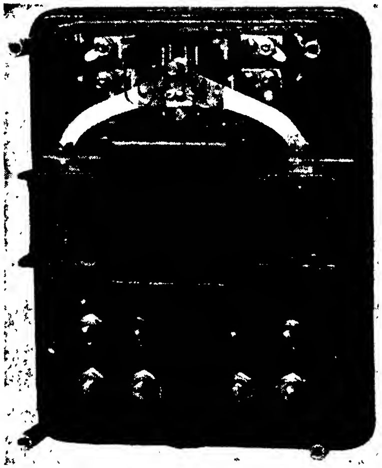


Fig. 301.—Instantaneous differential relay. (*General Electric Company.*)

*e. Differential Relays.*—As the name implies, these relays depend for their operation on the difference in currents that might flow in two parts of a system. In Fig. 302 is shown an elementary circuit diagram of a standard differential relay. It is composed of three windings, the two outside ones being known as the restraining coils and the inner one as the operating coil. They are so made and connected that the two restraining coils exert a downward pull, while the operating coil exerts an upward pull on the armature. In Fig. 302 is shown how the three windings, are connected.

Coils *a* and *b* are connected to their respective current transformers in the power circuit so that under normal conditions the sum of the current through them is zero, and hence the operating coil *c* will not exert any force upon the moving mechanism. When the difference in the current in the two lines protected becomes great enough to overcome the weaker of the two retaining windings, the moving contact mechanism will rise and throw to one side, thereby completing the circuit of the trip coil of the oil circuit breaker. A standard differential relay with cover removed is shown in Fig. 301.

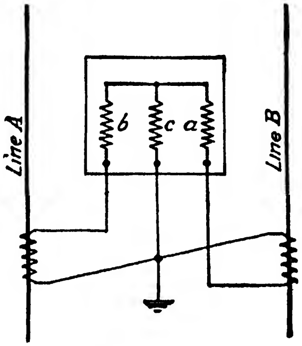


FIG. 302.—Differential-relay connections.

*f. Distance Relays.*—This relay involves a unique application of the induction type of moving element. The rotor is subjected to two torques which are in opposition to each other. One torque is proportional to current squared ($I^2$), while the second torque is proportional to reactive volt-amperes ($EI$ Sin $\phi$). Since these torques are in opposition, the relay will take up its balanced position when

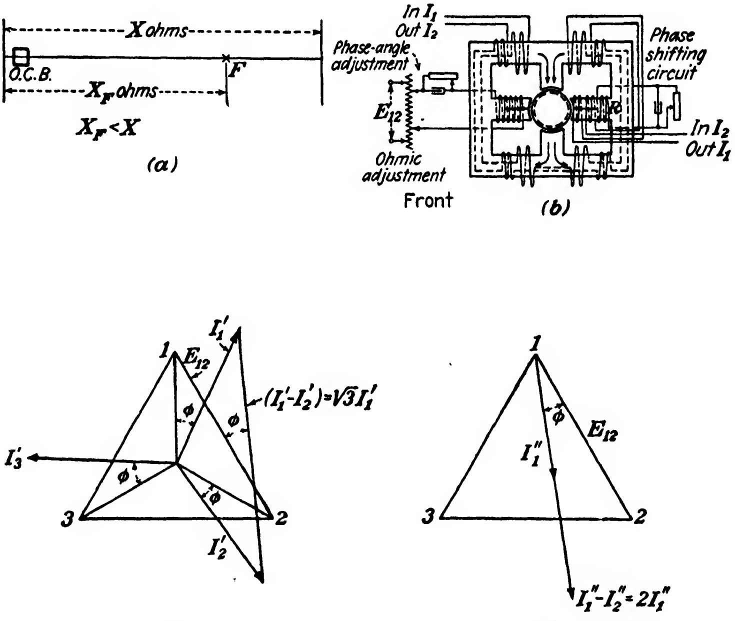
$$EI \sin \phi = KI^2$$

or

$$K = \frac{E \sin \phi}{I} = Z \sin \phi = X = \text{inductive reactance}$$

The relay is adjusted by controlling the voltage $E$, by means of an autotransformer, so that the value of $X$ is made equal to the transmission-line reactance for the section under protection (see Fig. 303*a*). In the event of a fault within the protective zone, such as at $F$, the resultant torque produced by the two torque elements will not be balanced and the relay will operate.

The circuit details of the ohm unit are shown in Fig. 303*b*. A field flux for both torques is produced by the current windings on the top and bottom magnetic poles. A flux proportional to the equivalent fault current, but shifted in phase angle, is produced by the auxiliary current windings on the right-hand pole. The reaction of the field flux, which is proportional to $I$, and the right-hand pole flux, also proportional to $I$, produces the operating torque, which is proportional to $I^2$. The torque produced by the



(c) Balanced three phase fault

(d) Line to line fault

FIG. 303.—Distance-ohm relay.

left-hand voltage coil in combination with the field flux is a restraining torque and is proportional to $KEI \sin \phi$.

Distance ohmic relaying is not commonly applied to detect single-phase ground faults, since the earth impedance is quite variable over seasonal changes.

The construction of the ohm unit is such that with Y-connected current transformers it will indicate the same reactance for phase-to-phase and three-phase faults. This is made possible by employing two separate sets of current windings on the same magnetic circuit. Thus the reactive element of the unit will register according to the value $E_{12}(I_1 - I_2) \sin \phi$, while the current element will register according to the value of $(I_1 - I_2)^2$, and the balance is obtained when

$$K(I_1 - I_2)^2 = E_{12}(I_1 - I_2) \sin \phi$$

or

$$K = \frac{E_{12} \sin \phi}{I_1 - I_2} = X = \text{inductive reactance}$$

For a balanced three-phase fault $(I_1 - I_2) = \sqrt{3}\, I_1'$, where $I_1'$ = line current (see Fig. 303*c*). For a line to line fault $I_1 - I_2 = 2I_1''$, where $I_1''$ = line current (see Fig. 303*d*). Because of the fact that the line current for a three-phase fault is equal to $2/\sqrt{3}$ times the line current for a line-to-line fault, the resultant values of relay-reactance measurement for both types of faults are the same.

Further discussion of the application of this type of relay will be given in Art. 204.

**200. Alternating-current Generator Protection.**—There are two possible ways of protecting generators against damage owing to excess current due to a short circuit. These may be stated as follows:

1. Overload protection.
2. Differential protection.

In Fig. 304 is illustrated the method of obtaining overload protection for generators. The disadvantage of using overload relays for generators is due to the fact that when synchronizing several machines to the same bus, there might be a large momentary circulating current present, which will open the generator circuit breakers and thereby cause a delay in synchronizing.

The modern tendency in the design of power equipment is to build alternators with very high values of internal impedance, so that they will stand a complete short circuit at their terminals without causing any damage to themselves. Such generators need not have any overload protection; as a matter of fact, the operating engineer, as a general rule, does not want any overload protection, as such protection might disconnect the generators from the power-plant bus on account of some momentary trouble outside the plant and therefore interfere with the continuity of the electric service. For such generators the sole protection required must be one that will only recognize an internal fault in the machine.

Differential protection is illustrated by Fig. 305 where the complete diagram of connections is shown for the case of a Y-connected generator, and only part of the system for a delta-connected generator. At each end of each phase of the armature windings identical current transformers are placed. In Fig. 305*c* is shown the elementary diagram. If the transformers are connected as shown, there cannot be any potential between the points *a* and *b* unless there is a difference of current in the secondaries of the two current transformers. Under normal conditions the current entering the winding is equal to current leaving the winding; hence there will be no difference of potential across *a* and *b*, and hence there can be no current through the relay coil. As soon as an internal short circuit or ground occurs on the winding, the currents flowing in the two current transformers are unequal, and a potential will be established across *a* and *b*, and therefore current will flow through the relay coil, causing its contacts to close.

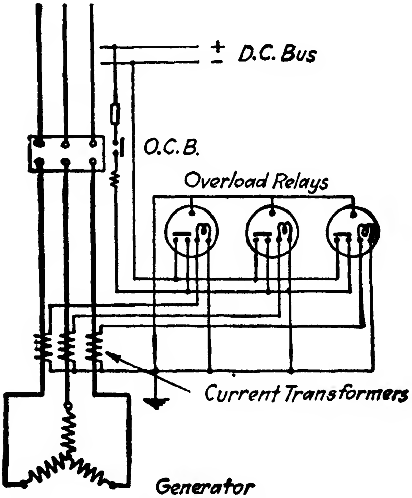
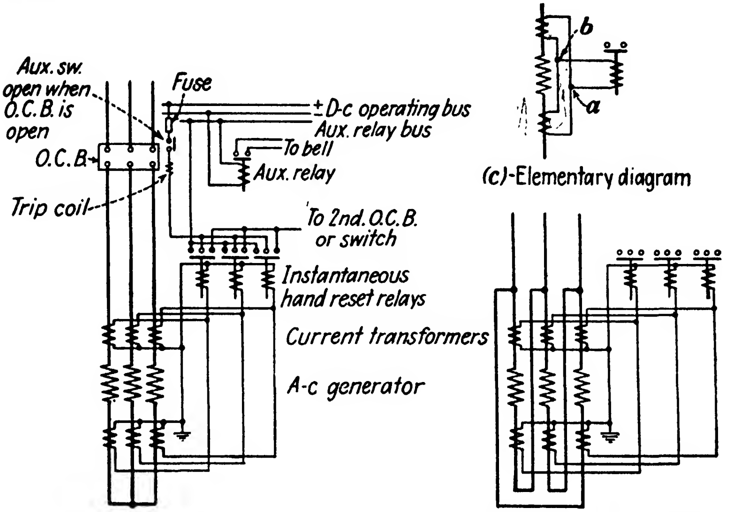


Fig 304 —Overload protection for alternators.

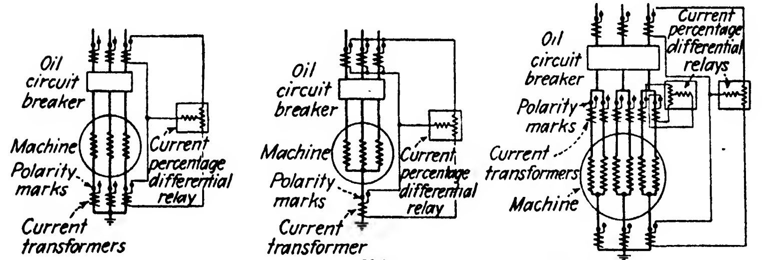
Plunger-type relays are illustrated in Fig. 305. These plunger relays may be equipped with several contacts, thus controlling more than one circuit breaker. An auxiliary relay is used in Fig. 305*a* to operate a bell alarm.

The plunger-type relays may be replaced with induction-type current relays of the same type used for overload protection in Fig. 304.



(a)-Y-connected generator (b)-Delta-connected generator

FIG. 305.—Differential protection of alternating-current generators.



(a) Schematic diagram of current-differential protection applied to one phase of a 3-phase, Y-connected machine and leads

(b) Schematic diagram of current-differential protection for ground faults only for 3-phase, Y-connected machine

(c) Schematic diagram of split-winding and current differential protection applied to one phase of a 3-phase generator

FIG. 306.

Alternator protection using percentage differential relays are shown in Fig. 306. In order to avoid confusion the relay contacts and tripping circuits have been omitted in the several sketches of Fig. 306.

Reverse power protection may also be applied to a generator when the generator forms a part of a network or operates in parallel with other alternators. In case of internal damage there will be a reversal of energy, which will cause operation of a reverse power relay. However, this type of protection must be used in conjunction with overload relays with sufficient time delay so that it will not function on temporary feedback to a generator during synchronizing surges.

**201. Transformer Protection.**—The protection that is most common for transformer banks is similar to the differential protection of generators (see Fig. 307). There is one important modification. Since the primary and secondary voltages are not alike, it is necessary to use relays having two separate coils or current transformers of different turns ratio for the primary and secondary sides of the power transformers. These coils must be so designed that when connected to their respective current transformers their pulls on the plunger of each relay is neutralized. In case of a short or ground in either the high- or low-tension side of the transformers, the pulls exerted upon the plunger will no longer be neutralized and the relay contacts will be closed, opening the oil circuit breakers on both sides of the transformer. In case the relay coils are identical, such a system requires current transformers of different primary to secondary ratios in order that the currents acting in the two coils of one relay be equal. These two currents must be in phase; hence this type of protection can be used only in case the power transformers are similarly connected on both sides.

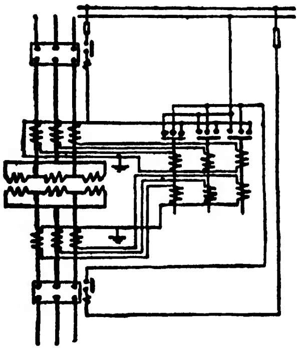


Fig. 307.—Differential protection for transformers. High- and low-tension sides connected alike.

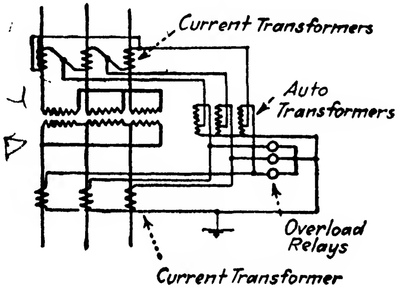
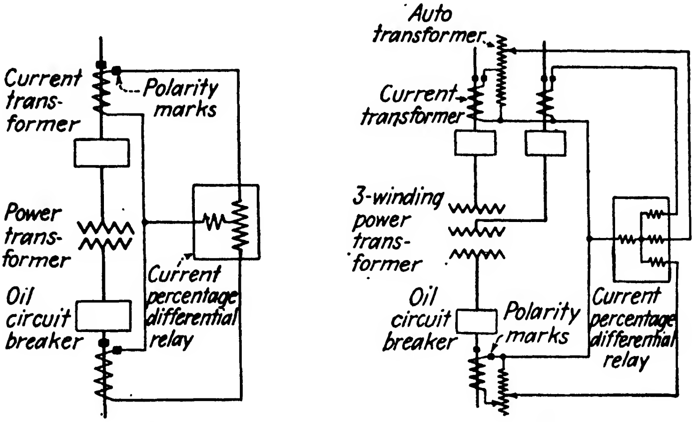


Fig. 308.—Differential protection for transformers. High- and low-tension sides connected differently.

A typical method of protecting a star-delta transformer bank is illustrated in Fig. 308. In such a case careful attention must be given to the phase relation of the current-transformer currents as well as to their magnitude. The current transformers on the star side of the power transformer bank must be connected in delta and balanced against the current transformers on the delta side of the power transformer bank which are star connected. This gives the proper phase relation under all conditions of short circuit, either three phase or single phase. It has been stated elsewhere in this article that the ratios of the current transformers should have values, such that the secondary currents from the two sets of current transformers balance each other exactly. Since the majority of voltage-transformation ratios are not even multiples and do not match the commercial rating of the current transformers, it is necessary to build special current transformers for each particular case, or to use an auxiliary autotransformer in the secondary of one of the current transformers in order to correct its ratio of transformation. Obviously the latter method is the preferable one since it permits the purchase of standard current transformers and also takes care of the condition that the majority of power transformers are provided with different voltage taps for normal operating conditions. These autotransformers are provided with a large number of taps so that the current from the two sets of current transformers can be very accurately balanced. Such a scheme is shown in Fig. 308.

In Fig. 309 are shown how "percentage-differential relays" are applied to two- and three-winding transformers. The relay contacts and tripping circuits have been omitted. For the case of three-phase transformer banks, the same method of connecting the current transformers is followed as shown in Fig. 308, namely, current transformers in Y on delta power units and current transformers in delta on Y power units.

**202. Bus Protection.**—In Fig. 310 are shown three examples of bus protection. In all three cases the protection is based on the fundamental proposition that for an external fault the vector summation of all currents flowing to a bus is equal to zero, and therefore the relay will remain in its balanced position. On the other hand, when an internal fault occurs on the bus, the summation of the currents will no longer be zero and current will flow through the relay, causing it to operate and thereby open all circuit breakers connected to the bus. An auxiliary multicontact relay is often used to trip the several circuit breakers.

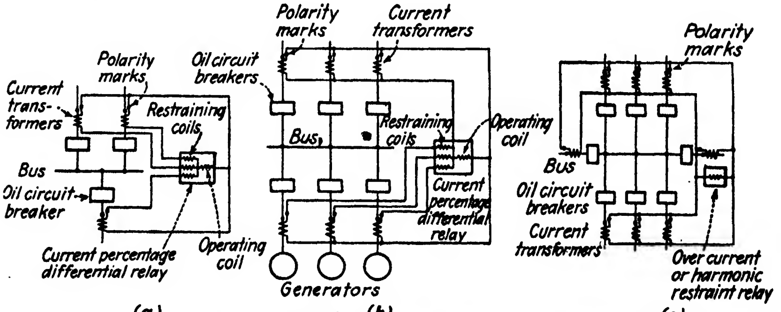


(a)
Schematic one-line diagram of current differential protection of 2-winding power transformers

(b)
Schematic one-line diagram of current differential protection of 3-winding power transformers

FIG. 309.

In case of a few connecting lines, it is possible to use percentage-differential relays (see Fig. 310*a* and *b*); for the case of many lines it becomes more desirable to use standard overcurrent relays (see Fig. 310*c*).



(a)
Schematic one-line diagram of current-differential protection of buses using percentage-differential relay

(b)
Schematic one-line diagram of current differential protection of buses using percentage-differential relay

(c)
Schematic one-line diagram of current-differential protection of buses using overcurrent relay

FIG. 310.

**203. Protection of Transmission Lines.**—The requirements of line protection can be summarized as follows:

1. In the event of a short circuit the circuit breakers nearest the fault should open, all other circuit breakers remaining in a closed position.

2. In case the nearest breaker to the fault should not open fast enough, backup protection should be secured from adjacent circuit breakers.

3. Line circuit breakers should not trip due to loss of synchronism or hunting of generators.

4. The relay time should be just as short as possible in order to preserve system stability, without unnecessary tripping of circuits.

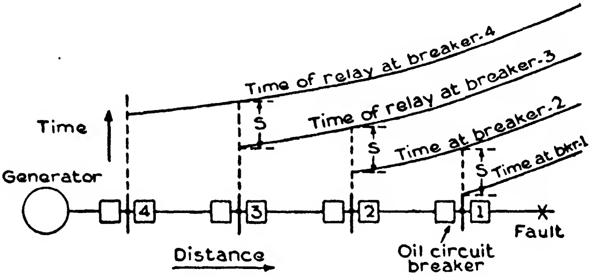


FIG. 311.

Common methods of line protection against short circuits include:

1. Overcurrent protection.
2. Distance or impedance protection.
3. Pilot protection and carrier-current protection.
4. Balanced current or balanced power protection.

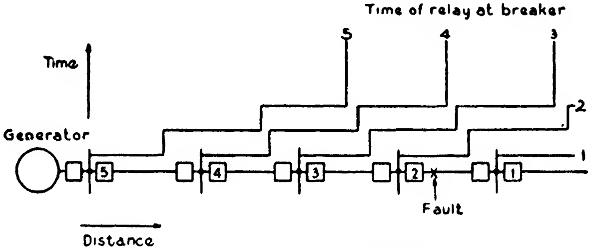
**204. Overcurrent Protection.**—This type of protection is the most elementary type of line protection available. It generally employs the induction-type inverse-time relay. Figure 311 illustrates such an application to a radial system involving one generating station and four substations. The relay-time settings are adjusted so that the first circuit breaker to trip, in the event of a fault, is the one nearest the fault. The selectivity between substations is obtained by the time interval "*S*."

**205. Distance Protection.**—For line-to-ground faults, the simple overcurrent protection of Art. 204 is probably more satisfactory than distance protection. However, for phase-to-phase faults, the distance protection is applicable, since the circuit impedance is quite constant and not subject to seasonal changes, as is the case with earth impedances.

Figure 312 illustrates the application of this method of protection to a radial system similar to Fig. 311.

A General Electric Company type GCX single-phase distance relay consists of one starting unit, one ohm unit, one transfer relay, and one timing unit, all mounted in a single case (see Fig. 313). The functions of the various elements are as follows:

The starting unit is a voltage-restricted-directional unit that primarily prevents operation of the GCX relay, unless the fault current is outgoing from the bus. The ohm unit is the distance-measuring element that determines the distance to the fault to permit tripping instantaneously for near-by faults, or in intermediate time for more distant faults. The ohm-unit contacts will close when the reactance ohms are less than the relay setting, indicating that the fault is within the zone for which the relay is set. Normally, the ohm unit has a setting equivalent to the reactance of 90 per cent of the length of the line section that the relay protects. This setting is increased by the operation of the transfer relay to a higher reactance value corresponding to the reactance of the protected line section plus a fraction (usually 50 per cent) of the next line section. The timing unit determines the time delay before the transfer from the first zone setting of the ohm unit to the second zone setting and from the second zone setting to the third zone setting determined by the starting unit which has a distance-measuring characteristic in addition to its directional characteristic.



Schematic one-line diagram of a transmission line with GCX relays at five breakers

FIG. 312.

The operation of the GCX relay under fault conditions is as follows:

Upon the occurrence of a fault within the range of the relay, the starting unit operates; its contacts close, energizing the timing unit and completing the tripping circuit up to the ohm-unit contacts. If the fault is within the ohm-unit setting, the contact of this unit closes, tripping the breaker and energizing the seal-in relay through the transfer relay contacts. If the fault is beyond the ohm-unit setting, the ohm unit will not operate, but after a suitable delay (intermediate setting of timing unit) the first contact of the timing unit closes, energizing the transfer relay which transfers the ohm-unit setting to a higher value of reactance and transfers the ohm-unit contact circuit from target 1 to target 2. If the ohm unit closes its contacts after the transfer has taken place, tripping in intermediate time will result. If the

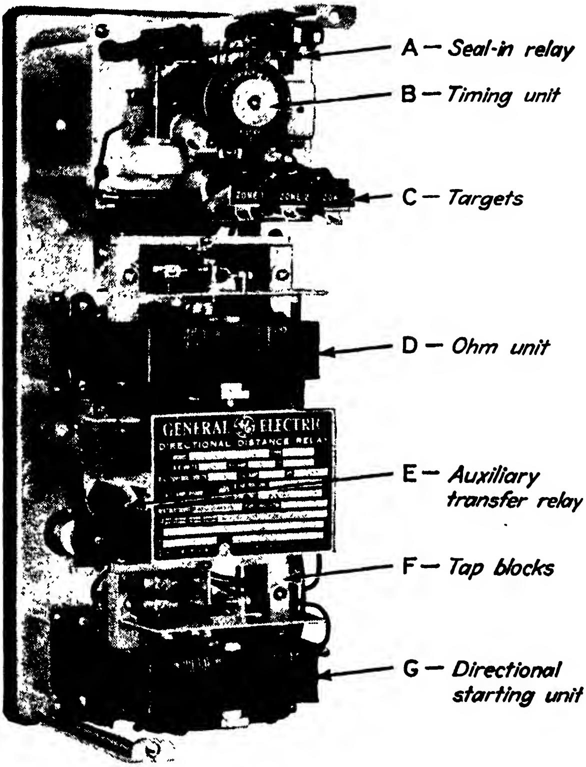


FIG. 313.—GC×15A, single-phase relay with cover removed. (*General Electric Company.*)

fault is still more remote, but within the range of the starting unit, the ohm unit will again not operate and tripping will be effected, after a further time delay (backup time), by the timing unit closing its second contact.

**206. A. Pilot-wire Protection.**—In the case of a short line it is possible to obtain very positive protection by the so-called "pilot-wire" method. This method is essentially differential protection applied to transmission lines. Current transformers are placed in each phase at both ends of the line and connected by means of pilot wires, as shown in Fig. 314. Only one phase is shown, in order not to obscure the fundamental principle involved. It is evident from the above diagram that this is identical in its principle of operation with the differential protection applied to generators. A short circuit at any point between the current transformers will cause the oil circuit breakers at both ends of the line to open. The relays used may be of either the induction or plunger type, but probably the induction inverse-time relay is the most common for this type of installation. The natural objection to the pilot wires is in the fact that they are likely to be broken or damaged. The expense of placing pilot wires on the transmission towers should also be considered. In the case of long lines in which the capacity effect is appreciable, this method of protection cannot be used.

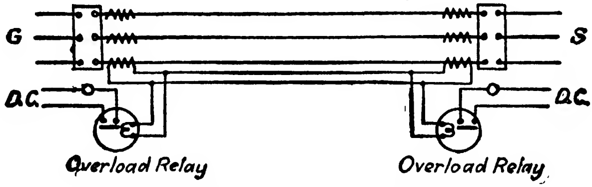


FIG. 314.—Pilot-wire method of protection.

**B. Carrier-current Protection.**—The objection of pilot wires has been to a great extent overcome by the use of carrier currents, in which the power lines act as the carrier channel, as shown in Fig. 315.

The direction of the fault is determined by the directional power units at each station. During a fault the directional and overload relays control the carrier-current transmitters, and the carrier-current receivers in turn control the tripping circuits. Two relay contacts appear in the transmitter circuit (Fig. 315), namely, the overload relay contacts and one set of contacts of the directional relay. When both of these are closed, negative bias is removed from the master tube of the transmitter, allowing it to oscillate and thus supply carrier current to the transmission line. High-frequency traps are provided at both ends of the line in order to prevent the carrier current from passing out of the section to be protected.

Normally, the carrier-current transmitting and receiving equipment is idle. It functions only when a short circuit occurs, and then only to prevent tripping when the short circuit is not in the protected section of line. Under normal operation the directional contacts are held open, regardless of the direction of load over the line, by voltage-restraining windings. Notice that under normal operation the receiver relay contacts in the tripping circuit are closed, but no tripping takes place because the directional units are in the central or open position.

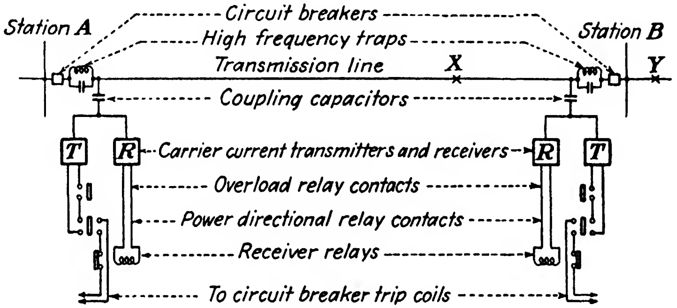


FIG. 315.—Schematic diagram illustrating carrier-current relay protection.

For a fault at $X$ (see Fig. 315), the directional relays will close toward the fault, the overload relays also closing. The directional relays thus close the tripping circuit of both circuit breakers, the receiver relay contacts remaining closed owing to the lack of carrier current.

For a fault at $Y$ (see Fig. 315), the overload contacts will both close. The directional elements will both close to the right. The transmitter at station $B$ will be placed in operation, supplying the line with carrier current. Both receiver relays will be energized and opened, thus preventing tripping of the circuit breakers at stations $A$ and $B$.

Similar schemes of protection are used on adjacent sections of lines. To avoid possible interference, adjacent sections are operated at different carrier-current frequencies.

**207. Parallel Transmission Lines.**—Figure 316 shows two parallel lines connecting a generating station to a substation. A study of this diagram will readily indicate that, in case of a short circuit in either line, power will flow to the short circuit from two directions as indicated. Several methods lend themselves to this particular case, the most important being as follows: (*a*) inverse-time-limit overload relay system, (*b*) balanced protection system, (*c*) pilot-wire system, (*d*) inverse-time-limit overload and reverse-power relay systems, (*e*) double-contact reverse-power relay system, and (*f*) differential relay system.

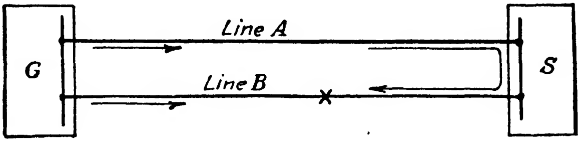


FIG. 316.—Protection of parallel lines.

*a. Inverse-time-limit Overload Relay System.*—In this case overload relays would be placed on each line at the power plant and also at the substation. The time setting should be such that the relays at the substation would be actuated first. This method is not used very extensively because some of the other methods are more effective.

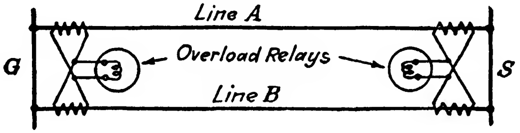


FIG. 317.—Balanced protection of two parallel lines.

*b. Balanced Protective System.*—This method is a further application of the differential method as described under generator protection. Its application in this case is illustrated by Fig. 317. Current transformers are placed in all phases of all lines at both ends, and transformers in corresponding phases of each line are connected in series. Under normal operating conditions there is no potential across the actuating coil of the relay, but in case of a short circuit in either line there is established a potential across the relay coil, and hence the tripping-circuit contacts are made.

In this case the relay must open the oil circuit breakers in both lines; hence the service is interrupted.

*c. Pilot-wire System.*—The application of this system to parallel lines is identical in its application to single lines.

*d. Inverse-time-limit Overload and Reverse-power Relay System.* Each line is arranged with an overload relay at the generating plant and a reverse-power relay at the substation, in exactly the same manner as applied to a single line.

*e. Double-contact Reverse-power Relay.*—A modification of the standard reverse-power relay has been developed for the protection of parallel lines. This particular relay is a single-phase instrument; hence three are needed in a three-phase installation. In Fig. 318 are shown the necessary connections for one phase, with the connections to the potential element left out. In a complete installation the three potential elements are connected in delta, and proper connections made to potential transformers also connected in delta.

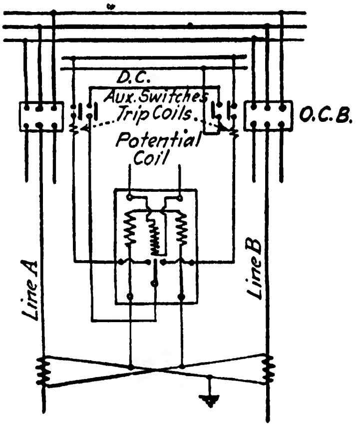


FIG. 318.—Double-contact reverse-power relays used for the protection of two parallel lines.

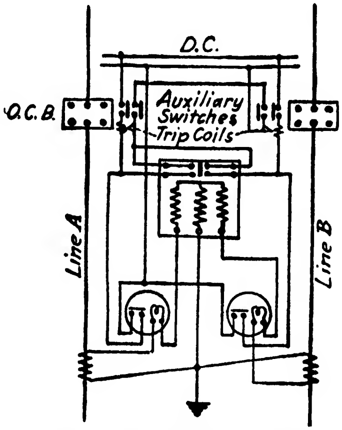


FIG. 319.—Application of differential relays for the protection of two parallel lines.

The relay itself is identical with a standard single-phase reverse-power relay with the exception that under normal balanced operation of the two lines there is no current flowing through the current element of the relay; hence there is no torque produced on the revolving disk. As soon as there is a difference of current in the two differentially connected current transformers, the current element of the relay will be energized and a torque produced upon the rotating disk. The direction of rotation of the disk will depend entirely upon which current transformer carries the larger current; or, in other words, the rotation of the disk may be in either direction, depending on which line is short-circuited. A double contact is provided so that either one of the two transmission lines can be opened, depending on which contact is closed. These double-contact reverse-power relays are extensively used either by themselves, giving instantaneous action, or with an overload relay, in which case any time setting can be obtained.

In order that only the damaged line be isolated, it is necessary to provide two auxiliary switches in the tripping circuit of each oil circuit breaker. These auxiliary switches are so arranged that they open when the oil circuit breakers open. If Fig. 318 is studied, it will be noticed that when one oil circuit breaker is in the open position the relay cannot operate the other breaker on account of the tripping circuit of the closed breaker being open through an auxiliary switch controlled by the position of the open oil circuit breaker.

*f. Differential Relay System.*—The details of the differential relay have been described in a preceding section, and a detailed diagram of the relay is given in Fig. 301; hence the description of its operation is omitted in this section. The diagram of connection of the equipment necessary for protecting one phase of each line is shown in Fig. 319. In order that only the damaged line be isolated, it is necessary to provide two auxiliary switches in the tripping current of each oil circuit breaker. These auxiliary switches are so arranged that they open when the oil circuit breakers open. If the diagram is studied, it will be noticed that, when one oil circuit breaker is in the open position, the differential relay cannot operate the other breaker on account of the tripping circuit of the closed breaker being open through an auxiliary switch controlled by the position of the open oil circuit breaker. In conjunction with the differential relay it is essential that an overload relay be used on each line, since the differential relay. does not protect the lines from an overload. It will be noticed that the contacts of the overload relays are in parallel with the contacts of the differential relay.

**208. Ring Bus System of Transmission.**—A simple ring of transmission is shown in Fig. 320 in which are found one generating station at *A* and four substations forming the connecting points of the ring. The relays that are most successful in such an installation are as follows: The two lines leaving the generating station should be equipped with inverse-time definite-minimum-time-limit overload relays. At each substation reverse-power relays equipped with a definite-minimum-time overload element should be placed in both the incoming and outgoing lines. These relays are set so that they will never trip when power flows into the substation no matter what its magnitude, but will trip when an overload current flows away from the substation.

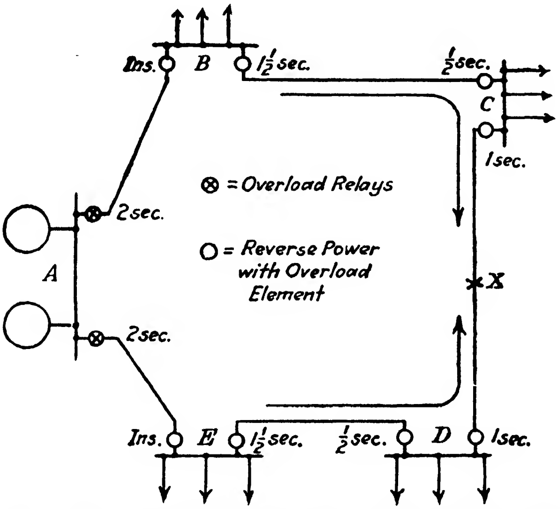


Fig. 320.—Relay protection for ring bus system of transmission.

An example of the relative time setting of the relays on such a system is very important, as, for example, going around the ring in the direction *ABCDE* the outgoing relays are set with decreasing time limits; for instance, *A* = 2 sec., *B* = 1½ sec., *C* = 1 sec., *A* = ½ sec., and *E* = instantaneous. Going around the ring in the opposite direction, the outgoing relays are also set with a decreasing time limit; for instance, *A* = 2 sec., *E* = 1½ sec., *D* = 1 sec., *C* = ½ sec., and *B* = instantaneous. To illustrate the operation of the system, consider a short circuit at *X*. Power will flow to this short circuit from *A* around *B* and *C*, and also from *A* around *E* and *D*. Since the relays on the incoming sides of the substation will not trip, it is evident that the relays on the outgoing sides of substations *C* and *D* will trip before any other relay in the system on account of their lower time setting, thereby eliminating the defective line from *C* to *D*.

**209. Underground Cable Protection.**—Practically all the methods of protecting overhead lines can be employed in the case of underground cables, but the so-called "split-conductor" method is so important that special mention is deemed advisable.

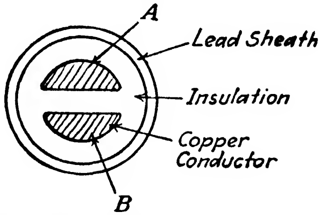


FIG. 321.—Split-conductor cable.

For this type of protection it is necessary that each cable be made with two entirely separate conductors properly insulated from each other but connected together at each end of the line, thereby placing the two halves of each cable in parallel. In Fig. 321 is shown a section of such a cable. If the two halves of each cable are identical, it is evident that the balanced protection as described for parallel transmission lines, can be employed between the two halves of each cable. A simplified diagram of the connections involved is shown in Fig. 322. In each half of the cable is placed a current transformer, the secondaries of which are placed in series. From Fig. 322 it is evident that the operation of such a system is exactly the same as illustrated in Fig. 317 for parallel transmission lines. In this case there is only one oil circuit breaker to be operated at each end of the line, while in the case of the parallel transmission lines there are two breakers at each end. The only big disadvantage to such a method is the fact that special cables are necessary, but in the

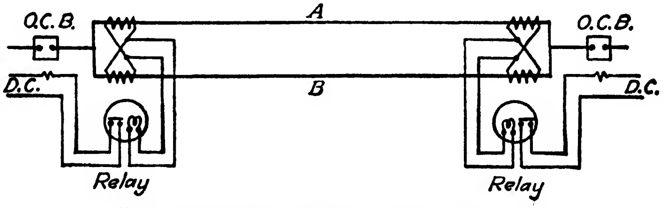


FIG. 322.—Split-conductor cable protection.

manufacture of some large cables it is sometimes desirable that they be made in two sections on account of the mechanical difficulties involved in making up a rather large section of copper conductor.

## Questions for Class Discussion

**1.** Classify relays according to their time action.

**2.** State and briefly explain the two most important principles upon which relays are built. Which of these principles is more commonly used today?

**3.** Name five general classes of relays, and state briefly the field of application of each class.

**4.** What are the three essential parts of a relay, and what is the function of each part?

**5.** Distinguish between "circuit-closing" and "circuit-opening" relays. Illustrate with diagrams of connections.

**6.** What features make it undesirable to install a circuit-opening relay in a system where very heavy short-circuit currents are likely to occur?

**7.** Explain the details and purpose of "differential relays."

**8.** What is the objection to using "instantaneous"-action relays in circuit-breaker applications? About what interval corresponds to instantaneous action? Why are "time-limit" relays preferable?

**9.** Give a typical application of each of the following kinds of relays, and justify their use in each particular case: (*a*) overload, (*b*) underload, (*c*) overvoltage, (*d*) no voltage, (*e*) reverse power, (*f*) reverse phase, (*g*) reverse current, (*h*) reverse polarity, (*i*) distance-ohm.

**10.** Name and illustrate by sketches three types of protection that can be given to alternators. Which of these methods is mostly used today? Why?

**11.** Show by means of sketches the general methods of protecting three-phase transformer banks (*a*) when connected Y-Y or delta-delta, (*b*) when connected Y-delta.

**12.** What are the three distinct types of systems for transmission, and state why each requires different types of protection?

**13.** Explain briefly the following schemes of relay protection as used for parallel transmission lines: (*a*) balanced or differential system, (*b*) inverse-time-limit overload and reverse-power relay system, (*c*) double-contact reverse-power relay system, (*d*) differential-relay system.

**14.** For what system is the split-conductor type of relay designed?

**15.** Give an example in which the use of the following relays will not afford proper protection: (*a*) inverse time, (*b*) balanced relays, (*c*) split-conductor type.

**16.** Show by sketches the application of the pilot-wire type of relay connection. What are its advantages?

**17.** Illustrate by sketch how protective relays should be used in a ring system of transmission. What should be the relative time settings of the relays?

**18.** How can protection against reversal of power and overload be obtained at the same time?

# CHAPTER XVIII

## TRANSMISSION-LINE DISTURBANCES AND PROTECTION

**210. Nature of Disturbances.**—Transmission-line disturbances may conveniently be discussed under two distinct heads: (1) those which are produced within the circuit itself and (2) those which are produced by a source of energy external to the circuit. The first class includes transients due to sudden overspeed of generators, poor regulation, resonance conditions within the circuit, arcing grounds, switching, and short circuits, and the second class includes all the effects of lightning. All these disturbances produce more or less the same results; in other words, any change in the steady state of the circuit will produce transients. The subject of lightning, however, is of such importance in the design and operation of transmission lines that it will be considered more in detail in Art. 211.

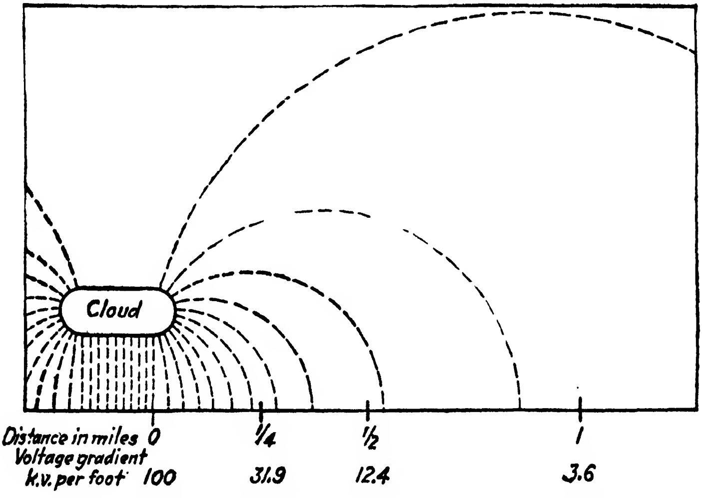


Fig. 323.—Electric field and potentials in space caused by charged cloud.

**211. Lightning.**—Before stating any of the effects of lightning, it is best to investigate the general nature of the phenomena

Consider a cloud of the shape designated in Fig. 323, which is located in space a distance of about 1,000 ft. above the surface of the earth. This cloud and the surface of the earth can be considered as the two plates of a huge condenser. Because of atmospheric electricity this condenser is slowly charged up to a certain potential aboveground. The electrostatic field obtained between the cloud and the earth is illustrated in Fig. 323. If the potential of the cloud aboveground becomes high enough, a lightning flash will occur. A lightning flash is, therefore, a short circuit upon the condenser formed by the cloud and the earth. It has been found that the maximum voltage gradient between the cloud and the earth is of the order of 100 kv. per ft. As indicated in Fig. 323 this gradient is directly under the cloud, where the electrostatic field is uniform; but at points away from the cloud the gradient is less, being approximately 32 kv. per ft. at ¼ mile, 12.4 kv. per ft. at ½ mile, and 3.6 kv. per ft. at 1 mile away from the point of maximum intensity. As the potential of the cloud is being raised, energy is being stored at a very slow rate, but when the flash occurs, energy will be discharged very rapidly; therefore the current may be very large. At a voltage gradient of 100 kv. per ft., it follows that the total potential of a cloud at 1,000 ft. aboveground must be 100,000,000 volts. The current in a lightning flash must be dependent on the voltage, the resistance, inductance, and capacity between cloud and ground, and also on the nature of the wave form of the discharge. It is the general belief of a good many engineers that currents of the order of 20,000 to 50,000 amp. in a flash are not uncommon.

Now consider a transmission line located directly under a cloud. The conductors of such a line can be considered as a secondary plate of the condenser formed by the cloud and the earth. As the potential of the cloud is slowly raised above that of the ground, it follows that the conductors on the transmission line must also be charged to a certain potential. There can be no disturbances set up on the transmission line during the charging process since this process is very slow, and ample time is allowed for this potential to cause a leakage of current between ground and line, thus producing the proper equilibrium. The voltage that the line assumes at the instant the cloud discharges is that of the equipotential surface at the point where the line is located. Furthermore, the potential of the line will depend upon the height of the conductors aboveground. In other words, if a transmission line with horizontally placed conductors that are 50 ft. aboveground is located within the equipotential surface of 100 kv. per ft., the voltage assumed by the conductors at the instant of discharge will be 50 × 100 = 5,000 kv. This value is a good deal larger than general indications tend to show. The voltage impressed upon a transmission line seldom exceeds 50 kv. per ft., or the voltage assumed by a line 50 ft. aboveground seldom exceeds 50 × 50 = 2,500 kv. As indicated by Fig. 323 the voltage gradient drops very rapidly as the horizontal distance between line and cloud increases; hence it is safe to assume that a large percentage of lightning discharges do not cause voltage gradients over 25 kv. per ft. at the point where the line is located.

If the voltage assumed by the line conductors at the instant of lightning discharge exceeds the spark-over voltage of the insulators, it is obvious that it will flashover and go to ground. On the other hand, if this voltage is less than the insulator spark-over voltage, it will travel to the ends of the transmission line at approximately the velocity of light and possibly damage apparatus at the power house or substation, or be harmlessly discharged to ground over a lightning arrester. It should be kept in mind, however, that the spark-over voltage of insulators is not the same for lightning and standard 60 cycle per sec. voltages. It has been found from tests that the lightning spark-over voltage for insulators is about twice the 60 cycle per sec. spark-over voltage.

A good many installations have conductors placed in a vertical plane instead of a horizontal plane. Under such conditions, the voltage assumed by each of the conductors will be different, depending on the particular height of conductor aboveground. It is therefore evident that under such conditions there will also be established a difference of potential between conductors as well as from conductors to ground.

Many field and laboratory tests have been conducted on the effects of lightning on transmission lines and power stations. Two effects are possible, namely, direct hits and induced voltages due to strokes in the neighborhood of the line. It has been estimated that every 50 miles of power line will be hit by lightning an average of 50 times every year. Each stroke will have a potential of 20 to 30 million volts. Other estimates indicate that an average of 10 lightning strokes bombard every square mile of the United States every year and that the average stroke consists of 20,000 amp. Strokes that hit the earth near power lines will induce such electrical voltage 50 times a year on every 50 miles of power line. This is in addition to the average of 50 direct strokes that will hit the same stretch of wire. Ninety per cent of the time, induced voltages range from 100,000 to 300,000 volts, but occasionally will reach a magnitude of 1 million volts.

FIG. 324.—Lightning discharge striking a transmission line.

Two decades ago nearly every one of the 50 direct strokes that hit a 50-mile power line each year knocked the line out of service at least temporarily. Today, a properly designed power line is unlikely to be put out of service by lightning more than once in 5 years.

An example of lightning discharge is shown in Fig. 324.

Ideal lightning protection would involve complete shielding of power lines so that they would be free from direct strokes and also induced potentials. This not being possible, protection takes two forms, namely (1) partial shielding as accomplished with ground wires and (2) the use of some form of lightning arrester to drain off the lightning surge energy from the line.

**212. Arcing Horns or Rings.**—As indicated in Art. 211, if the voltage induced on a transmission line is higher than the spark-over voltage of the insulators a flash will occur over the insulator surface. It is obvious that such an arc will damage the porcelain, and even if the arc does not completely ruin the entire insulator thereby causing a dead short circuit, one or more units of the insulator may be so damaged that a future surge will cause breakdown. It must be kept in mind that a ruined insulator string which may be located many miles from the nearest plant or substation may tie up a line for a long time, thereby causing a large financial loss due to service interruption. If such arcs can be kept away from the insulator surface, there will be no damage done; the arc will dissipate the surge and then cease, without in any way decreasing the effectiveness of the transmission-line insulation. This can be accomplished by placing arcing rings or rods at the two ends of the insulator strings as shown in Fig. 294. In some cases, when the transmission-line supports are made of steel construction, the upper arcing horn can be omitted, the steel structure acting as the upper horn. It has been found that, by properly placing arcing horns or rings, insulators are completely shielded from lightning arc-overs as well as arc-overs at the operating frequency.

**213. Ground Wire.**—By a ground wire is meant a wire, generally of steel, supported from the top of transmission-line towers and solidly grounded at each tower. In case of wood poles it is essential that a good conductor connect the ground wire to a solid ground. In case of steel supports the ground wire may be fastened to the steel structure, but it is essential that the footings of the structure be well grounded. When concrete foundations are used, it is essential that a good permanent ground be provided other than the footings themselves. The ground wire when solidly connected to ground through a very small resistance has the effect of reducing the height of the conductors above the earth and hence reducing the amount of voltage induced upon the line conductors due to the electrostatic field produced by a charged cloud (see Art. 211). Investigations conducted by F. W. Peek, Jr.,[1] showed that one ground wire, when properly installed, reduces the induced lightning voltage to approximately one-half,

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[1] Lightning, *Gen. Elec. Rev.*, July, 1916.

two ground wires to one-third, and three to one-fourth. The following table shows the results of these tests.

TABLE XVII.—LIGHTNING VOLTAGES ON TRANSMISSION LINE (Kilovolts Maximum)

| Height of tower, feet | No ground wire | | Ground wire | | | Lightning flash-over voltage of line insulators | | |
|---|---|---|---|---|---|---|---|---|
| | Theoretical highest | Probable usual highest | Direct stroke to ground wire, (one wire) | Usual highest. One ground wire | Usual highest. Three ground wires | 220-kv. line | 154-kv. line | 110-kv. line |
| 75 | 7,500 | 3,750 | 3,750 | 1,875 | 900 | | | |
| 50 | 5,000 | 2,500 | 2,500 | 1,250 | 625 | 1,800 | | |
| 40 | 4,000 | 2,000 | 2,000 | 1,000 | 500 | 1,800 | 1,400 | 900 |
| 30 | 3,000 | 1,500 | 1,500 | 750 | 375 | 1,800 | 1,400 | 900 |
| 20 | 2,000 | 1,000 | 1,000 | 500 | 250 | | | |

The effectiveness of the ground wire is entirely dependent on whether a good ground is obtained or not. The resistance and reactance of the ground connection should be very low. Dry country provides poor grounds, while damp country is especially good for producing effective grounds. It is also essential that grounds be made at every pole or tower. From the tests mentioned above, it appears that ground wires will give almost complete protection against direct lightning strokes. It has generally been recognized that unprotected lines running through dry country are more subject to direct strokes than unprotected lines running through wet country. Just how many ground wires should be used and how they should be placed is hard to say. At least, they should be placed above the current-carrying conductors, and it is generally desirable to place the ground wire so that the conductors are included within a 60-deg. angle from the vertical. This is not always possible with one ground wire or even two with horizontally placed conductors. In the case of flexible tower lines the ground wire is also useful as a convenient supporting member.

**214. Ideal Lightning Arrester.**—The ground wire, as described above, is in a general sense a preventive device, but it does not entirely prevent the formation of traveling waves on a line. Furthermore, those lines which are not equipped with ground wires will be subjected to disturbances which produce surges that must be allowed to escape to ground, or the apparatus connected to the line must be strong enough to reflect or absorb these surges until they are entirely damped out. Lightning arresters are devices to provide the necessary path to ground for such surges, yet prevent any power current from following the surge. An ideal arrester must therefore have the following properties:

1. Ability to remove the surge energy from the line in a minimum time.[1]
2. High resistance to flow of power current.

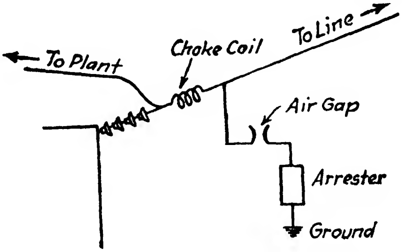

FIG. 325.—Method of connecting choke coil, air gap, and arrester.

3. A valve action automatically allowing surge to pass and then closing up so as not to permit power current to flow to ground.
4. Always ready to perform.
5. Performance such that no system disturbances are introduced by its operation.
6. Economically feasible.

There are a large number of lightning arresters on the market, some more dependable than others, some very expensive, and some less expensive. The particular one to be chosen for a particular installation is a question of economic balance between investment cost and value of continuity of service. The equipment for complete lightning-arrester protection includes choke coils, air gaps, and the arrester itself. The method of utilizing this equipment is illustrated in Fig. 325. A brief description of the most important types of arresters and their general field of application is given below.

**215. Choke Coil.**—Whenever a surge of high frequency or a steep wave front due to lightning or any other cause travels

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[1] For a good treatment of surges see V. Karapetoff, A Graphical Theory of Traveling Waves, *Jour. A.I.E.E.* Vol. 48, p. 508, April, 1929; See also, J. G. Tarboux, "Introduction to Electric Power Systems," International Textbook Company, Scranton, Pa.

along a line and strikes an inductive winding, it builds up a high voltage to ground, a large portion of the surge being reflected back on to the line. A choke coil is an especially designed reactor which should be connected between any apparatus and the line, in order that the end turns of such apparatus may be relieved of any excess voltage. A typical choke coil is shown in Fig. 326. The reactance of any reactor varies with the frequency; hence on a high-frequency disturbance, such as lightning, the reactance will be high, whereas at commercial frequencies the reactance is practically nil. No definite method can be given as to how a choke coil should be chosen or when one should be used. If one is not used, it means that the end turns of transformers or other apparatus must be strong enough to stand the stresses imposed by the surges. When used, it will always allow part of a surge to go through, but it reduces the steepness of the wave and hence lowers its harmful effects.

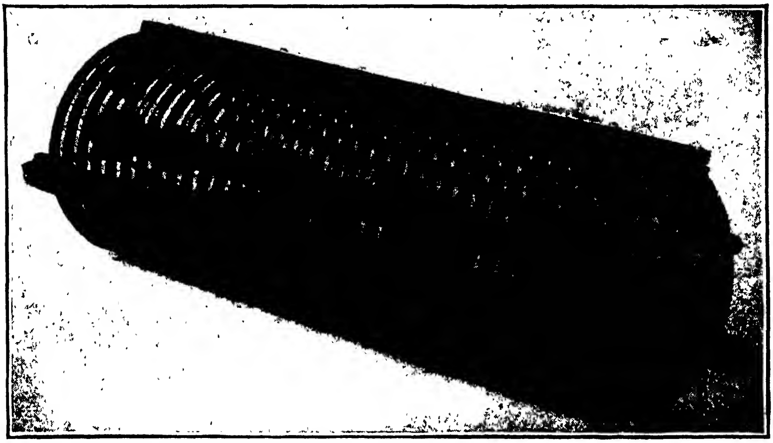


Fig. 326.—Typical choke coil. (*Hi-Voltage Equipment Company.*)

✓ **216. Horn-gap Arresters.**—There are a large number of different types of arresters on the market which embody some arrangement of horn gaps and resistances. When an arc is obtained across a gap, the surrounding air becomes heated, thereby causing upward air currents which tend to move the arc. If the gaps are made in the shape of horns, with an increasing distance apart toward the upper ends, the arc will be lengthened as it is carried upwards by the air currents, finally reaching a point where it cannot be maintained. Such arresters are rather slow and limited to moderate transmission voltages.

As stated in Art. 214 an ideal arrester should have very low resistance, and the gaps should have a rapid discharge characteristic. The distance apart to which the gaps are set is determined by the line voltage, and therefore it is desirable that any surge voltage slightly in excess of line voltage will discharge across the gaps. The only gap that has equal spark-over voltage characteristics for lightning and operating frequencies is a sphere gap. Needle gaps have a lightning spark-over voltage about twice as high as the spark-over voltage at standard operating frequencies. It follows, therefore, that gaps on lightning arresters, to be fully effective, should be spheres. Another important factor is that the spark-over voltage at normal frequencies is less when the gaps are subjected to rain; hence it is best that sphere gaps be covered in order that a fixed setting may be utilized. Rain, however, seems to have no effect upon the lightning spark-over voltage. The use of series resistances,

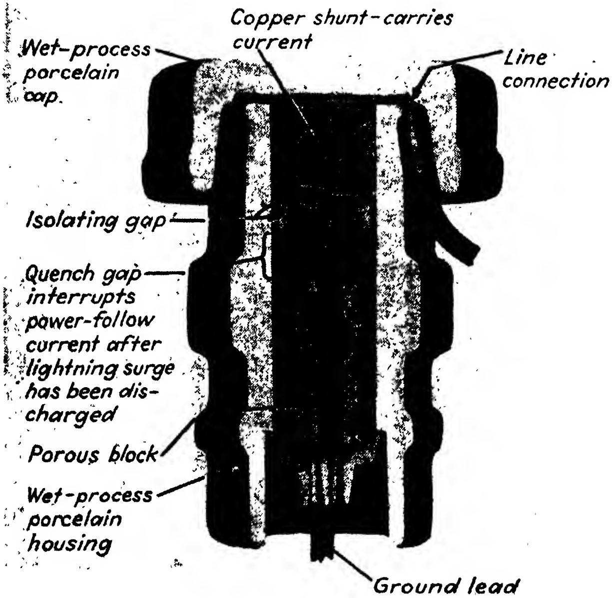


FIG. 327.—The 3-kv. autovalve arrester. Higher ratings are similar, except for additional isolating gaps and porous block elements. (*Westinghouse Electric Corporation.*)

though necessary with certain types of arresters, has the detrimental effect of slowing up the discharge of the surge, thereby shifting a heavier duty upon the line insulators, or apparatus at the end of the line.

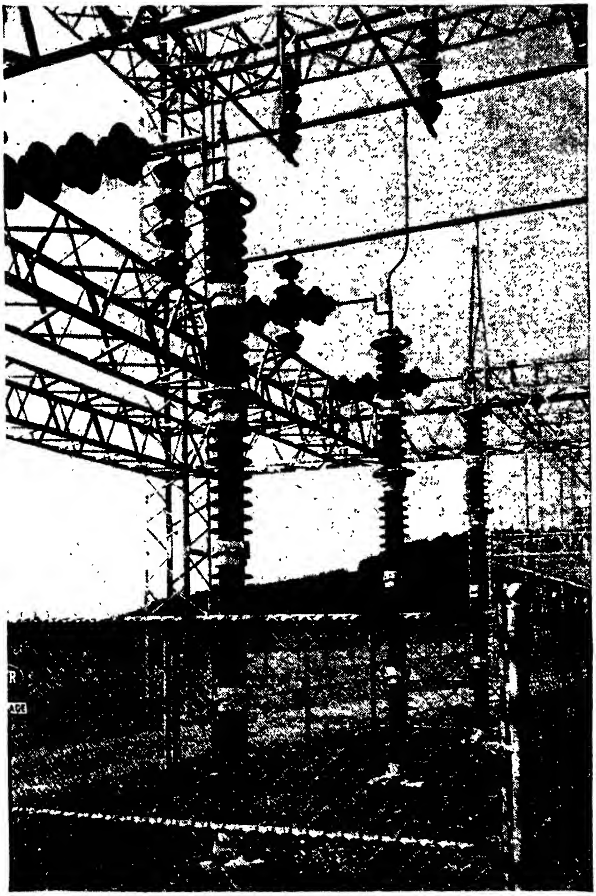


FIG. 328.—A 169-kv., 3-phase, 3-pole, autovalve arrester installation. (*Westinghouse Electric Corporation.*)

**217. Autovalve Arrester.**—The autovalve arrester depends for its operation upon the principle that a current flowing across an air gap may be in the form of an arc of a glow discharge. The voltage required to maintain an arc is low, of the order of 50 volts or less, while that of a glow discharge is of the order of several hundred volts. To form an arc there must be a concentration of current and hence heating; therefore, if the electrodes of small gaps are made of material of considerable resistivity, the discharge is distributed over the face of the electrode, thereby preventing the formation of an arc, the discharge being maintained as a glow. Thus, a structure composed of a column of flat electrodes separated by mica spacers approximately 5 mils in thickness will operate as a valve, the critical voltage being equal to about 350 volts per gap, and the characteristic for voltage above this value being dependent on the resistance of the electrodes

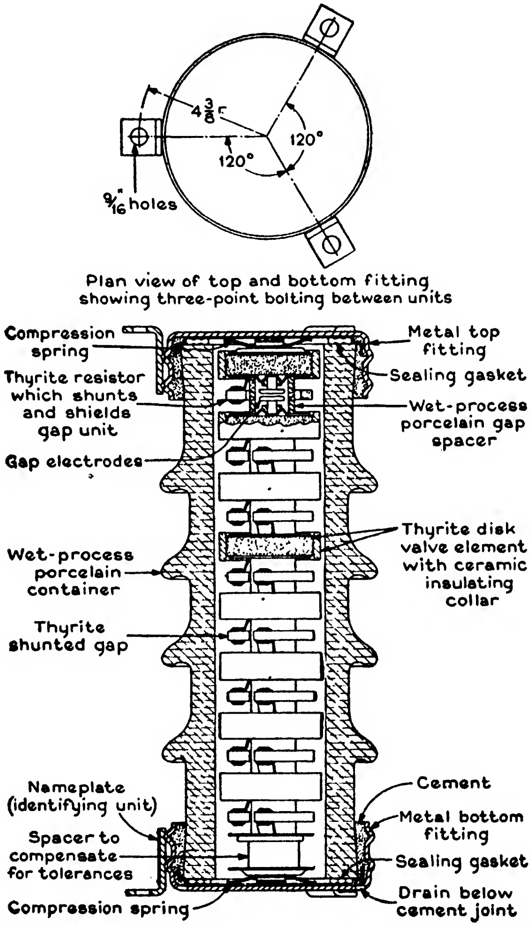


FIG. 329.—Cross section of thyrite distribution arrester unit. (*General Electric Company.*)

between plane surfaces. The discharge current capacity may be controlled by proper selection of disk area and thickness to give the characteristics required for any particular service. The voltage at which the discharge starts is 350 volts per gap; hence as many gaps as necessary can be placed in series to meet the requirements of different commercial voltages.

There are two general arrangements of this arrester which are used. The first arrangement, known as the distribution type, is composed of a single stack of units with a small gap in series, the entire element being enclosed in a porcelain case, with the two terminals brought out at the top and bottom of the case (see Fig. 327). This type is made for circuits up to 15,000 volts.

For higher voltages and station use the autovalve arrester is made up from several series units. A typical installation is shown in Fig. 328.

**218. Thyrite Arresters.**—This type of arrester is shown in Fig. 329. Its characteristics are essentially those of thyrite, a dense homogeneous organic compound of a ceramic nature. This material possesses the characteristic of being substantially an insulator at one voltage and becoming an excellent conductor at a higher voltage. The electrical resistance of thyrite is a function of voltage only, the resistance decreasing and the current increasing 12.6 times as the voltage is doubled. This material seems to adhere to this characteristic indefinitely without change, and it also appears to have no time lag in its operation.

FIG. 330.—A 73-kv. thyrite station-type arrester. (*General Electric Company.*)

The complete assembly is enclosed in a porcelain shell. For higher voltages, as many of these units as are necessary are bolted together (see Fig. 330).

**219. Pellet-type Arrester.**—The construction of the pellet arrester is illustrated in Fig. 331. The electric elements consist of a column of pellets and a series-gap assembly. The pellet column forms the valve element, preventing the flow of system power current following discharge, while the series gap isolates the valve element from the line until it is sparked over by the lightning impulse.

The pellets are made of lead peroxide, with a thin porous coating of litharge, and are assembled in a porcelain-tube container

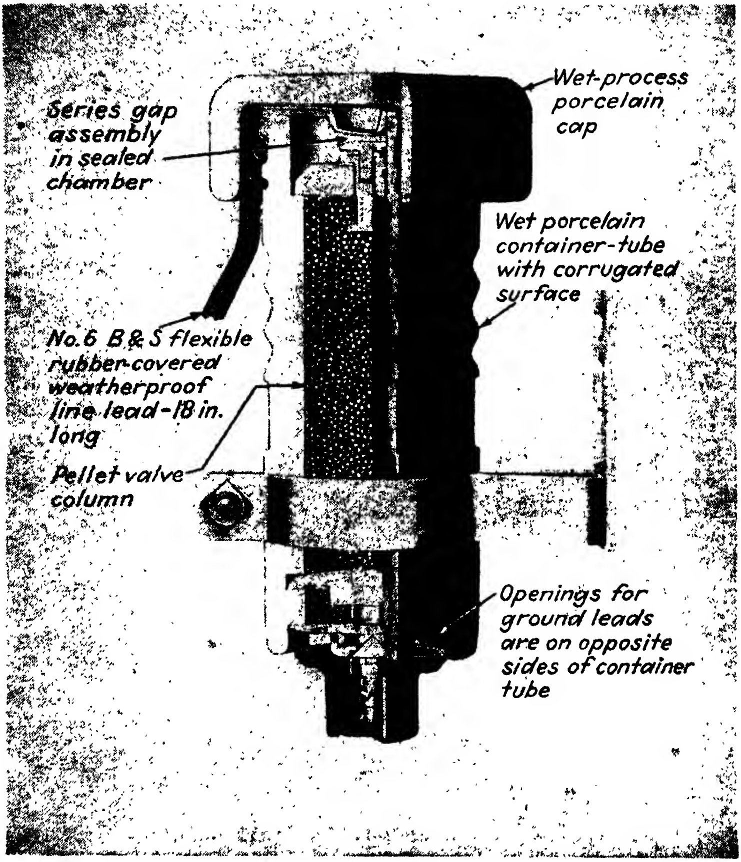


Fig. 331.—Pellet arrester. (*General Electric Company.*)

with metal electrodes in contact with each end of the pellet column. The length of the column is about proportional to the arrester-voltage rating.

The series-gap assembly is sealed within a gap chamber, which is entirely isolated from the pellet-valve column.

**220. Deion Gap.**—The deion gap is a simple device mechanically, consisting essentially of a fiber tube housing two specially

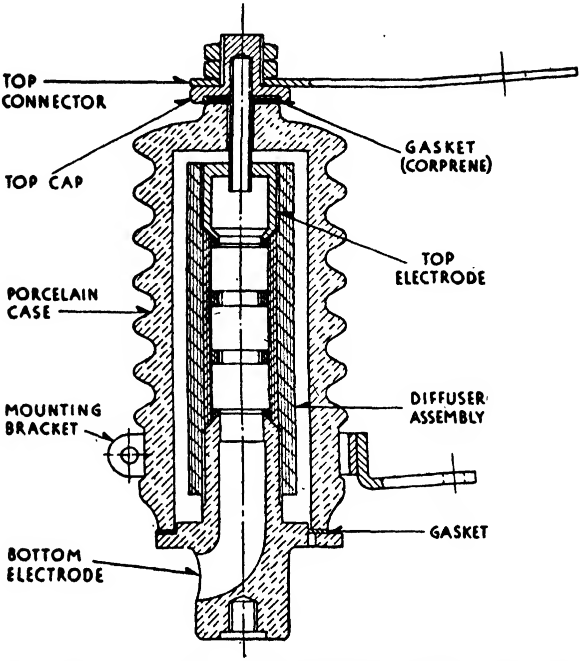


FIG. 332.—Deion gap. (*Westinghouse Electric Corporation.*)

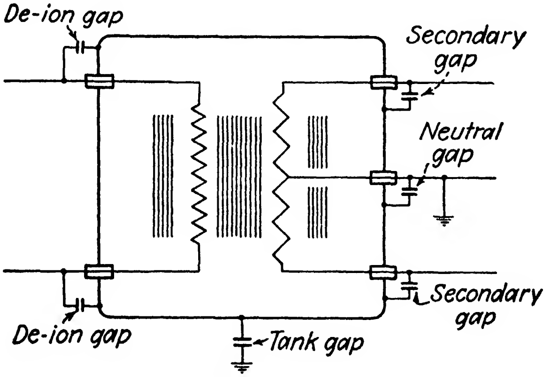


FIG. 333.—Typical lightning protection applied to distribution transformers.

designed electrodes. Between these is a fiber diffuser, which deionizes the arc and stops the further flow of current. After a surge is discharged to ground, the power follow arc, which would attempt to remain, volatilizes the walls of the diffuser, generating additional gases which are discharged at high pressure from the bottom vent. This action further deionizes the power arc stream by the sudden introduction of un-ionized particles, weakening the arc path. The arc is extinguished because the system voltage is unable to strike across the inner electrodes.

A typical deion gap is illustrated in Fig. 332. The application of these gaps to the high-voltage winding of a distribution transformer is shown in Fig. 333.

### Questions for Class Discussion

**1.** What is the purpose of arcing horns, as used on transmission-line insulators?

**2.** Why is a ground wire desirable on a transmission line?

**3.** What is the purpose of lightning arresters?

**4.** Name the principal features of the apparatus used for lightning protection.

**5.** Name the various types of lightning arresters in use, and give the range of application of each. Is any one of them limited to either alternating current or direct current? Why?

**6.** Describe the action of the autovalve arrester.

**7.** What is the effect of resistance in the lightning-arrester circuit?

**8.** Which is the better protection against lightning: (*a*) lightning arresters or (*b*) overhead grounded wire on the transmission line? Why?

**9.** State some of the disadvantages of the overhead grounded wire.

**10.** What determines the value of a surge coming into a plant?

**11.** Why are choke coils used between the apparatus of a plant and the ground line?

**12.** What is the objection to too large a choke coil? Explain.

**13.** What are some of the causes producing transmission-line disturbances? Explain.

**14.** Discuss briefly what is meant by (*a*) oscillations and (*b*) traveling and standing waves.

**15.** What is meant by "surge impedance" of a transmission line? Of what importance is this quantity?

**16.** Explain what is meant by a "quarter-wave-length" transmission line? Can such a line be stable? Explain.

**17.** In what two distinct ways does lightning affect the operation of a transmission line?

**18.** What is the maximum voltage gradient between a charged cloud and the earth? How does this voltage gradient vary for points away from the cloud?

**19.** Assuming a conductor located 50 ft. above the ground, what is the maximum voltage obtained by the conductor at the instant after a lightning discharge? (Conductor located directly under the cloud.)

**20.** Describe the general theory and details of construction of a thyrite arrester. How can it be adapted to high voltages?

# CHAPTER XIX

## SUBSTATIONS

**221. Purpose and General Classification.**—The purpose of a substation is to transform the characteristics of the electrical energy supplied to some form suitable for use, as for example, a conversion from alternating current to direct current for the use of city railway service, or a change from one voltage to another, or one frequency to another. Substations can, therefore, be classified according to:

| | |
|---|---|
| Service | Alternating current |
| | Alternating to direct current |
| Mounting | Indoor |
| | Outdoor |
| Function | Tap |
| | Distributing |
| | Industrial |
| | Sectionalizing |
| | Transmission-line supply |
| | Power-factor correction |
| | Frequency changer |
| | Railway, portable |
| | Direct current for light and power |
| Type of apparatus | Transformer |
| | Rotary converter |
| | Motor generator |
| | Frequency changer |
| | Synchronous condenser |
| | Power rectifier |
| Control | Manual |
| | Semiautomatic |
| | Automatic |
| | Supervisory |

**222. Functions Performed by Substations.**—In Art. 221 are enumerated a number of functions that are fulfilled by substations. It should be clearly understood that this tabulation includes the most common requirements and also that one particular station may fulfill one, two, or more of the functions enumerated. It is convenient, however, to discuss each type separately.

*a. Tap.*—To be economical, transmission of large amounts of power over long distances must be done at voltages above 110,000 volts. Substations for supplying small amounts of power from such high-voltage lines are not satisfactory from the standpoint of operation and are also uneconomical. It is, therefore, common practice to install a few substations at advantageous points along the high-tension lines and step down the high-transmission voltage to a lower secondary-transmission voltage from which numerous small loads may be supplied. For example, a power company may use 110,000 volts for their main transmission lines and 44,000 volts for their secondary lines. In many cases the 44- and 110-kv. lines may run parallel along the same right of way. Local loads can be economically supplied from the 44-kv. line when their supply from the 110-kv. line would not be economically feasible. Such a substation between the 110- and 44-kv. lines is known, as a "tap substation." Its equipment may comprise high- and low-tension switching equipment, transformers, and lightning arresters.

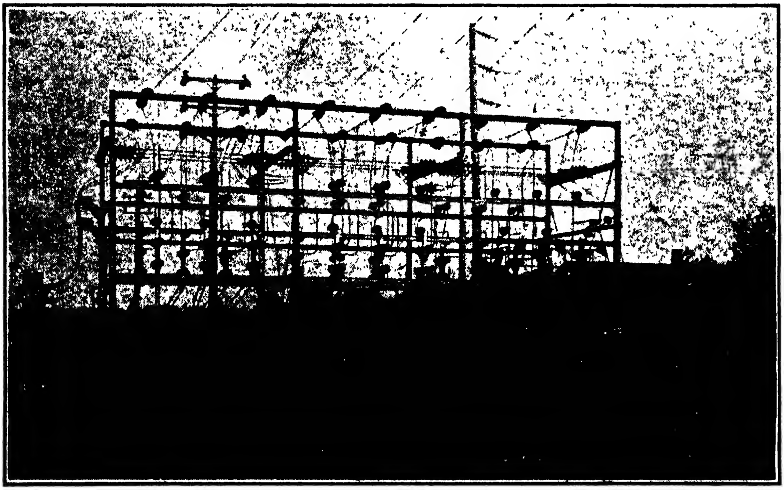


FIG. 334.—A 33,000-volt substation. (*Delta Star Electric Company.*)

*b. Distribution.*—Any substation that is used to transform electrical energy to a potential that is low enough for general distribution and utilization is a distributing substation. Such a substation will generally receive its energy over a few comparatively high-tension lines and distribute it over a large number of low-voltage lines. For local distribution 2,400 volts has been recognized as a standard voltage; for longer distances and larger blocks of power, distribution at 6,600, 13,200, and 22,000 volts has been used. A large number of substations, fulfilling a wide range of demands, are included under this head.

*c. Industrial.*—When fairly large blocks of power are required by industrial plants, it often becomes necessary and advisable to install an individual substation to supply such a load direct from the main high-voltage line or secondary line of lower voltage.

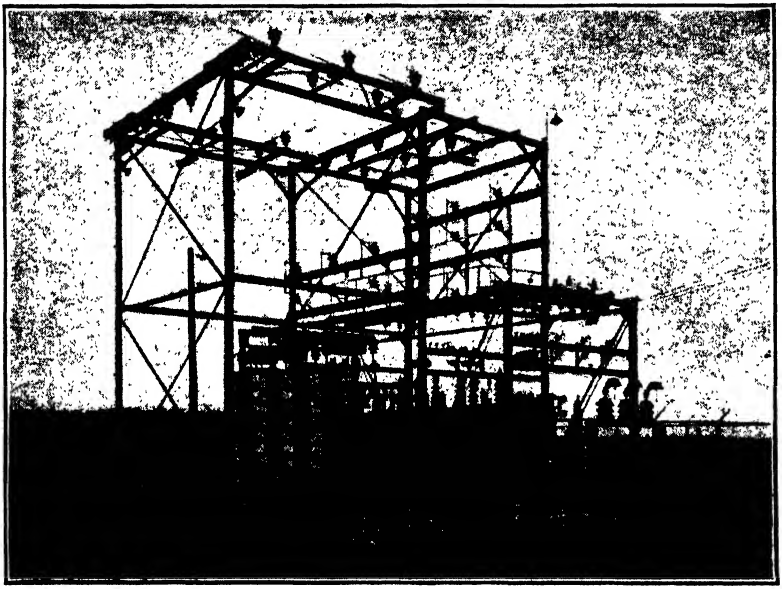


Fig. 335.—A 66,000-volt substation. (*Delta Star Electric Company.*)

Such a substation is obviously known as an industrial substation. Its simplest form would comprise only switching equipment, there being no voltage transformation. In most cases a voltage transformation is probably needed; hence transformer equipment is included.

*d. Sectionalizing.*—In very long high-voltage large-capacity lines, particularly when several circuits are run in parallel, it is often necessary to split the lines into sections, in order that proper protection to the line and service be obtained. Such a substation, is therefore, helpful in sectionalizing damaged sections of a line, providing continuity of service. Often when two circuits are run in parallel, one circuit in a short section may be damaged. It is possible to shift the entire load over to the remaining good circuit for the length of that particular section without any serious results while repairs are carried on upon the damaged line. Such a substation will generally comprise only switching equipment. In long lines it may also serve to supply power-factor-correcting equipment.

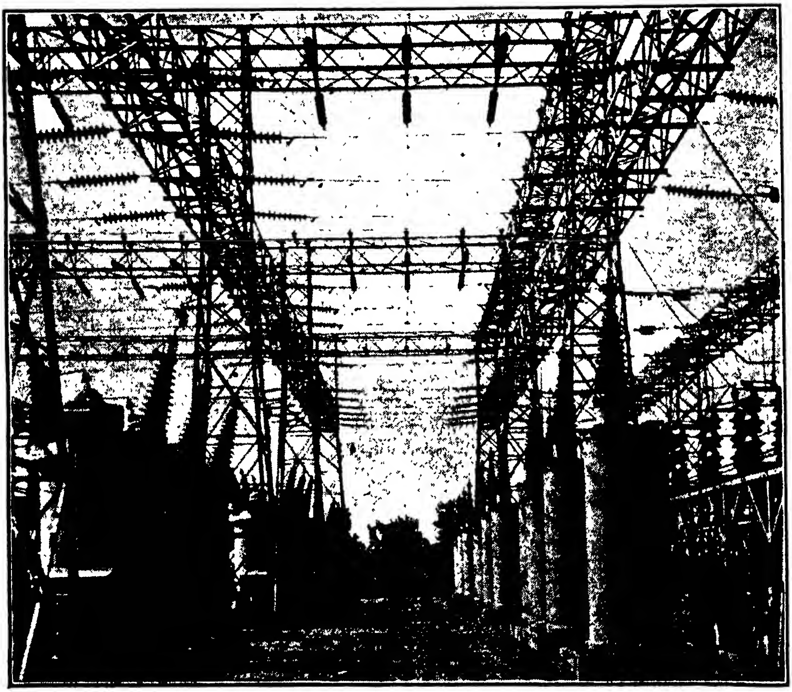


FIG. 336.—A 132,000-volt substation. (*Delta Star Electric Company.*)

*e. Transmission-line Supply.*—It is becoming more and more common to install the high-tension equipment of a power plant outdoors, the installation becoming nothing more than a step-up substation receiving its power at generator voltage, then stepping up its voltage and finally sending it out over high-voltage transmission lines. Such a substation is nothing more than an outdoor distributing substation turned around, the voltage being stepped up instead of stepped down.

*f. Power-factor Correction.*—A study of long transmission lines will reveal the fact that the voltage at the end of the line tends to

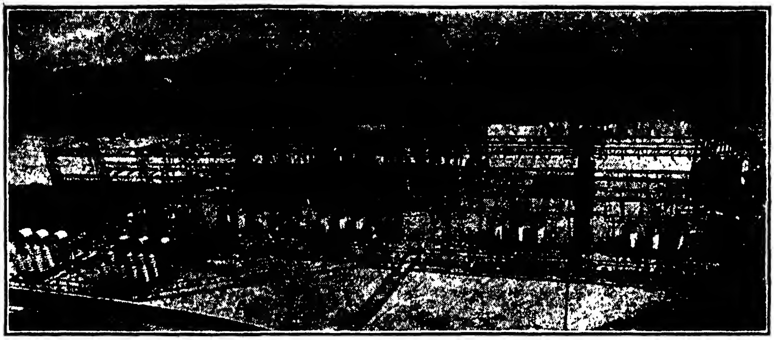


Fig. 337.—A 132,000-volt Philo substation, of the Ohio Public Service Company. (*Delta Star Electric Company.*)

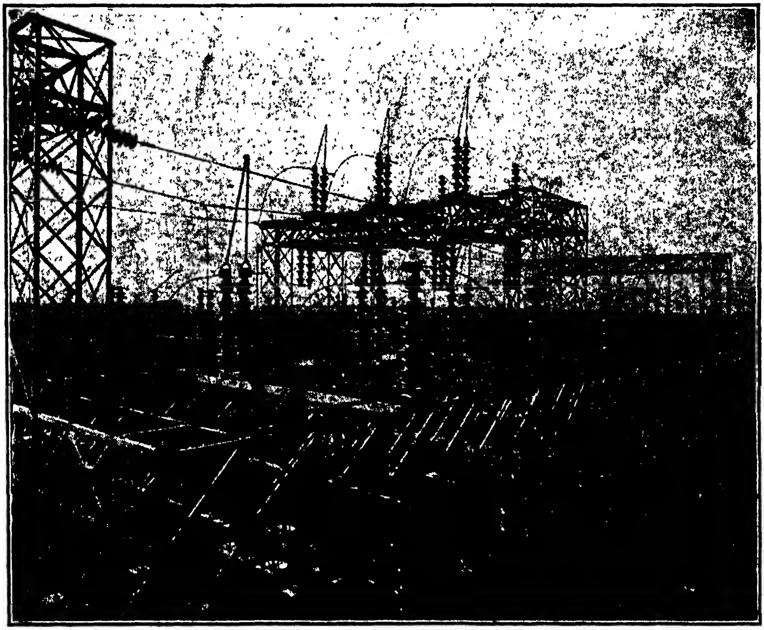


Fig. 338.—A 220,000-volt substation of the Pacific Gas and Electric Company. (*Pacific Electric Manufacturing Company.*)

increase as the load supplied is decreased, while on the other hand it tends to decrease as the load is increased. Owing to the inductance and capacity effects this variation in voltage is accompanied by a wide variation in power factors. In order to control the voltage and also the power factor of a line, it is necessary to use synchronous condensers at the end of the line, the control of their excitation being obtained directly through the action of a regulator similar to the type of regulators used on alternating-current generators. In Fig. 339 is shown a 40,000-kva. synchronous condenser. To supply such a machine the transmission-line voltage must be stepped down; hence a power-factor-correcting substation will include switching equipment, transformers, and all equipment necessary for the operation of synchronous condensers. A synchronous condenser is essentially a synchronous generator operated as a motor without any mechanical load. The current taken by such a motor can be made to lead or lag the applied voltage by practically 90 electrical degrees by properly adjusting the field excitation. An over-excited synchronous motor will take a leading current, while an underexcited motor will take a lagging current from the line. It is possible, therefore, so to control a synchronous condenser that power factor and voltage regulation may be had at the end of a long transmission line.

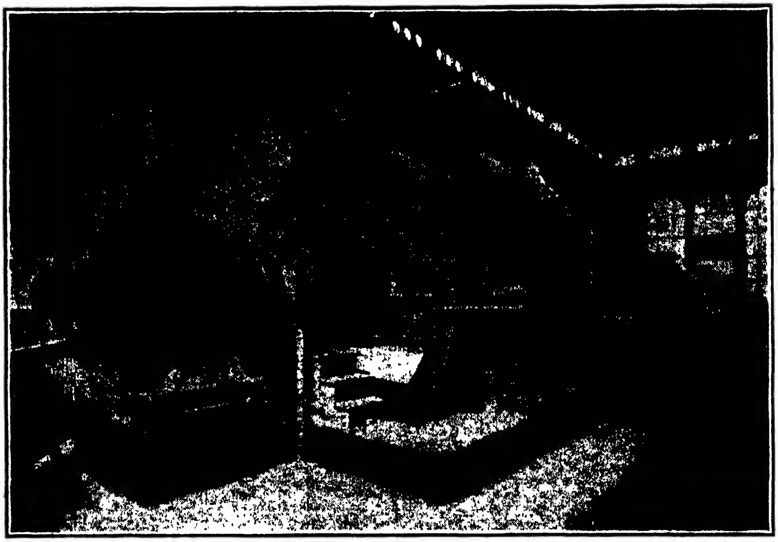


Fig. 339.—A 40,000-kva. synchronous condenser. (*Westinghouse Electric Corporation.*)

*g. Frequency Changer.*—Frequency-changer sets have been discussed in Art. 54 and illustrated in Figs. 69 and 70. Their application to a power system is also illustrated in the circuit layout of Fig. 17. As has been stated elsewhere in this text, 25 and 60 cycles per sec. are considered as the two standard frequencies of this country; nevertheless, there are still a few systems at other frequencies. To interconnect two systems of different frequencies it is absolutely necessary that frequency changers be used. Invariably a station of this type will necessitate transformers to step down or step up the voltage supplied to or delivered from the frequency changer, since the highest voltage that is normally feasible for rotating machinery has been found to be about 13,200 volts.

*h. Railway.*—Substations supplying railways may be generally classified under two heads, namely, as alternating current and as direct current. For main-line electrification there seems to be a difference of opinion as to which is better, alternating or direct current. There are railways in operation with both systems and operating satisfactorily. On the other hand, it has been generally recognized that direct current is better suited to city railway service. In the case of alternating-current substations the problem is generally one of voltage transformation and of supplying single-phase power to the trains. If the power is generated purely for the utilization of the railway load, it may appear reasonable that generation be done single phase. This is not generally the case, since power can be more economically generated and controlled from three-phase units than from single-phase generators. It follows, therefore, that when supplying single-phase loads from a three-phase system care should be exercised to balance the loads upon the three-phase system. In Europe there are a considerable number of installations utilizing three-phase systems for railways, but the complications arising in transferring three-phase power to the locomotives are so many that three-phase supply has not been favored in this country. It is, however, possible to supply single-phase power to the locomotive and then convert the single-phase to three-phase inside the locomotive by the use of a phase converter, such as discussed in Art. 58. This system has the advantage that polyphase-driving motors may be used and also the simplicity of the single-phase supply is obtained.

In the case of direct-current railways, the substations are generally supplied with three-phase power and converted to direct current by means of rotary converters, motor-generator sets, or power-arc rectifiers. In the case of a rotary-converter or power-arc-rectifier station, special transformers are necessary together with all the required switching and control equipment. In the case of motor-generator stations, standard transformers may be used. Power-arc rectifiers have been installed in a good many cases, and it is the belief of some engineers that they will supplant the converter as a means of obtaining direct current for the use of railways.

*i. Direct Current for Light and Power.*—There are still a few sections in some of our large cities which are supplied with direct-current three-wire systems. Such a supply is invariably obtained from synchronous converters. There are also certain types of motor loads in industrial plants which require direct current; these are as a general rule supplied from rotary converters. For electrolytic work, low-voltage direct current is absolutely essential; hence motor generators or rotary converters are also applicable. There are, in addition, a large number of small-capacity applications of direct current, the supply being obtained by means of conversion equipment of some type which, because of their simplicity, are hardly recognized as falling under the head of substations.

**223. Outdoor Substations.**—The necessary clearances between conductors and the space required for switches, circuit breakers, transformers, and other equipment become so great for voltages above 22,000 volts that it is generally more economical to install all such equipment outdoors. In Figs. 334 to 338 are shown a few typical outdoor substations. In all these the construction is of either standard iron sections or typical built-up box frames. The student should inspect these illustrations carefully, noting particularly the disconnecting switches, oil circuit breakers, transformers, lightning arresters, and instrument transformers. In Fig. 336 are shown a number of current transformers used on a 132,000-volt system. In many cases, particularly for distributing substations, all high-tension equipment is placed outdoors, while the low-tension equipment is placed indoors. The simplest outdoor substation is found in the pole-mounted transformer supplying local loads.

**224. Indoor Substations.**—As stated above, it is not uncommon to find a substation partly outdoors and partly indoors. All rotating equipment, such as frequency changers, rotary converters, motor-generator sets, and synchronous condensers (Fig. 339), together with all control equipment for such machines, must be placed indoors. In large outdoor substations all oil circuit breakers and often the disconnecting switches are remote electrically controlled, the control being placed indoors. In addition to these types which must be placed indoors, a large number of installations for voltage below 22,000 volts are also placed indoors. An example of such a substation is shown in Fig. 340. This station receives power over the primary distributing circuits at 13,200 volts and steps it down to 2,400 volts for local distribution. An inspection of Fig. 340 will indicate the application of current-limiting reactors in the 13,200-volt side, the use of air-blast transformers, and also induction-voltage regulators in the 2,400-volt circuits. In Figs. 341 to 343 are shown the control switchboards of such a station. It will be noticed that a portion of the 2,400-volt equipment is remote electrically controlled. In Fig. 343 will be noticed the application of a number of protective relays.

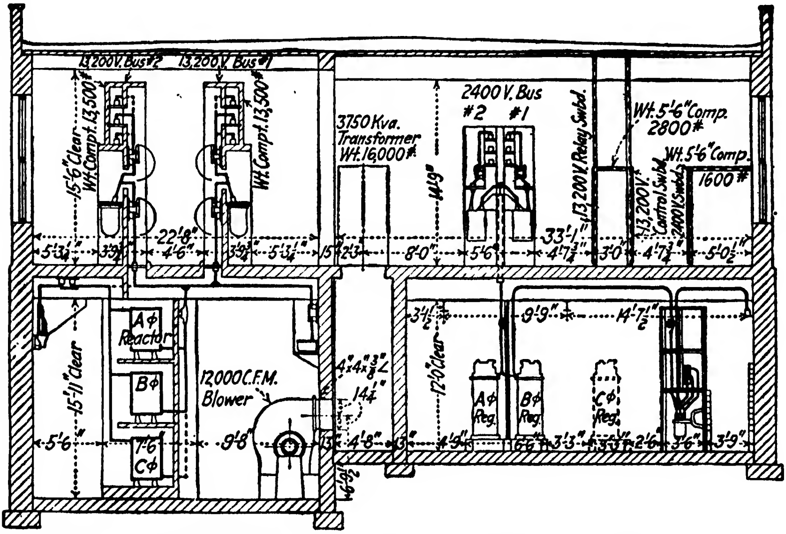


Fig. 340.—Cross-section line and circuit compartments, Wister substation. (*Philadelphia Electric Company.*)

**225. Control of Substations.** *a. Manual.*—This type of control is applicable only to small-capacity substations. All the disconnecting switches, circuit breakers, and other equipment are manually controlled.

*b. Semiautomatic.*—The majority of stations fall under this class. Control is obtained from a switchboard through mechanically or electrically remote methods, but all control is dependent upon the operator in charge at the substation.

*c. Automatic.*—Full automatic substations have obtained a considerable favor for various purposes, particularly among railway engineers. Such substations are entirely unattended; they are started up automatically when a train comes into the range of the particular station and stopped when the train passes out of the range of the station. The details of such control cannot be covered in the scope of this text, but it is sufficient to state that in most cases the control is obtained by a contact-making voltmeter which actuates a main relay when the trolley voltage drops below a certain value. This relay will in turn operate other relays in their proper sequence, thereby performing all operations, even to the starting up of rotary converters, checking polarity and synchronism, and finally closing the units on to the trolley line. After the train passes out of the range of a particular substation, another substation farther down the line is similarly started up, while the first one is shut down. In this manner no attendant is required and the substation is operated only when necessary.

FIG. 341.—Wister substation, 2,400-volt control board. (*Philadelphia Electric Company.*)

*d. Supervisory.*—In a good many cases it is desirable that the operation of a substation be under the direct control of an operator located at a considerable distance away. This can be accomplished by what is known as supervisory control. By means of only three or four control wires running between the operator and the substation, it is possible to operate the substation very satisfactorily. The control circuits are arranged so that after the operator has energized a certain relay an indicator will properly show the condition of the apparatus under control, thereby indicating whether the operator can go ahead with the next performance or not. In one type of control each desired operation is obtained by a code consisting of dots and dashes similar to a telegraphic code. A selector switch at the distant

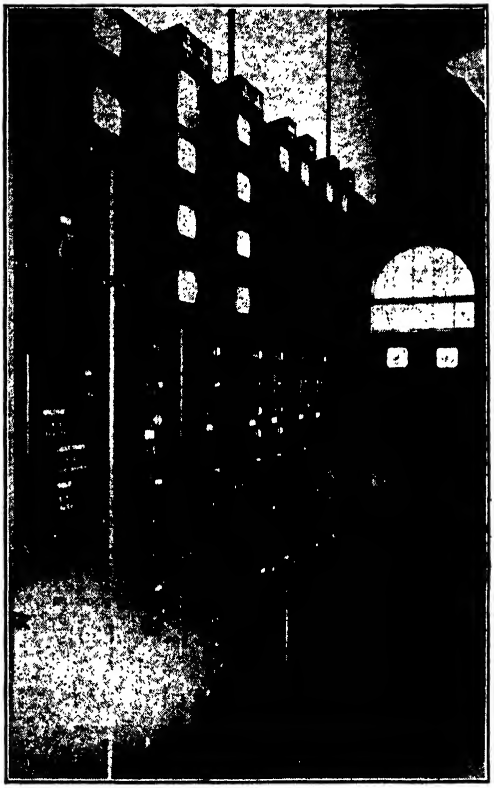


FIG. 342.—Wister substation, 13,200-volt control board. (*Philadelphia Electric Company.*)

station picks out the code, thereby causing a control relay to produce the required operation. After the particular unit has been operated, a set of code impulses is sent back to the operator, indicating the proper state of the unit. In a second type of control four wires are used between the operator and distant substation. Two of these wires connect signal relays at the operator's desk and at the station. Each signal consists of as many terminals as there are operations to perform. Closing any one of the contacts at the operator's desk will cause the equivalent contact at the station to close also. This will cause the other two wires to be switched over between proper supervisory points at the operator's desk and proper control points at the substation, thereby placing the operator in direct connection with the par-

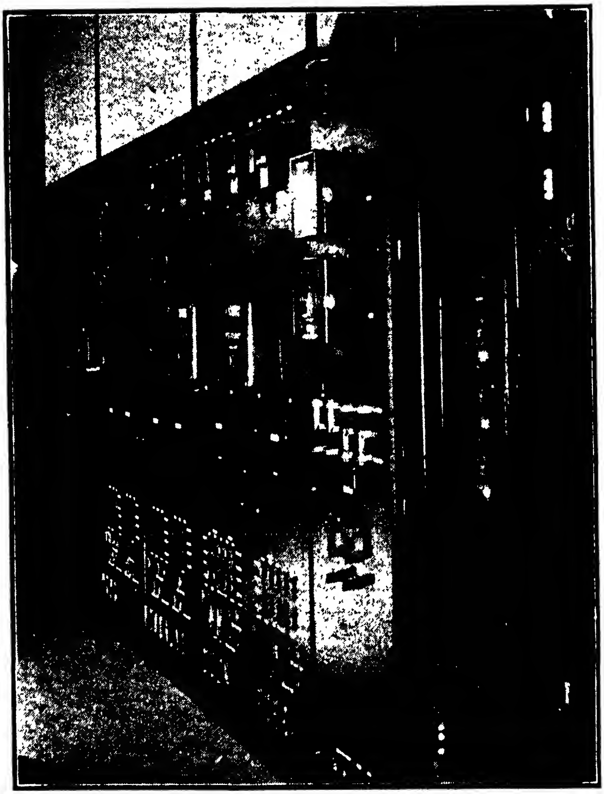


Fig. 343.—Wister substation, 13,200-volt relay board. (*Philadelphia Electric Company.*)

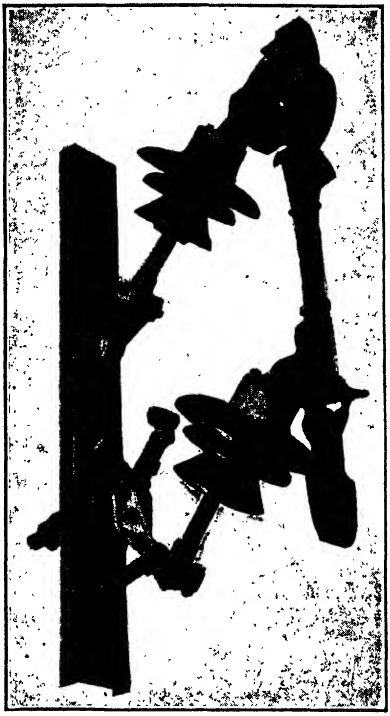


Fig. 344.—Typical disconnecting switch. (*Hi-Voltage Equipment Company.*)

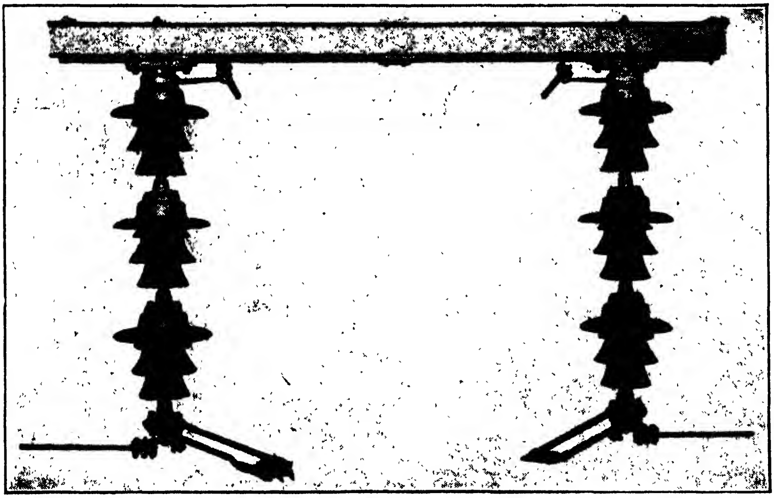


Fig. 345.—Typical disconnecting switch. (*Pacific Electric Manufacturing Company.*)

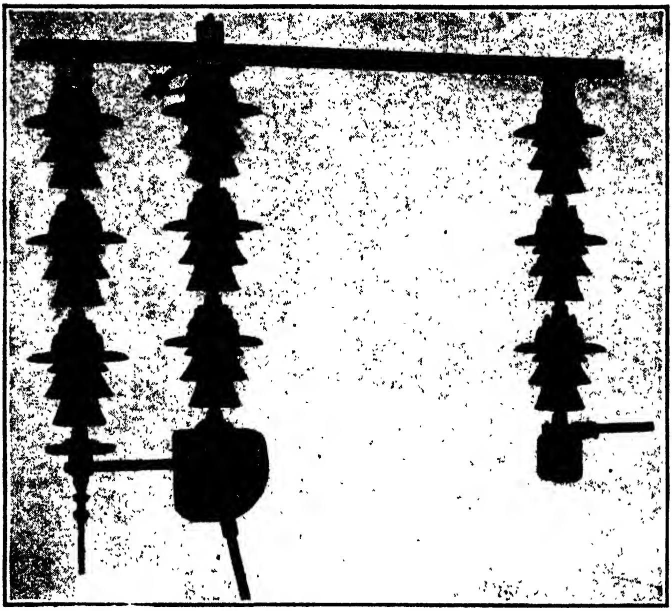


FIG. 346.—Typical disconnecting switch. (*Pacific Electric Manufacturing Company.*)

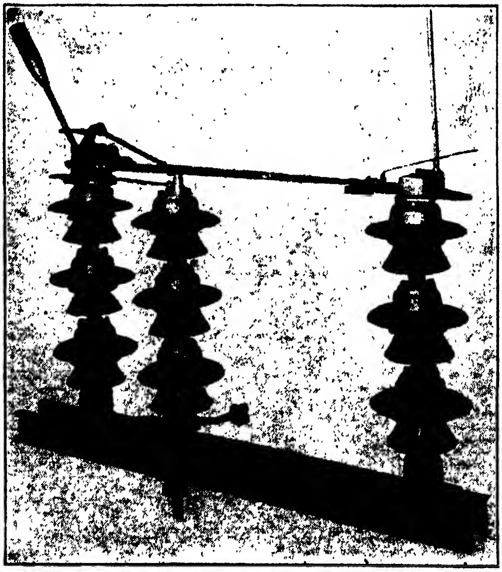


FIG. 347.—A 132,000-volt air-break switch. (*Hi-Voltage Equipment Company.*)

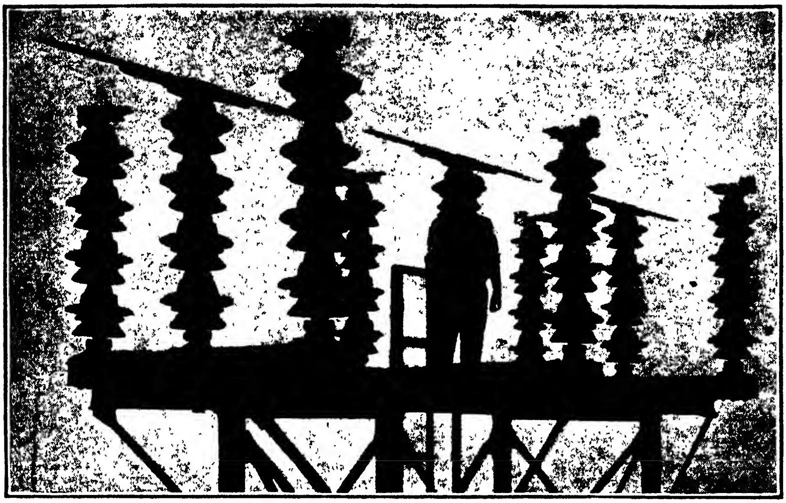


FIG. 348.—A 132-kv. 600-amp. motor-operated three-pole switch. (*Delta Star Electric Company.*)

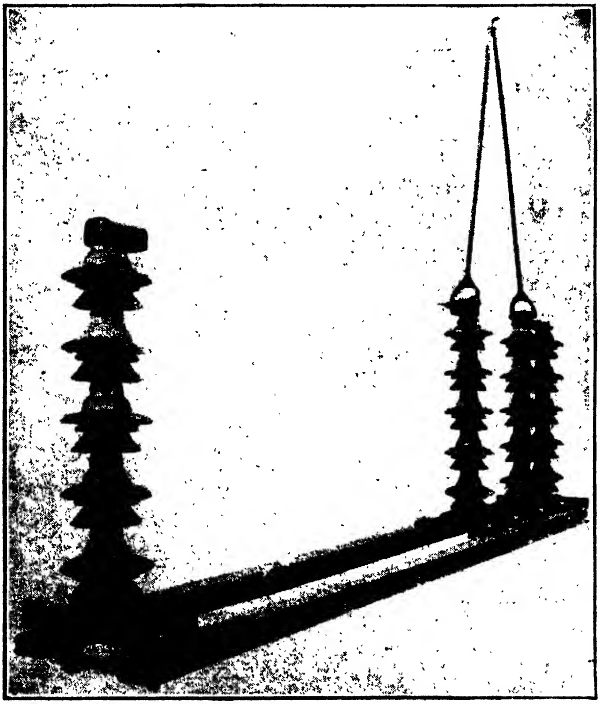


FIG. 349.—A 220,000-volt disconnecting switch. (*Pacific Electric Manufacturing Company.*)

ticular unit desired. After the operation has been completed, a signal lamp indicates the condition of the apparatus under control. Such systems of control can be adapted to sending the operator proper impulses, thereby recording meter reading, such as wattmeters, voltmeters, and ammeters, so that an accurate record can be obtained of such stations.

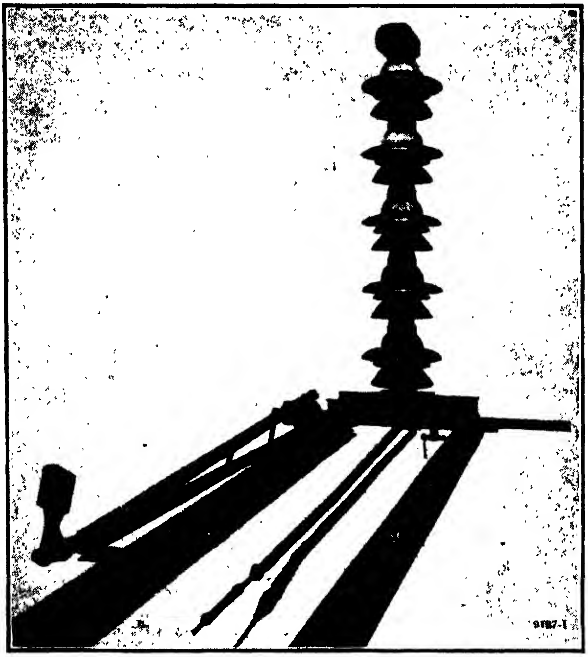


Fig. 350.—Grounding mechanism for a 220-kv. disconnecting switch—open. (*Pacific Electric Manufacturing Company.*)

**226. Outdoor Switches.**—A few typical outdoor switches for voltages between 33 to 220 kv. are illustrated in Figs. 344 to 350. The control of these switches is obtained by means of levers and bell cranks connected to a control handle at the base of the outdoor framework. For the larger sizes it is desirable to have these switches controlled from the main substation control board; hence they must be motor operated. In the case of long lines, there is always the danger of the line being charged up to a considerable potential when disconnected; hence it is necessary that such a line be grounded when any repair work is necessary. A grounding switch for a 220,000-volt circuit is shown in Fig. 350.

## Questions for Class Discussion

**1.** Classify substations according to: (*a*) service, (*b*) mounting, (*c*) function, (*d*) type of apparatus, (*e*) control.

**2.** Contrast the advantages and disadvantages of motor-generator sets, converter sets, and power-arc rectifiers as sources for direct current.

**3.** Explain why power-factor-correcting stations are used. Where?

**4.** Give a general rule as to the relative layout of a substation.

**5.** What is meant by "supervisory control"?

**6.** Give a brief description of the details of an outdoor substation.

**7.** How are high-voltage disconnecting switches generally controlled?

**8.** What is "grounding switch"? Explain.

## CHAPTER XX

## DISTRIBUTION SYSTEMS

**227. Classification.**—It is often impossible to draw a line between the distribution and transmission systems of a large power network. What was considered as a high voltage a few years ago is now considered as a low voltage; hence it is impossible to distinguish between transmission and distribution systems merely by their voltage. In general, distribution systems comprise that part of the network of a power system which distributes power for local use. Distribution systems may, therefore, be classified according to:

- Nature of current
  - Direct current
    - Two wire
    - Three wire
  - Alternating current
- Method of connections
  - Series
    - Open loop
    - Parallel loop
    - Combination of open and parallel loops
  - Multiple
    - Tree system
    - Feeder and main
    - Network
    - Loop system
    - Ring system
- Number of phases
  - Single
    - Two wire
    - Three wire
  - Two
    - Three wire
    - Four wire
    - Five wire
  - Three
    - Three wire
    - Four wire
- Mounting
  - Overhead
  - Underground

**Voltage**..{115/230, 550, 1,100, 2,200, 6,600, 11,000, 12,000, 13,200, 22,000

**Frequency**, 25, 60, and sometimes 50.

**228. Nature of Current.**—Direct current is particularly adaptable to small-distance transmission for the operation of variable-speed machinery and for the supply of congested districts where storage-battery reserves are necessary; for electro-chemical work direct current is absolutely necessary.

The great advantage of alternating current lies in the fact that different voltages may be readily obtained without the use of revolving machinery. The transformer, in other words, is the apparatus that causes alternating current to be used so much more than direct current. By means of the transformer, the alternating-current method of distribution is simpler and more economical than the direct-current method with the present knowledge of the science.

**229. Series Systems.**—Series or constant-current systems are applicable to alternating- as well as direct-current systems. Series systems are used for street lighting, the current required for such service being 5 to 10 amp. Alternating-current series circuits are supplied from constant-current transformers, as described in Art. 83. The first direct-current series systems were supplied from constant-current generators, but a later method is to use mercury-arc rectifiers connected to the secondary of constant-current transformers. The operation of series incandescent lamps is so satisfactory that they have practically replaced the old type of direct-current series arc lights. There are three general methods used in practice whereby a series circuit is not interrupted in case one lamp burns out.

The first type consists of an especially designed socket having two springlike clips that tend to make contact under tension at all times. They are, however, held apart by means of a small insulating film. When the socket is in place, the two spring clips form the two terminals of the lamp; hence when the lamp burns out, full voltage is impressed across the insulating film which will be punctured, thereby allowing the burned-out lamp to be short-circuited. The constant-current transformer supplying such a circuit will then regulate the circuit to its constant-current value at reduced voltage with one lamp short-circuited. When the burned-out lamp is replaced by a new one, it is also necessary to insert a new insulating film between the clips.

A second method is to supply each lamp from a small transformer, the primary of which is connected in series with the line. In this way the series circuit cannot be interrupted when a lamp burns out, and hence the remaining lamps will continue to operate.

The third method, which is adaptable only to small installations, consists of a reactance permanently connected in parallel with each lamp. The value of the reactance is so designed that when the lamp burns out the effect of the drop across the reactance is not materially different from the effect of the drop across lamp and reactance in parallel. In other words, with one lamp burned out, constant current will be maintained at practically the same voltage. With such a system constant-current transformers are not necessary, and constant-voltage transformers can be used, since the object of the shunt reactance is to maintain practically constant current through the series circuit at the same voltage.

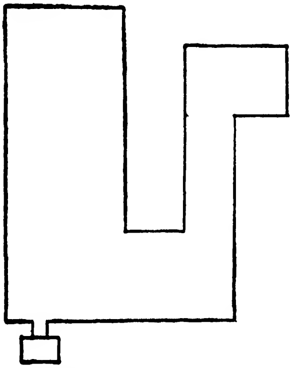


Fig. 351.—Open loop.

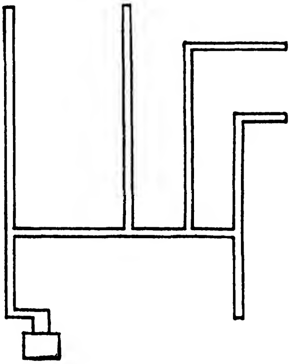


Fig. 352.—Parallel loop.

**230. Types of Series Systems.** *a. Open Loop.*—In the open-loop circuit the lamps are connected in series in a line following the shortest distance from the plant around the loop and back, as illustrated in Fig. 351. At no point around the loop are the two conductors located on poles in the same street.

*b. Parallel Loop.*—In the parallel-loop system the two conductors are always placed on the same poles as shown in Fig. 352.

*c. Combination Open and Parallel Loop.*—As the name implies, such a system involves an open loop in certain sections and a parallel loop in other sections. The main advantage of the open loop is the fact that with it a minimum length of wire is needed. Such a circuit, however, is difficult to test, and for alternating-current circuits it produces the maximum magnetic interference with telephone lines. Parallel loops, on the other hand, need a greater mileage of conductor, and, since the two conductors are near each other, frequent tests can be made along the circuit to determine the position of faults. In addition the parallel loop minimizes inductive interference with adjacent circuits. By a proper combination of these two systems, an economical and also satisfactory circuit can be obtained.

**231. Types of Multiple Systems.**—With the exception of series street-lighting circuits as discussed in Arts. 229 and 230, practically all distribution of electrical energy is done by the multiple- or constant-voltage system. The several multiple circuits that are generally used in practice are briefly discussed below and with the exception of Fig. 357 are illustrated by single-line diagrams in Figs. 353 to 358.

*a. Tree System.*—In this system, lines branch out of a substation in various directions, the appearance of the network being that of a tree (see Fig. 353). Such a system is adaptable to short distances only.

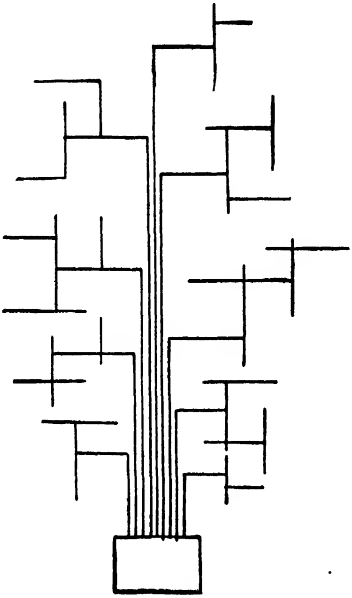


Fig. 353.—Tree system.

*b. Feeders and Mains.*—When applied to alternating-current distribution, this system takes the form illustrated in Fig. 354. From the main substation, heavy-capacity feeders supply other central points from which go out a large number of mains, generally at lower voltage. This system is probably used more than any other for the distribution of alternating current. For highly congested districts a slight modification of this system is sometimes used, namely, the so-called "feeder, primary, and secondary mains" (see Fig. 355). The main substation supplies other central points or substations by means of large, comparatively high-voltage lines as, for example, at 22,000 volts. From these central points leave primary mains, which might be at 6,600 volts, and feed other central points from which leave the secondary mains at possibly 2,200 volts, from which local distribution is obtained. These systems (Figs. 354 and 355) are known as

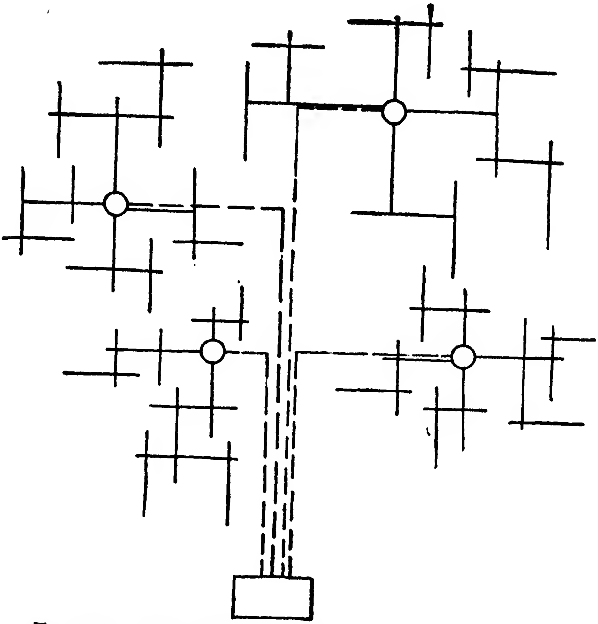


FIG. 354.—Alternating-current feeder and main system.

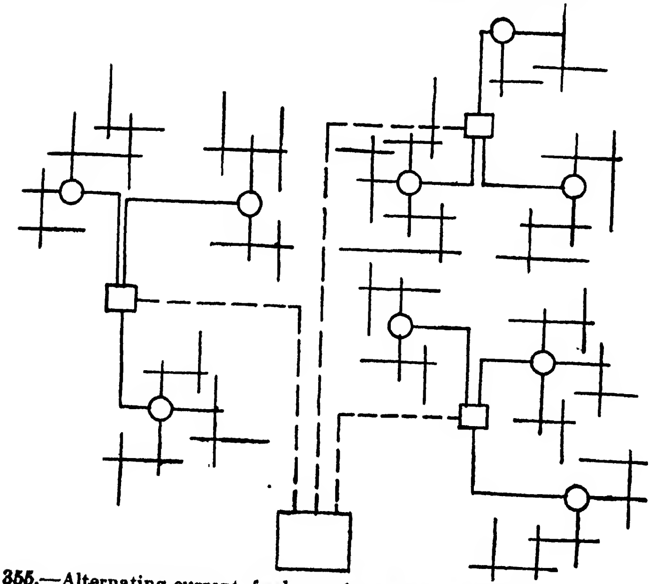


FIG. 355.—Alternating-current feeder, primary, and secondary main system.

"dead-ended" systems because any particular main receives its power from only one circuit.

c. *Network.*—For highly congested districts, such as found in large cities, a complete network has been found to possess certain important advantages. This network (see Fig. 356) is fed at advantageous points by heavy-capacity feeders from one or more substations. The feeders should be so located as to maintain a uniform voltage, within a few per cent variation, over the entire network. Such a system has been applicable to direct-current distribution for a considerable time, and of late years it has also been used for alternating-current distribution with about the same amount of success. The great advantage of such a system lies in the fact that any particular load receives its power over a larger number of circuits.

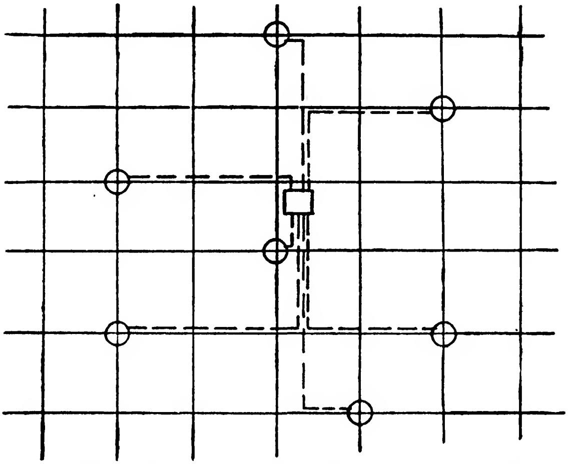


Fig. 356.—Direct-current feeder and main network.

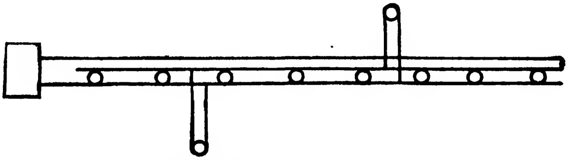


Fig. 357.—Multiple-loop system.

d. *Loop System.*—This system is illustrated in Fig. 357. It will be noticed that the return conductor starts from the nearest load to the substation and goes out to the farthest load and then returns without any connection being made to any particular load. Such a circuit is adaptable to distribution in a long continuous line with very few side branches. Such a circuit will provide a more uniform pressure across the loads than can be obtained by other methods. It is not used to a great extent in general distribution system because it cannot be applied to scattered loads.

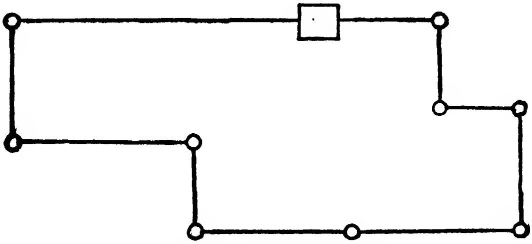


Fig. 358.—Ring feeder system.

*e. Ring System.*—The ring system of distribution (Fig. 358) is exactly the same type of circuit as used for the ring system of transmission (see Art. 190). It has the same advantages and must be handled in the same way as the ring system of transmission.

**232. Single-phase System.**—One of the most important things which should govern the layout of a distribution system is that all transformers should be operated at as high a load factor as possible. If this is not obtained, there will be an excessive outlay for equipment, thereby making the system unnecessarily costly not only in its initial outlay but also in its fixed charges and operating expenses. As many diversified loads as possible should therefore be delivered by each transformer. Single-phase transformers are generally wound with two secondary coils, so that two voltages can be obtained, such as 115 volts for lamps and 230 volts for motor loads (see Fig. 359). In congested residential sections there is often no demand for power loads, and transformers supplying only lighting loads are required.

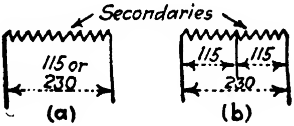


Fig. 359.

**233. Two-phase System.**—A two-phase system can be obtained as a three-, four-, or five-wire circuit (see Fig. 360). The three-wire system gives two voltages, but if one is standard for lamps, the other is an odd voltage that is not standard, and therefore the two-phase three-wire system offers no advantages except copper economy. The four-wire system (Fig. 360*b*) has also available two different voltages, one of which cannot be standard; hence this method is really less desirable than the three-wire system on account of the extra conductor necessary. By bringing out the neutral of a two-phase four-wire system, a five-wire circuit is obtained which has certain marked advantages. Three different voltages can be obtained of the order of 100, 141, and 200 per cent. From at least two of these can be supplied the standard lighting load at 115 volts and motor loads at 230 volts. The disadvantage of such a system is in the large number of conductors necessary which may cause complication of wiring and also high costs.

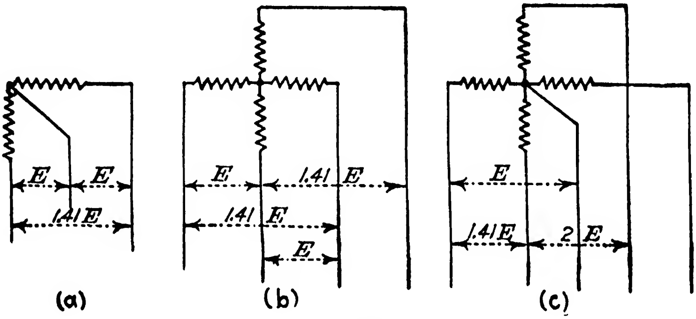
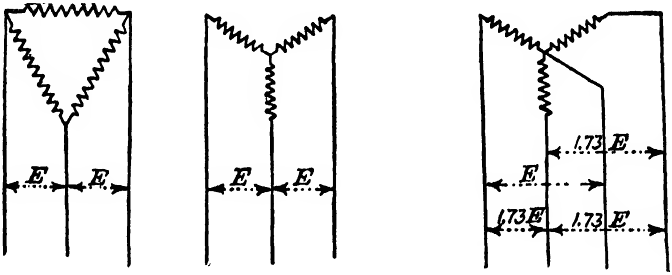


Fig. 360.

**234. Three-phase System.**—The three-phase system (Fig. 361) has the disadvantages that are present in the two-phase three- and four-wire systems. Owing, however, to the fact that three-phase power can be more economically generated and transmitted, three-phase distribution systems are used more than any other system. Lighting loads are supplied by tapping off any two wires of the three-phase circuit. Three-phase motors are standard in a large number of voltages and can therefore be used at practically any point in the system. Notwithstanding the fact that three-phase generation and transmission are more economical, there are still a number of companies that are distributing power with two-phase systems. In such cases two phase is readily obtained from three phase by the Scott transformer connection (see Art. 102).

**235. Mounting.**—Distribution systems may be mounted overhead on pole lines or placed underground. Overhead lines are generally mounted on wood, concrete, or steel poles, which are arranged to carry the distributing transformers in addition to the conductors. Overhead lines are probably the cheaper system and also better from an operating standpoint, because all wiring and equipment are easily accessible. The main objection to them is their appearance. In congested city districts it has become necessary to place all distribution wiring underground, thus involving the expense of conduits, cables, manholes, and other special equipment. A few of the main features of underground distribution are discussed in the following articles.



(a) (b) (c)

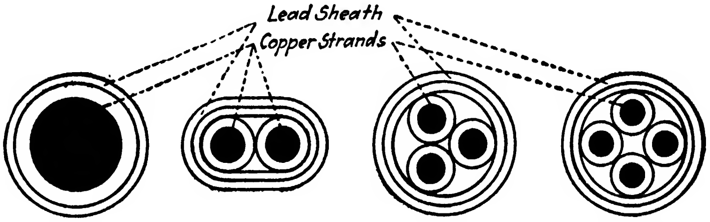
Fig. 361.

**236. Underground Cables.**—Underground cables consist of one or more conductors properly insulated, all surrounded by a lead sheath, which excludes air and moisture and also acts as a protecting cover. Cables for underground service may be classified according to:

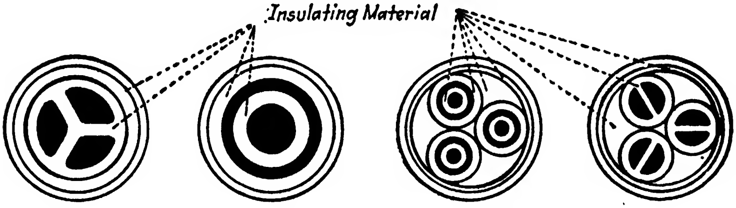
| | |
|---|---|
| Number of conductors................. | Single conductor<br>Multiconductor |
| Arrangement of conductors............. | Single<br>Sector<br>Concentric |
| Number of phases...................... | Single<br>Polyphase |

| | |
|---|---|
| Type of insulation.................... | Rubber<br>Varnished cambric<br>Oiled paper<br>Graded<br>Oil filled |
| Special features, split conductor......... | Concentric<br>D-shaped |

In Fig. 362 are illustrated several types of underground cables. The single-conductor cable (Fig. 362*a*) is generally used for low-tension service because it permits a large copper section. As a rule, railway and direct-current power feeders are of single-conductor cable. It has the advantage that when service taps are to be made only one side of the circuit is exposed at once, which is an important factor when service taps must be made on live circuits. Two-conductor cables can be used for low-voltage distribution lines with few service taps, or for series systems of the parallel-loop type. Two-conductor cables are cheaper and require only one duct as compared with single-conductor cables. Two-, three-, and four-conductor cables are generally used for



(a) Single Conductor (b) Two Conductor (c) Three Conductor (d) Four Conductor



(e) Sector-type Three Conductor (f) Two Conductor Concentric (g) Three Concentric Split Conductor (h) Three D-shaped Split Conductor

FIG. 362.—Diagrams illustrating different types of underground cables.

two- and three-phase service. Comparatively high-voltage three-phase feeder lines are generally of three conductors, either of the circular or the sector type. The sector-type conductor has the advantage that its outside diameter is smaller than that of the circular-type conductor cable for the same sectional area of copper. The two-conductor concentric cable (Fig. 362*f*) is sometimes used for low-voltage direct-current service, where the number of available ducts is limited. Such a cable may also incorporate pressure wires which are generally placed in the outer layer of strands, properly insulated from the cable conductor. Such pressure wires are used to indicate and regulate, at the station, the pressure that may exist at the end of the cable. Split-conductor cables of either single conductors or multi-conductors are used when it is desirable to protect such circuits as outlined in Art. 209. Two typical split-conductor cables, known as the concentric and D-shaped conductors, are shown in Figs. 362*g* and *h*.

**237. Insulation of Cables.**—There are three different materials used for insulating cables, namely, rubber, varnished cambric, and oiled paper. At first cables were insulated with rubber, which for the lower voltages proved satisfactory. As higher voltages were introduced, it was found that rubber deteriorated under the formation of corona. Corona, which is an ionization of the air surrounding the conductor, causes ozone to be liberated. It was found from experience with rubber-covered cables that this ozone attacked the rubber, thereby causing its breakdown. For this reason high-voltage cables are insulated with varnished cambric and oiled paper. It has been found that paper, well saturated with oil, forms about as good an insulation as can be obtained. It can be operated at higher temperatures than either rubber or cambric and is not subject to deterioration caused by electrostatic strains. Furthermore, paper-insulated cables are generally cheaper than any others. Graded insulation is often used in high-voltage cables and also to lessen the cable cost. It is a known fact that the voltage gradient through the insulation thickness is greater at the surface of the conductor and decreases toward the outer surface. Hence, by the use of different insulating materials of different specific-inductive capacities, a smaller over-all cable can be obtained than when insulated with only one type of material. In the last few years a number of high-voltage cables have been installed. In practically all cases these cables are insulated with oil under pressure. The cable is made with a hollow center in which oil is maintained under static pressure.

**238. Conduits and Manholes.**—All underground cables should be pulled through proper conduits, one cable to a duct. The standard conduits used in practice are of the following materials: tile, stone, and fiber.

Tile conduits are made with single or multiple ducts. The openings in the ducts may be circular or square, multiple-duct conduits generally being of square opening. The standard size of opening is 3½ in.

Stone conduits are made from a mixture of limestone and cement which is poured into special forms, thereby producing single-duct conduits of circular openings.

Fiber conduits are made of wood pulp thoroughly saturated with a bituminous compound of high creosote content. The creosote prevents rotting by killing the organisms that might cause deterioration of the wood pulp. The life of fiber conduits has been found to be very long, and because of their light weight they have met with a great deal of favor. They are generally made in single ducts of 3½-in. circular opening.

All types of conduits, when used for power cables, should be laid in concrete, thereby making the entire system rigid and protected from moisture and damage. Conduits should be, furthermore, laid in straight lines between manholes in order that the cable be not subjected to bends which are likely to cause insulation trouble. The conduits should be laid so that they will drain toward the manholes, in order that water may not collect in any part of the ducts.

Manholes are necessary at frequent intervals to provide terminals at which cables may be pulled through the ducts, to provide accessible places for splicing cable sections and for providing points where local taps may be made. When a change in voltage is required, suitable transformers must also be placed in the manholes. The types of construction generally recommended for manholes are brick, monolithic concrete, and concrete blocks.

In a good many cases brick and concrete blocks are cheaper than monolithic concrete but are as a general rule not as highly satisfactory. Manholes should always be provided with proper drains to carry off any water that might collect in them and also sufficient ventilation to carry off any gases that might accumulate. Such gases as sewer gas, illuminating gas, coal gas, water gas, and also, with the extensive use of automobiles, gasoline vapors are often present in manholes. Such gas mixtures are very poisonous and with air form a highly explosive mixture.

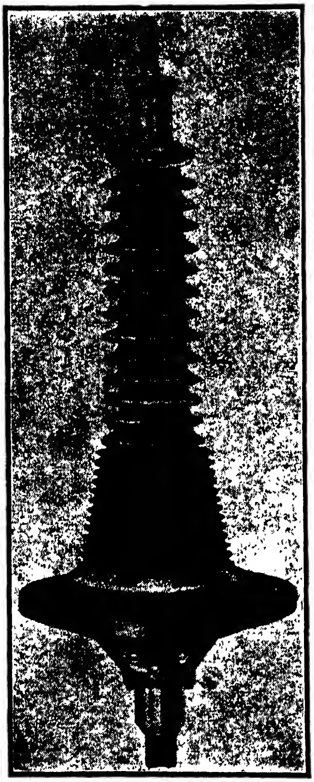


Fig. 363.—Pothead for 66,000-volt service. (*G. & W. Electric Specialty Company.*)

**239. Potheads.**—It is often necessary to connect underground circuits with overhead lines. This must be done with some kind of terminal cable bushing, generally known as a pothead, which will provide an air- and moisture-tight joint at the cable end. Such potheads are made for single- or multiple-conductor cables. A single-conductor type recommended for use with a 66,000-volt cable is shown in Fig. 363. Generally, potheads are composed of a porcelain sleeve with the cable terminal at the lower end and the overhead line terminal at the upper end. The through conductor is insulated from the porcelain sleeve by means of a suitable compound. Potheads are generally designed for pole mounting, the cable leading down from the pole to the underground conduits.

**240. Electrolysis.**—Lead-covered cables are often subjected to deterioration due to circulating currents in the ground. This is an important reason why power cables should not be laid in the ground without any protection. Even concrete is not entirely impervious to moisture; hence it will often form a conductor for stray currents. In most cases stray ground currents are produced by grounded telegraph lines and especially by the ground return of direct-current railways. No serious damage is done at points where the current enters the lead sheath unless lime is present, the lime attacking the lead. Most of the damage occurs where the current leaves the lead sheath, corrosion and pitting of the lead taking place. Such corrosion and pitting when continued over a long enough period will eat away holes into the sheath, thereby exposing the insulation of the cable to moisture. It has been found that 1 amp. flowing steadily for a year will carry into solution about 74 lb. of lead. The remedies against electrolytic action on lead-covered cables may be briefly stated as follows:

1. Maintain low-current density in railway rail circuits and provide good bonds between rails, so that current will not tend to flow through the ground.
2. Keep cables far away from railway tracks.
3. Attach drainage wires on the cable at points where the current tends to leave the cable, thus providing a metallic path for the current between sheath and ground, and thereby decreasing the flow directly from sheath to ground.
4. Lay all cables in proper conduits as described in Art. 238, with all joints properly insulated with moisture-insulating compound.

### Questions for Class Discussion

**1.** What are the advantages of direct-current distribution? What are the advantages of alternating-current distribution?

**2.** What are the relative merits of the "series" and "multiple" systems? Illustrate their application.

**3.** Name three types of series systems, and explain their application to alternating current and direct current.

**4.** Name and explain four types of multiple systems. What are the relative merits of each type?

**5.** What is a direct-current network? For what class of service has this system been used? What are its advantages and disadvantages?

**6.** Why is good voltage regulation essential for lighting loads? About what variation of voltage is allowed?

**7.** Illustrate the application of induction-voltage regulators to a three-phase distributing line.

**8.** Discuss briefly the advantages and disadvantages of the following alternating-current systems: (*a*) single phase, two or three wire; (*b*) two phase, three or four, or five wire; (*c*) three phase, three or four wire.

**9.** What are the standard voltages that are used for distribution? What are the standard frequencies used on alternating-current systems?

**10.** Explain the general construction of an underground cable. Illustrate by sketches the differences between the following types of cables: (*a*) single conductor, (*b*) two conductor, (*c*) three conductor, (*d*) sector conductor (*e*) concentric conductor, (*f*) split conductor.

**11.** What is the purpose of using a split-conductor cable? What is the difference between a concentric and D-shaped split-conductor cable?

**12.** What are the different materials that are used for cable insulation? What are their relative merits? Explain what is meant by graded cable insulation.

**13.** Explain the general construction that should be used in laying conduits for underground cables. Name the materials generally used in the manufacture of conduits.

**14.** What is the purpose of manholes when used in connection with underground distribution? Describe a few types of construction that are generally used.

**15.** What is the purpose of a "pothead"? Describe the general details of construction of a typical pothead.

**16.** Discuss the effects of electrolysis upon lead-covered underground cables, and state the remedies against electrolytic action.

# CHAPTER XXI

# ECONOMICS OF ELECTRIC SERVICE

**241. Introduction.**[1]—The business of generating and distributing electric service can be divided into three general classes:

1. Unrestricted competition.
2. Monopolistic control.
3. Government ownership and operation.

In the early history of central stations, small plants were installed through private enterprise, and the entire business of selling electric service was one of unrestricted competition. It was soon realized that this method, as applied to public utilities, was not economically sound. The duplication of equipment and the inefficiency of small plants caused higher costs of generation and distribution, so as entirely to overbalance any possible advantages obtained by unrestricted competition. For this reason public utilities have been generally considered as a natural monopoly. In order properly to protect the public as well as the public utilities, government control in some degree has been recognized as necessary. In exchange for its franchise, the utility must submit to regulation by the state or Federal government. There are today a good many public utilities which are owned and operated by the Federal government or by municipalities. The greater proportion of light and power systems, however, are private enterprises, operating under government regulations (see Fig. 1).

A good example of government ownership is that of the Tennessee Valley Authority. The system consists of two general types of dams: long, comparatively low dams on the Tennessee

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[1] It is impossible to do justice to this important phase of engineering in only one chapter. A few of the important factors, however, have been given in order to introduce the subject. A more detailed summary of this subject is covered by the author in the "Standard Handbook for Electrical Engineers," Sec. 11.

For latest information, consult annual statistical number of *Elec. World*, issued in January of each year.

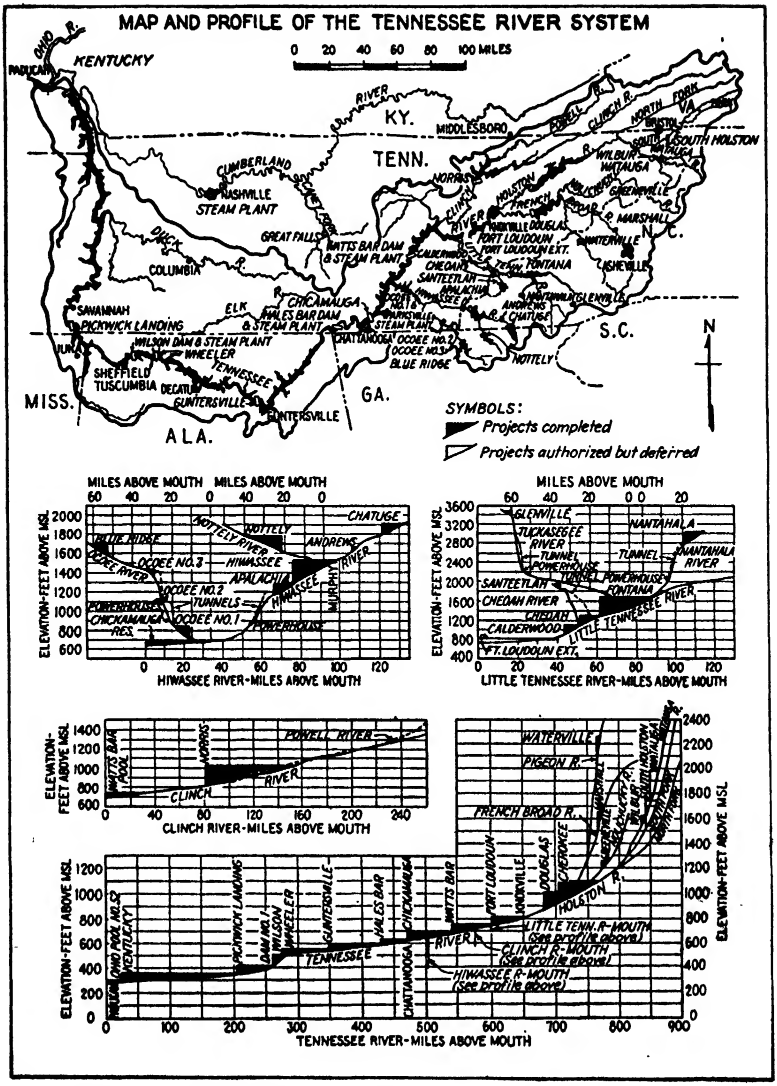

Fig. 364.—General power development in the Tennessee Valley area.

River and high dams, with resulting water storage, on the main tributaries (see Fig. 364) together with considerable fuel-power resources. Two of its developments are shown in Figs. 13 and 14. The Tennessee Valley Authority has three major functions, namely: flood control, navigation, and power generation. In addition to the hydroelectric projects, the Authority utilizes six major fuel plants and several small plants having a total installed capacity (as of 1945) of 450,400 kw. (see Table XVIII). The total hydro installed capacity as of 1945 amounted to 1,745,582 kw., giving a total installed capacity, both hydro and fuel, as of 1945 of 2,195,982 kw. The total energy sales for the 1945 fiscal year is reported as 10,314,745,700 kw-hr., approximately 85 per cent being from hydro-plants and 15 per cent from fuel plants.

TABLE XVIII.—FUEL PLANTS OF THE TENNESSEE VALLEY AUTHORITY
(Oct. 1, 1945)
Steam Plants

| Plant | Location | Installed capacity, kw |
|---|---|---|
| Hales Bar | At Hales Bar Dam, 33 river miles downstream from Chattanooga, Tenn. | 40,000 |
| Memphis (leased) | Memphis, Tenn. | 20,000 |
| Nashville | Nashville, Tenn. | 48,000 |
| Parksville | At Ocoee No. 1 hydro-plant on the Ocoee River, 16 miles east of Cleveland, Tenn. | 13,000 |
| Watts Bar | At Watts Bar Dam on Tennessee River, 10 miles from Spring City, Tenn. | 240,000 |
| Wilson | On Tennessee River, 3 miles from Sheffield, Ala. | 64,000 |
| Bowling Green | Bowling Green, Ky. | 7,250 |
| Corinth | Corinth, Miss. | 1,800 |
| Hopkinsville | Hopkinsville, Ky | 4,300 |
| Tupelo | Tupelo, Miss | 2,500 |
| Watauga | Elizabethton, Tenn. | 8,500 |

Internal-combustion Plants

| | | |
|---|---|---|
| Fort Payne | Fort Payne Ala. | 850 |
| Murray | Murray, Ky. | 200 |
| Total | | 450,400 |

As of August, 1945, the Authority was selling power at wholesale to 92 municipal and county electric systems, 46 cooperative associations, 10 large industrial plants, and 22 electric utility systems with which it is interconnected for purposes of energy interchange.

### TABLE XIX.—PRINCIPAL FEATURES OF WATER-CON

| Project | Date of first use | River | Max.xx height, ft. | Dam and appurtenances | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Over-all crest length, ft. | Max. spillway capacity, C.F.S. | Volume of concrete, cu. yd. | Volume earth and/or rock fill, cu. yd. | Power [g] | |
| | | | | | | | | Installed or under construction, kw. | Ultimate capacity, kw. |
| Kentucky.... | 1944 | Tennessee | 206 | 8,412 | 1,300,000 | 1,355,000 | 4,063,400 | 160,000 | 160,000 |
| Pickwick Landing......... | 1938 | Tennessee | 113 | 7,715 | 750,000 | 630,300 | 2,966,000 | 144,000 | 216,000 |
| Lock and Dam No. 1....... | 1926 | Tennessee | 20 | 220 | x | x | x | 0 | 0 |
| Wilson........ | 1925 | Tennessee | 137 | 4,862 | 765,000[a] | 1,259,400 | 0 | 335,200 | 436,000 |
| Wheeler....... | 1936 | Tennessee | 72 | 6,342 | 687,000 | 626,200 | 0 | 129,600 | 259,200 |
| Guntersville... | 1939 | Tennessee | 94 | 3,979 | 625,000 | 289,700 | 813,900 | 72,900 | 97,200 |
| Hales Bar..... | 1914 | Tennessee | 83 | 2,315 | 600,000 | x | x | 51,100 | 99,700 |
| Chickamauga . | 1940 | Tennessee | 129 | 5,800 | 600,000 | 491,800 | 2,635,800 | 81,000 | 108,000 |
| Watts Bar .... | 1942 | Tennessee | 112 | 2,960 | 550,000 | 480,200 | 1,173,000 | 150,000 | 150,000 |
| Fort Loudoun. | 1943 | Tennessee | 122 | 4,190 | 380,000 | 575,000 | 1,783,000 | 64,000 | 128,000 |
| Fort Loudoun Ext........ | e | Little Tenn. | 100 | 3,120 | 86,400 | 65,000 | 2,035,000 | | |
| Apalachia..... | 1943 | Hiwassee | 150 | 1,308 | 153,000 | 448,500 | 0 | 75,000 | 75,000 |
| Hiwassee...... | 1940 | Hiwassee | 307 | 1,287 | 150,000[b] | 793,000 | 14,200 | 57,600 | 115,200 |
| Andrews[p]..... | 1924 | Hiwassee | 50 | 385 | x | x | x | 1,800 | 1,800 |
| Chatuge....... | 1942 | Hiwassee | 144 | 2,850[1] | 39,000 | 21,900 | 2,347,400 | 0 | x |
| Ocoee No. 1... | 1912 | Ocoee | 135 | 840 | 45,000 | 160,000 | 0 | 18,000 | 18,000 |
| Ocoee No. 2... | 1913 | Ocoee | 30 | 450 | x | 0 | 0 | 19,900 | 19,900 |
| Ocoee No. 3... | 1943 | Ocoee | 110 | 612 | 100,000 | 111,000 | 82,000 | 27,000 | 27,000 |
| Blue Ridge.... | 1931 | Toccoa | 167 | 1,000 | 55,000 | x | 1,500,000 | 20,000 | 20,000 |
| Nottely....... | 1942 | Nottely | 184 | 2,300[2] | 48,000 | 17,700 | 1,552,300 | 0 | x |
| Norris........ | 1936 | Clinch | 265 | 1,860 | 240,000[b] | 1,002,300 | 181,700 | 100,800 | 100,800 |
| Calderwood†.. | 1930 | Little Tenn. | 230 | 897 | 260,000 | x | 0 | 121,500 | 121,500 |
| Cheoah†...... | 1919 | Little Tenn. | 230 | 770 | 200,000 | x | 0 | 76,000 | 95,000 |
| Fontana...... | 1944 | Little Tenn. | 480 | 2,385 | 218,000[b] | 2,795,000 | 100,000 | 135,000 | 202,500 |
| Santeetlah†... | 1928 | Cheoah | 200 | 1,150 | 92,000 | x | 0 | 45,000 | 45,000 |
| Nantahala†... | 1942 | Nantahala | 250 | 1,042 | 59,000 | x | 1,829,000 | 43,200 | 43,200 |
| Glenville†..... | 1941 | Tuckasegee | 150 | 900 | 56,000 | x | 458,000 | 21,600 | 21,600 |
| Douglas....... | 1943 | French Broad | 202 | 1,705[3] | 330,000[b] | 548,200 | 622,800 | 60,000 | 120,000 |
| Marshall[p]..... | 1910 | French Broad | x | x | x | x | x | 3,000 | 3,000 |
| Greenville..... | 1913 | Nolichucky | x | x | x | x | x | 10,560 | 10,560 |
| Waterville[p].... | 1930 | Big Pigeon | 200 | 870 | 60,000 | 124,200 | 0 | 108,000 | 108,000 |
| Cherokee...... | 1942 | Holston | 175 | 6,760[4] | 288,000[b] | 681,400 | 3,240,300 | 60,000 | 120,000 |
| South Holston. | e | S. Fork Holston | 290 | 1,550 | 105,000 | 90,500 | 5,958,000 | 0 | 50,000 |
| Wilbur........ | 1912 | Watauga | x | 363 | 25,000 | x | x | 3,700 | x |
| Watauga...... | e | Watauga | 318 | 900 | 62,000 | 65,300 | 3,533,000 | 0 | 50,000 |
| Great Falls*... | 1916 | Caney Fork | 92 | 800 | 150,000 | x | x | 31,860 | 31,860 |

* Not in Tennessee Valley.

† Property of Aluminum Company of America; operation coordinated with TVA system.

x No definite figure available.

xx From deepest excavation on base line to roadway or deck.

[1] Saddle dams and spillway, 1,480 ft. additional.

[2] Saddle dam, 340 ft. additional.

[3] Saddle dams, 3,670 ft. additional.

[4] Saddle dams, 1,770 ft. additional.

[a] Not maximum capacity, but capacity at 20.5-foot head.

[b] Includes capacity of discharge conduits.

[e] At clearing line elevation.

TROL PROJECTS IN THE TENNESSEE RIVER BASIN

| Lock | | Reservoir data and operating levels | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Size, ft. | Max. lift, ft. | Area at top of gates, acres | Total volume below top of gates, acre ft. | Useful[h] controlled storage, acre ft. | Length[c] of shore line, miles | Backwater length, miles | Maximum controlled pool level, el. | Minimum[n] expected pool level, el. | Average tail-water level, el. |
| 110 × 600 | 73 | 261,000 | 6,002,600 | 4,010,800 | 2,200 | 184.3 | 375 | 354 | 310 |
| 110 × 600 | 63 | 46,800 | 1,091,400 | 418,400 | 496 | 50.1 | 418 | 408 | 362 |
| 60 × 297 | 8 | x | x | 0 | 5 | 2.6 | x | x | x |
| 60 × 300<br>60 × 292 | 92[f] | 15,900 | 562,500 | 52,500 | 154 | 15.5 | 507.88 | 504.5 | 414 |
| 60 × 360 | 52 | 68,300 | 1,151,800 | 348,900 | 1,063 | 74.1 | 556.3 | 550 | 507 |
| 60 × 360 | 45 | 70,700 | 1,018,700 | 162,900 | 962 | 82.1 | 595.44 | 593 | 557 |
| 60 × 267 | 38 | 6,100 | 135,100 | 11,800 | 100 | 39.9 | 631 | 629[m] | 598 |
| 60 × 360 | 55 | 39,400 | 705,300 | 329,400 | 810 | 58.9 | 685.44 | 675 | 635 |
| 60 × 360 | 70 | 43,100[d] | 1,132,000[d] | 377,600[d] | 783[d] | 72.4 | 745 | 735 | 682 |
| 60 × 360 | 80 | 15,500 | 386,400 | 109,300 | 368 | 55.0 | 815 | 807 | 739 |
| ......... | ... | 17,600 | 455,000 | 130,000 | 268 | 33 | 815 | 807 | 739 |
| ......... | ... | 1,123 | 58,570 | 35,730 | 31 | 9.8 | 1,280 | 1,240 | 840[r] |
| ......... | ... | 6,280 | 438,000 | 364,700 | 180 | 22 | 1,526.5 | 1,415 | 1,272 |
| ......... | ... | x | 283 | x | x | 1.5 | x | x | x |
| ......... | ... | 7,150 | 247,800 | 229,300 | 132 | 13 | 1,928 | 1,860 | 1,804 |
| ......... | ... | 1,900 | 91,300 | 33,100 | 18 | 7 | 837.65 | 816.9 | 724 |
| ......... | ... | x | x | 0[k] | x | 0 | 1,106.2 | x | 843[r] |
| ......... | ... | 606 | 14,440 | 9,370 | 24 | 7 | 1,435 | 1,413 | 1,119[r] |
| ......... | ... | 3,290 | 197,500 | 183,000 | 60 | 10 | 1,690 | 1,590 | 1,543 |
| ......... | ... | 4,290 | 184,400 | 184,000 | 106 | 20 | 1,780 | 1,640 | 1,612 |
| ......... | ... | 40,200 | 2,567,000 | 2,281,000 | 800 | 72 Clinch<br>56 Powell | 1,034 | 930 | 826 |
| ......... | ... | 538 | 41,160 | 4,090 | x | 8 | 1,087.5 | 1,079.5 | 872[r] |
| ......... | ... | 640 | 35,670 | 7,260 | x | 10 | 1,276.6 | 1,263.6 | 1,087.6 |
| ......... | ... | 10,670 | 1,444,300 | 1,157,300 | 274 | 29 | 1,710 | 1,525 | 1,278 |
| ......... | ... | 2,850 | 156,000 | 131,000 | 85 | x | 1,939.8 | 1,864.8 | 1,275[r] |
| ......... | ... | 1,605 | 137,300 | 124,900 | x | 4.6 | 3,012.1 | 2,882.1 | 2,007[r] |
| ......... | ... | 1,462 | 71,110 | 66,670 | x | 4.5 | 3,491.7 | 3,416.7 | 2,275[r] |
| ......... | ... | 31,600 | 1,514,100 | 1,419,700 | 556 | 43 | 1,002 | 920 | 873 |
| ......... | ... | x | x | x | x | x | x | x | x |
| ......... | ... | 930 | 16,000 | 8,050 | x | x | x | x | x |
| ......... | ... | 340 | 25,280 | 20,500 | x | 5.5 | 2,258 | 2,175 | 1,397[r] |
| ......... | ... | 31,100 | 1,565,400 | 1,473,100 | 463 | 59 | 1,075 | 980 | 925 |
| ......... | ... | 9,100 | 783,000 | 660,000 | 241 | 25 | 1,742 | 1,616 | 1,490 |
| ......... | ... | 61 | x | 427 | 3 | 1.5 | 1,644.5 | 1,637.5 | 1,585 |
| ......... | ... | 7,100 | 677,000 | 627,000 | 117 | 17 | 1,975 | 1,815 | 1,650 |
| ......... | ... | 2,280 | 54,500 | 49,400 | 120 | 22 | 804.9 | 762 | 655[r] |

[d] Includes Little Tennessee area above proposed Fort Loudoun Extension Dam.

[e] Construction deferred, features shown are for proposed projects.

[f] Two lifts.

[g] Based on rated capacity.

[h] From maximum controlled level to minimum expected pool level.

[k] Reservoir silted.

[m] Minimum for navigation to Chattanooga.

[n] Except during drawndown in advance of floods at main-river plants.

[p] Privately owned plant.

[r] At remote powerhouse.

A detailed outline of the water-control projects of the Tennessee Valley Authority is given in Table XIX.

**242. Government Regulation.**—The regulation of a privately owned and operated utility is generally intrusted to a commission which may be appointed by the state. Practically every state in the United States has some form of commission, the power and duties of which are rather varied but in most cases comprise some or all of the following definite powers:

1. To fix and adjust rates.
2. To ascertain a proper basis for taxation.
3. To determine a fair purchase or sale price.
4. To pass upon the necessity of a utility to issue additional securities.

**243. Evaluation of Property.**—In order to determine the yearly fixed charges on a particular property, it is first necessary that its "fair value" be known. The determination of the fair value of an established business is not such an easy problem as might be expected. Some of the factors that should always be considered in arriving at such a figure are as follows:

1. Original cost of the property.
2. Reproduction cost or replacement cost.
3. Amount and market value of its securities.
4. Probable earning capacity of the utility under a rate prescribed by statute.
5. Operating expenses.
6. Value of service to the customer.

In addition to these general factors, a particular utility may have other factors of similar importance that should be carefully considered in determining the fair value of the property.

**244. Principles of Rate Making.**—There have been two distinctly different fundamental principles upon which have been based the rates for service as charged by different utilities, namely, value of service and cost of service. The first of these, the value-of-service theory, is the outcome of the old belief that a utility is entitled to as much income as the traffic will bear. It is applicable to all business enterprises that are conducted under unrestricted competition where the law of supply and demand controls.

It is generally conceded by everyone concerned that the gross income of any public utility should be sufficient to pay the cost of service and allow a fair profit or return upon the "fair value" of the property. The cost of service includes the yearly charges upon the initial investment and also the yearly operating costs. There are a good many classifications that can be given these two items, but the following seem to be simple and also clear:

- Fixed charges
  - Interest
  - Depreciation
    - Physical
    - Functional
  - Taxes
  - Insurance
    - Fire
    - Property damage
    - Liability
- Operating costs
  - Operation
  - Maintenance and repairs
  - Superintendence
  - Administration
    - Promotion
    - Legal
    - Engineering
    - Accounting

**245. Fixed charges,** as ordinarily defined with reference to power plants, are the charges necessary to carry the investment and to replace the equipment when it is worn out or destroyed. Interest and taxes carry the investment, while insurance and accumulated depreciation funds cover retirements of physical property.

**246. Interest,** as used in engineering computations, is the annual cost of the money required for the work. It is affected by the credit of the company and the condition of general business at the time money is borrowed. If money is raised by bonds sold below par, as is frequently the case, the cost of money is not only the interest rate on the bond, but this amount is increased in proportion to the amount the bond is sold below par and, also, by an amount which set aside annually will make up this deficit below par when the bond is retired or paid. Six per cent should be used as an average cost of money, but it varies between 4 and 8 per cent, the lower figure for municipalities and the higher for industrial corporations.

**247. Taxes** are proportionately more variable than interest, ranging from less than 0.5 per cent to as high as 2.0 per cent. It is generally the case, however, that high taxes and low interest coincide, so that the probable variation of the total of interest and taxes is from 6 to 9 per cent; 7.5 per cent is the figure frequently used. Besides the common taxes on real estate and other property, public utilities are also subject to business licenses, income taxes, and other special imposts depending upon different state laws or local franchises.

**248. Insurance** of power plants against fire varies from less than 0.1 per cent for fireproof modern plants to as high as 1 per cent for the old type of plant with oil-soaked wooden floors, etc. Insurance in a modern plant may seem unnecessary, but the regular visits of insurance inspectors have a beneficial influence on the operation of the plant and are frequently worth more than the cost of the insurance. The figure commonly used for the cost of insurance is 0.5 per cent. Common types of insurance carried by electric utilities are: fire, boiler, accident, employers' liability, automobile, hurricane, tornado, etc.

**249. Depreciation** of property and equipment takes place continually and at some time most equipment will reach a condition at which it has only a small residual value or no value at all. A retirement reserve should be established and maintained such that replacement of worn-out units may be made, thereby protecting the integrity of the initial investment. The subject of depreciation is discussed in greater detail in Arts. 251 to 266.

**250. Fair return on investment**[1] involves the amount that should be earned in addition to operating expenses, taxes, insurance, retirement provisions, and surplus—in other words, the proper gross income after all the above costs have been provided for. Among the items of cost that are embraced in gross income are interest upon funded debt or other borrowed capital and dividends upon outstanding stock. In addition, gross income should take care of amortization of discount, brokerage, and other expenses connected with financing, to the extent that such costs are not included in the property value.

The returns obtained from any investment include, besides pure interest, an insurance item against the risk involved in the investment. The higher the risk involved, the higher is the reasonable rate of return. The general ranges of yields from standard securities, as given by L. R. Nash,[2] are: on bonds, 5.25 to

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[1] NASH, L. R., "Economics of Public Utilities," p. 223, McGraw-Hill Book Company, Inc., New York, 1931.

[2] *Op. cit.*, p. 229.

6.75 per cent; on preferred stock, 6.5 to 8 per cent; and on common stock, 7.5 to 12 per cent. The total fair rate of return ranges from 7 to 8 per cent.

**251. Depreciation,** as applied to power plants, is conveniently divided into two classes, namely: physical depreciation and functional depreciation.

**252. Physical depreciation** is the result of deterioration due to some physical action, such as wear and tear, decay, or corrosion. This type of depreciation begins at the time the equipment is installed, and its continual presence causes a gradual decrease in value. In the course of time, under ordinary service conditions, a given unit of equipment will become finally unservicable.

**253. Functional depreciation** is the result of lack of adaptation to function, caused by *obsolescence* and *inadequacy.* Obsolescence is due to changes or advances in the art which renders a piece of apparatus, or a whole class of it, obsolete and uneconomical of use, as compared with new types which have been developed at a later date and which are much more efficient and better adapted to the service requirements. Other causes of functional depreciation are growth of business, public improvements, competition, and local conditions, such as cost of property. This type of depreciation is not present from the date of installation but comes into being as the arts advance and the service requirements undergo change.

**254. Salvage or scrap value** is the value of equipment at the time it is removed from service in any given location, either to be installed elsewhere or to be sold as junk.

**255. Removal costs** covers all items of cost that are incurred in the removal of any equipment, at the time it is taken out of service.

**256. Net depreciation value** is the original cost plus removal cost, less the salvage value. It is this net amount which must be provided in order that the property may be maintained on as sound a financial basis as at the time of its inception.

**257. Forecasting Depreciation.**—Physical depreciation can usually be estimated with some degree of accuracy, but functional depreciation cannot be estimated in advance except from general experience. In some industries it is probable that the item of physical depreciation is by far the most important, but in the case of public utilities this is not always the case. Functional depreciation may in some cases be considerably greater than physical depreciation; when this is true, the problem of building up an adequate retirement reserve may present complications.

**258. Life tables** covering various kinds of physical property associated with power plants as a whole have been compiled by various authorities from experience in different localities and under a wide range of service conditions. Such figures should always be accepted with caution, because what holds for the past is not likely to hold for the future, particularly in a rapidly growing industry in which the future course of functional depreciation is most difficult if not impossible to predict. Moreover, the useful life of any particular unit of equipment, when definitely known in any specific case, is ordinarily the consequence of a numbers of factors that are difficult to separate and are unlikely to be repeated in the same combination in future.[1]

**259. Depreciation Expense.**—It is well recognized that the gradual wearing out and ultimate retirement of units of physical property are one of the necessary costs of rendering service. Consequently it is a proper charge to operating expenses. In some cases the method of charging operating expense with the cost of depreciation is left in large degree to the discretion of the utility, but in other cases it is necessary to comply with the accounting requirements of regulatory bodies, such as public-utility commissions. There are several methods[2] in use for determining the charge to operating expense; each method involves certain individual features in accounting procedure, as described briefly in Arts. 260 to 264.

**260. Maintenance Method.**—In this method all depreciation is taken care of through maintenance accounts covering repairs and renewals. This method is applicable to very large companies, in which the replacement of its largest single element would be but a small percentage of the total investment. For smaller industries this method would be likely to produce too

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[1] In this connection see L. R. Nash, "The Economics of Public Utilities," pp. 75–96, McGraw-Hill Book Company, Inc., New York, 1931, on accounting for depreciation, where the divergence of mortality estimates on physical property is discussed at some length.

[2] FOWLE, F. F., The Philosophy of Depreciation, *Telephony*, Nov. 3, 1928,

much irregularity in the maintenance expense and corresponding fluctuation in net income. In most public utilities it is preferable to accumulate a reserve for retirements, charging to maintenance expense only the ordinary repairs and minor replacements.

**261. Straight-line Method.**—The original book cost, plus the cost of removal, less salvage, divided by the years of expected life, gives the annual depreciation rate. This can be reduced to an annual percentage of first cost, one-twelfth of which is charged monthly to operating expenses and concurrently credited to the reserve for retirements, or accrued depreciation. Under this method the reserve bears no interest. The method has the great advantage of being very simple in its application.

**262. The amortization or sinking-fund method of computing depreciation** assumes that the accumulated depreciation fund is invested and bears interest. The effect is to make the annual rate less, of course, than it would be if the fund bore no interest. This method is not easy of application to actual conditions. Some authorities consider that it represents, more nearly than the straight-line method, the depreciation in actual value of the property as determined by what a purchaser could afford to pay for it.

**263. Calculations of depreciation** by the methods of Arts 261 and 262, should be made separately for each type of equipment, taking into account its expected life, removal cost, and its scrap value. There is much chance for error in deciding on a percentage to apply to an entire property, and if used it should be determined from a detailed calculation. It is evidently subject to some variation from time to time as new equipment is added.

**264. Retirement Reserve Method.**—The methods of Arts. 261 and 262 depend upon estimates of the servicable life of each class of equipment. However, it has been pointed out in Arts. 257 and 258 that it is difficult if not often impossible to make such forecasts without the possibility of considerable error. In order to overcome this difficulty it has been proposed that the method of accumulating the necessary reserve to take care of depreciation be left somewhat flexible and subject to the judgment of the management in order to meet the varying conditions of the business, including fluctuations of revenue which are caused by cycles in business prosperity. Such a procedure is suggested by the National Association of Railway and Utilities Commissioners in their "Uniform Classification of Accounts for Electric Utilities." In practice the retirement reserve may be accumulated through credits from operating expense or surplus or both. Upkeep of the property under this method is effected through the maintenance accounts and the retirement reserve.

**265. Distinction between Maintenance and Depreciation.**—Maintenance and retirement or depreciation have the same fundamental purpose, namely, to protect the integrity of the initial investment. The question as to how the upkeep cost should be apportioned between these accounts is usually determined by definitions of more or less arbitrary nature. Generally, short-lived small-priced elements are chargeable to maintenance; long-lived high-priced elements are chargeable to retirement expense. A company may under certain conditions keep its retirement service intact, charging to maintenance all upkeep, so long as such charges do not produce any great irregularity in that account.

**266. Effects of Interconnection.**—The complexity of power systems is becoming so great, due mainly to the modern trend of interconnection, that any mathematical theory of depreciation is seldom applicable. Less efficient and obsolete plants which are held as reserves for emergency duty have a definite value above that of salvage. Holding such plants for stand-by service corresponds to increasing their length of servicable life. On the other hand, the duty of a new plant of high economy and high load factor is relatively more severe. Other plants fall between these two limits. How properly to take care of depreciation for all these classes of plant units is a problem requiring complete understanding of the financial structure of the business. These considerations emphasize the advantages of the flexible retirement reserve as outlined in Art. 264.

**267. Summary of costs in 16 modern steam plants** with ratings of 50,000 to 300,000 kva.[1] Costs are in cents per kilowatt hour.

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[1] MORROW, L. W. W., Power Costs in Large Plants, *Elec. World*, p. 827. Oct. 27, 1928.

| Costs | Maximum | Minimum | Average | Range |
|---|---|---|---|---|
| Operating cost, total | 0.489 | 0.189 | 0.322 | 2.6:1 |
| Fuel | 0.418 | 0.142 | 0.240 | 2.9:1 |
| Wages and superintendence | 0.115 | 0.031 | 0.067 | 3.7:1 |
| Water, lubrication, and supplies | 0.016 | 0.003 | 0.009 | 5.3:1 |
| Miscellaneous | 0.041 | 0.001 | 0.012 | 4.1:1 |
| Maintenance cost, total | 0.056 | 0.018 | 0.038 | 3.1:1 |
| Buildings | 0.009 | 0.0007 | 0.0052 | 1.3:1 |
| Boilers and accessories | 0.041 | 0.006 | 0.022 | 6.8:1 |
| Prime movers and accessories | 0.022 | 0.001 | 0.0062 | 2.2:1 |
| Generators and electrical equipment | 0.01 | 0.001 | 0.0034 | 10:1 |
| Production cost, total | 0.545 | 0.207 | 0.36 | 2.7:1 |
| Fixed charge, total | 0.895 | 0.146 | 0.50 | 6:1 |
| Total cost of power | 1.44 | 0.353 | 0.86 | 4:1 |

**268. Comparison of power costs in different plants** will lead to unreliable results unless certain fundamental conditions are taken into account. The chief of these are:

*a. Certainty that costs include the same items* for each plant. Management, general expenses, and building repairs are frequently omitted; and care must be exercised to ascertain just what makes up the total cost.

*b. Load factors,* if different, require reductions of costs to the same basis. Fixed charges are inversely as the first power, and production costs inversely as the 0.7 power of the load factors. Variations from 20 to 60 per cent can be compared closely by this method.

*c. Coal costs* must be compared on some common basis, such as the cost per 1,000,000 B.t.u. available after deducting the B.t.u. in the ash.

*d. Labor costs* must be treated similarly on the basis of the average wage per hour per man.

*e. Fixed charges* must be on the same basis, not necessarily with the same life of equipment, but with the same method of figuring depreciation costs. It is also important to know how much spare apparatus is being maintained and whether or not the plant is complete, or one in which there is room for considerable additional apparatus.

**269. Cost of Hydro-energy.**—Production costs are generally much smaller in the case of hydro-plants than in steam plants. There is no fuel cost, which is the largest item of the cost of steam power. Generally the other costs of operation and maintenance are also smaller. The principal item of operating cost is that of wages and superintendence. On the other hand, the smaller production costs are counterbalanced by higher fixed charges. It is impossible to compare figures of total power cost of hydro-plants because of the wide range of development costs and operating conditions. Production costs may be divided roughly into two classes, inside and outside.

*Outside production costs* cover such items as raking racks, installing flashboards, removing ice and trash, operating gates, and other outside items of repair and maintenance. This cost is variable, depending upon the conditions of operation, type, and location of plant.

*Inside production costs* are subject to some comparison. These costs include all oil, waste and ordinary supplies, salaries of inside operators, and small miscellaneous repairs and maintenance. Extraordinary repairs, including wages of repair gang, are not included in this estimate.

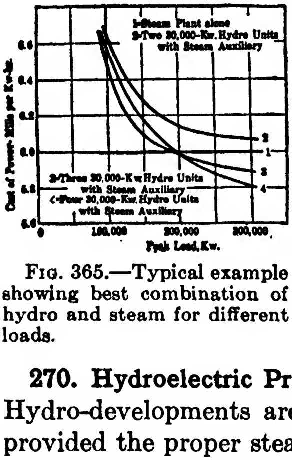


Fig. 365.—Typical example showing best combination of hydro and steam for different loads.

**270. Hydroelectric Production with Auxiliary Steam Plant.**—Hydro-developments are generally more economical if there is provided the proper steam auxiliary. In Fig. 365 are given the results of a particular estimate. The cost of power includes the fixed charges and production costs for both the hydro and steam plants. The loads considered were assumed to have the same load factor. The amount of steam capacity in each case depends upon the maximum capacity obtainable out of the hydro-plant during periods of low water. These curves illustrate very clearly that a combination of hydro and steam power may under certain conditions yield the lowest cost of energy. On the other hand, unless the conditions are favorable, a steam plant without hydro-power may be the best. No hydro-development should be undertaken without first making a thorough study of power costs as illustrated in Fig. 365. The values of Fig. 365 are true only for the particular study to which they apply and should therefore not be taken as representing any general results.

**271. Labor Shifts.**—Labor costs can frequently be reduced by arranging overlapping shifts, thus providing the necessary men during peak loads, without unnecessary men before and after. The efficiency of labor should be measured not alone by its cost per kilowatt-hour, but by the cost per unit of work performed.

**272. Repairs** should be made as soon as their necessity is discovered. A high grade of maintenance is usually cheaper than lax maintenance and increases the effective life of the apparatus. Even when the need for repairs is not apparent, a periodical inspection and overhauling of all equipment are very essential to forestall trouble and ensure reliable service.

**273. Economy in supplies** does not mean cheap materials, but the choice of those best adapted to the work and which give the lowest total cost for the object accomplished.

**274. Effects of Interconnection.**—The interconnection of systems tends to produce higher load factors on the generating plants, thereby causing a decrease in the unit cost of fixed charges and production cost. Interconnection, of course, requires high-voltage transmission, the cost of which must be taken into account in the final analysis of production costs.

**275. Rates and Methods of Selling Service.**—In developing any system of rates for electric service, there are three very important factors that must be kept in mind:

1. Fairness to the utility.
2. Fairness to the consumers collectively.
3. Fairness among consumers.

To comply with these principles properly, it is absolutely necessary that a thorough study be made of the consumers' load demands and characteristics, with particular attention to the following factors: (*a*) connected load, (*b*) demand, (*c*) demand factor, (*d*) diversity factor, (*e*) load factor, and (*f*) power factor. A typical classification of consumers, according to the characteristics of their load demands, is as follows:

1. Residence lighting.
2. Heating or cooking.
3. Commercial lighting.
4. Street lighting.

5. Commercial power.
6. Mine power.
7. Railway power.
8. Wholesale power.

It is obvious that it would not be fair to all consumers if a common rate schedule was adopted for each of the above types of loads. The proper apportioning of the entire costs of service among the different types of consumers is of necessity a rather hard problem, to which a great amount of experience and good judgment should be applied.

A good rate schedule, for any of the types of loads mentioned above, should contain charges based on the following factors of cost:

1. Customers' cost.
2. Demand cost.
3. Energy cost.

An analysis of the different items that make up the entire cost of service will indicate that a certain portion of the entire cost will vary with the number of customers, another portion will vary with the maximum demand of the different loads, and still another portion will vary with the energy consumed. If the entire cost of service is divided among these three classes, it is then necessary to apportion each class among the different types of loads as indicated above. Having determined the percentage of the total cost of service that should be charged aganist each type of load, it is then necessary to devise proper rate schedules that will redistribute these charges among the various customers within each class of load.

In general, rate schedules may be of any of the following forms:

1. Flat rates
2. Energy rates........................
    - Straight-line rates
    - Step rates
    - Block rates
3. Demand rates

Flat rates consist of a fixed rate per month or year for each energy-consuming device. It is often used in street-lighting contracts where a flat rate per lamp per month or year is charged.

The term "energy rates," as the name implies, represents any system of rates in which charge is made for the actual energy used by the customer. Such service must be metered, the standard meters recording kilowatt-hours of electricity. By "straight line" is understood a constant-unit charge independent of the amount of electricity used. The term "step" is applied to all energy rates in which the unit charge decreases with an increase of consumption of energy. Such a rate may read as follows: for any consumption up to 10 kw.-hr. at 10 cents per kw.-hr.; for any consumption between 11 and 20 kw.-hr. at 8 cents per kw.-hr. With such a schedule a customer using 10 kw.-hr. would be charged $1, while another customer using 12 kw.-hr. would be charged only 96 cents. In the block system of energy rates any consumption within a specified block is billed at a given unit charge, any excess above each preceding block receiving a smaller unit charge. For example, such a rate schedule may be used: the first 10 kw.-hr. at 10 cents per kilowatt hour; the next 15 kw.-hr. at 8 cents per kw.-hr.; and all above 25 kw.-hr. at 4 cents per kw.-hr.

Demand rates include any system in which charges are based upon the maximum demand. Such a rate might read: $50 per kilowatt of maximum 15-min. demand per year. It is obvious that to apply such a rate schedule it is necessary that the maximum demand be known. Different types of demand meters are available for this purpose, but in a good many cases an estimated maximum demand is used, as, for example, in the case of residences it is sometimes assumed to be proportional to the room area, to the number of outlets, or even to the number of active rooms. In other cases the maximum demand may be taken as a fraction of the connected load. Any of these methods of estimating maximum demands are subject to error; hence, as far as possible, it is best to use some type of demand meter in arriving at the consumers' maximum demand.

In most cases a better apportioning of the cost of service can be obtained by using combination rate schedules, which are generally as follows:

| | |
|---|---|
| Two charge............ | Fixed charge and energy charge<br>Demand charge and energy charge |
| Three charge........... | Fixed charge<br>Demand charge<br>Energy charge |

A common residential lighting rate schedule is based upon a fixed monthly charge, which is supposed to cover the general expense of accounting, meter reading, etc., plus an energy charge which may be of the "straight-line," "step," or "block" type. The other combination rate schedules are particularly applicable to commercial and industrial service.

In a good many cases it has been found advisable to introduce certain clauses into the rate schedule to take care of certain changes in operating conditions as, for example, the following:

1. Off-peak power.
2. Power-factor variation.
3. Fuel rate.

It is a recognized fact that to supply a particular demand the power plant must have sufficient generating capacity; hence it is obvious that such consumers who can take their load during the "off-peak" hours are entitled to a lower rate schedule. Poor power factor means a higher current for a given amount of power delivered, higher transmission-line losses, and increased capacity of equipment and hence higher fixed charges and operating costs. It is, therefore, advisable either to penalize the consumer who takes his load at poor power factor, or to give a discount to the one who takes his load at high values of power factor. A better scheme would be to base all rate schedules on kilovolt-ampere hours instead of kilowatt-hours, but this has not been possible on account of the lack of a suitable meter that will integrate kilovolt-amperes. A good many systems that derive their power from fuel-burning plants have used a fuel clause in addition to the regular rate schedule, the object of the fuel clause being to take care of variation in the cost of fuel.

### Questions for Class Discussion

**1.** What are the three general theories as to the methods of public-utility business? Discuss the merits of each and state which method is predominant in this country.

**2.** What are the functions of government regulating bodies?

**3.** Discuss methods of evaluating property and explain the purpose of such evaluation.

**4.** What are the component costs that are involved in the cost of energy?

**5.** What fundamental principles must be kept in mind when rates for service are developed?

**6.** State the component parts of fixed charges, and explain the meaning of each.

**7.** What is "fair return on investment"? How can one judge its fairness to the public and also the utility?

**8.** Discuss differences in physical and functional depreciation. What is the difference between obsolescence and inadequacy?

**9.** What is meant by the following: (*a*) salvage or scrap value, (*b*) removal cost, (*c*) net depreciation value?

**10.** How can depreciation be determined? State methods in common use.

**11.** How are "life tables" used, and can they be used under all conditions?

**12.** What is the maintenance method of accounting for depreciation?

**13.** What is the straight-line method of accounting for depreciation?

**14.** Discuss the amortization or sinking-fund principle of taking care of depreciation.

**15.** How may a retirement reserve be created? What are the difficulties involved in the application of this method?

**16.** Discuss differences between maintenance and depreciation.

**17.** How does interconnection affect the cost of depreciation?

**18.** How does load factor influence the cost of fixed charges and production cost?

**19.** How does cost of fuel affect cost of power? Compare total cost of energy as produced by a steam and hydro station. Consider items of cost separately.

**20.** Name three basic principles involved in establishing rates for service. Explain these, and state what effect is obtained if these principles are not given proper consideration.

**21.** Why should different types of service have different rates for energy? Name a number of types of service.

**22.** What is meant by "customers' cost," "demand cost," and "output cost"?

**23.** What are "flat rates," "energy rates," and "demand rates"?

**24.** How are the "two" and "three charges" rates worked out? What is the justification for such methods?

**25.** Should there be any modification of rates for "off-peak power," "power-factor variation," or "fuel prices?" Explain.

# APPENDIX I

To illustrate the general trend of power-plant design a few typical plants are illustrated on the pages following. In Figs. 366 to 368 are shown three typical steam plants, while in Figs. 369 to 373 are shown four hydro-plants. It will be noticed that there is a general similarity between the three steam plants, while the hydro-plants, the details of which are governed by the topography of the plant location, are rather different in their general layouts. A more or less complete description of these plants can be found in the technical literature of the engineering societies.

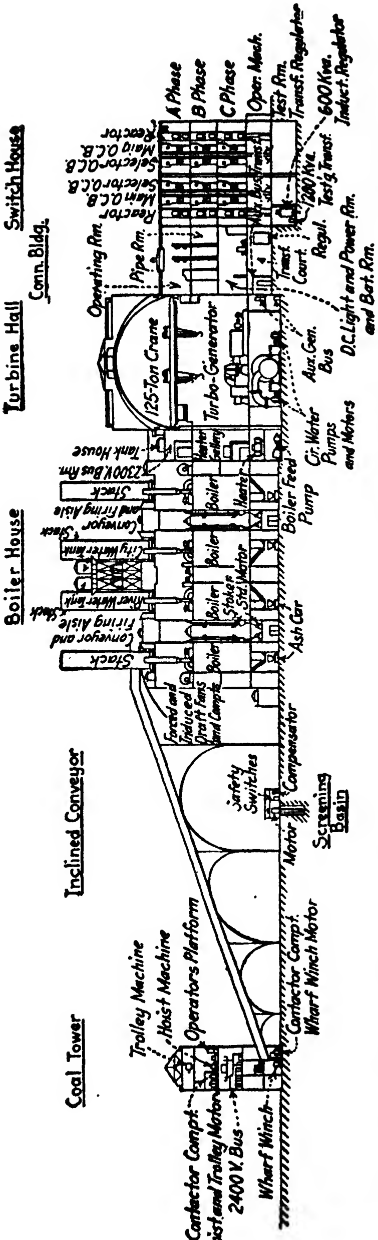


FIG. 366.—Cross section, looking down river, Richmond Station, of the Philadelphia Electric Company, 600,000-kw. ultimate capacity.

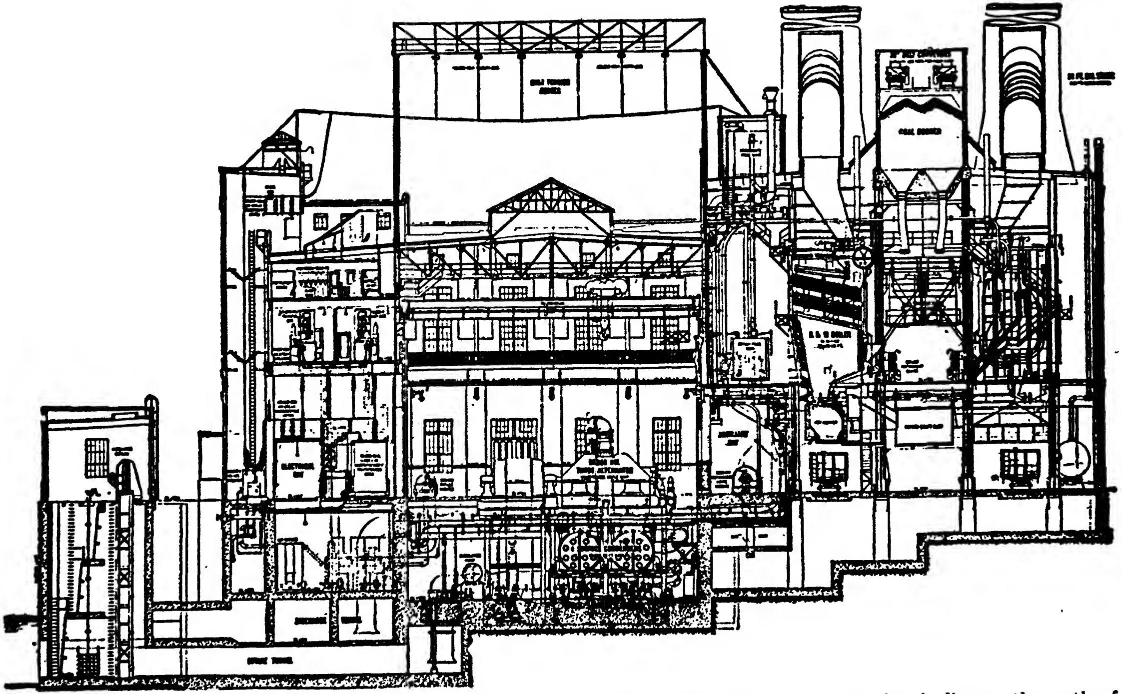


FIG. 367.—Cross section of Colfax power plant, ultimate capacity 300,000 kw. This section indicates the path of the coal from bunker through weighing larry to stoker through ash hopper to railroad car. It also shows the path of the circulating water from intake through screen well, intake tunnel, circulating pumps, and condensers to discharge tunnel. The arrangement of the apparatus in the electrical bay is well shown. (*Dwight P. Robinson & Co., Inc.*)

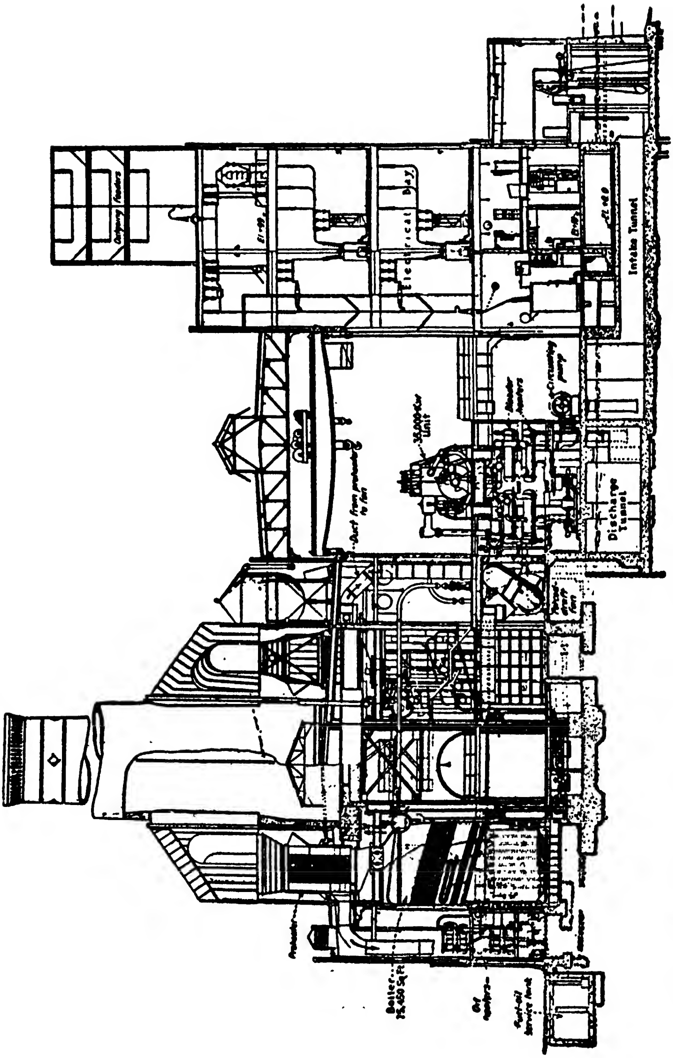


FIG. 368.—Seal Beach station of the Los Angeles Gas and Electric Corporation is designed for oil and gas burning. Ultimate rating 200,000 kw., present (1926) provision for two 35,000-kw. units. (*Dwight P. Robinson & Co., Inc.*)

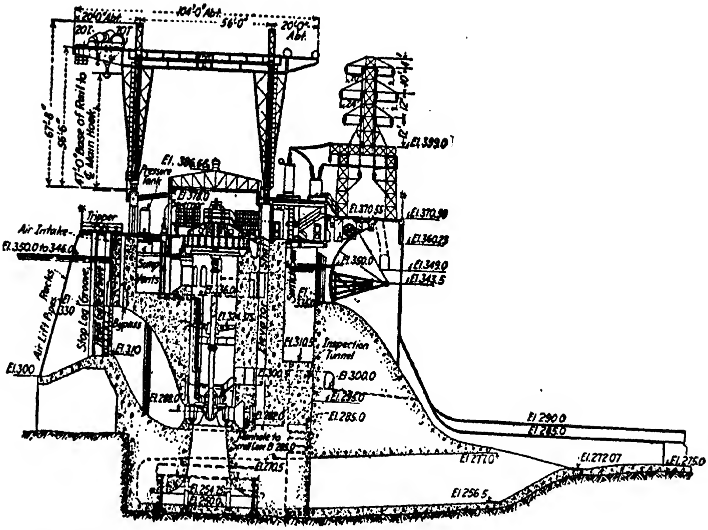


FIG. 369.—Mitchell Dam powerhouse of the Alabama Power Company.

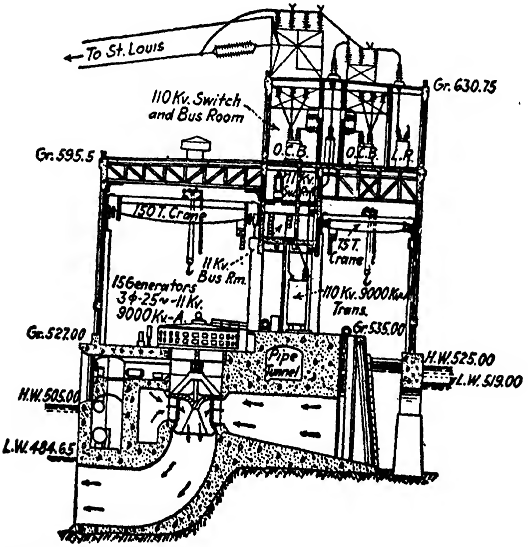


FIG. 370.—Typical cross section of the Keokuk Power station, Mississippi River Power Company, Keokuk, Iowa.

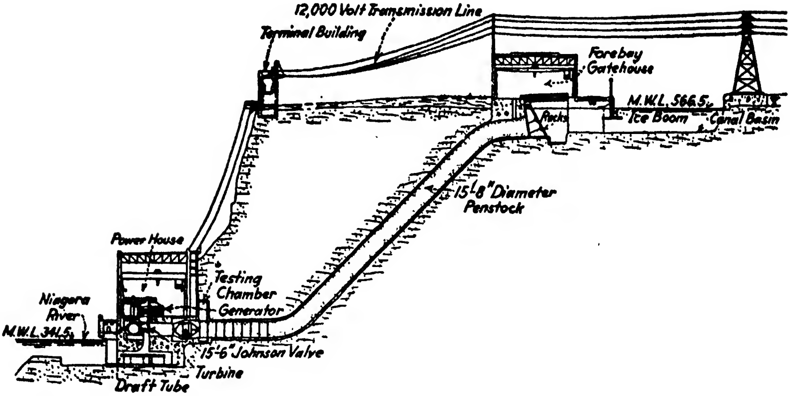


FIG. 371.—Cross section of station No. 3B, hydraulic plant of the Niagara Falls Power Company, showing one of the 37,500-hp. units. (*Niagara Falls Power Company.*)

**FIG. 372.—Interior of station 3B and 3C, hydraulic plant of the Niagara Falls Power Company, showing the three 32,500-kva. (Fig. 371) and the three 65,000-kva, units (Fig. 12). (*Niagara Falls Power Company.*)**

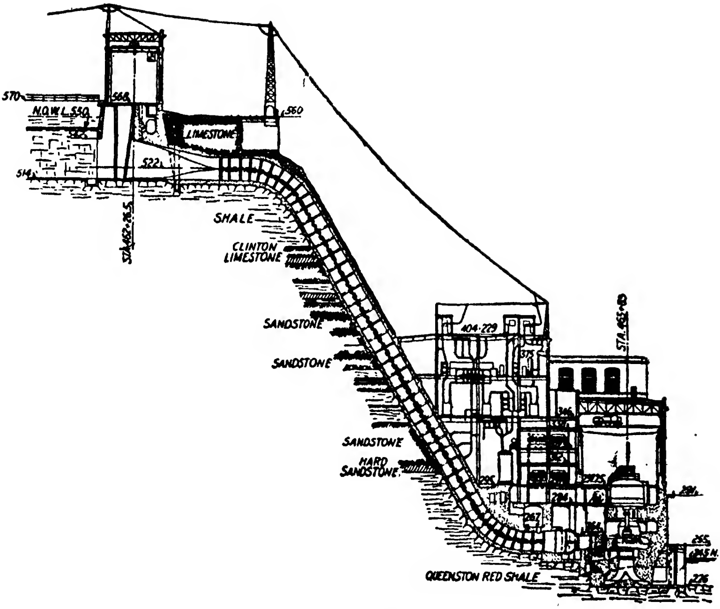


FIG. 373.—Section of screen house, penstock, and powerhouse of the Queenstown plant of the Hydroelectric Power Commission of Ontario, Canada. (*Hydroelectric Power Commission of Ontario.*)

# APPENDIX II

In this appendix are given a few project problems that can be used as the basis for more advanced study in the application and performance of electric power equipment.

### Report 1

## ALTERNATING-CURRENT PROJECT: STEAM-ELECTRIC POWER PLANT

Consult technical journals and other references, and prepare a report on the most important engineering features of an existing steam-electric power station (preferably over 50,000-kva. capacity). The report should be reasonably complete, but with the data arranged in concise form so as to make it most convenient for reference. Consult the indexes of *Electrical World, General Electric Review,* etc., and "Engineering Index of Science Abstracts."

Note particularly the following points:

1. Generators.
2. Exciters.
3. Wiring diagram.
4. Layout.
5. Instrument transformers.
6. Reactors.
7. Switches.
8. Switchboard arrangement.
9. Generator panel, exciter panel.
10. Voltage regulation.

### Report 2

## ALTERNATING-CURRENT PROJECT: HYDROELECTRIC POWER PLANT

Prepare a report on the important engineering features of an existing hydroelectric development, similar to the preceding report on a steam station. Mention and give probable reasons for differences in steam and hydroelectric practice, in the plants you select.

### Report 3

## SMALL-POWER PLANT

It is desired to install electric service in an isolated community. Investigation of the community has shown that there will be immediate need for two types of service, namely, lighting and industrial. From a study of a similar installation the two demands have been estimated and are given below.

### Problem 1

*a.* Plot the resultant winter and summer load curves of the system. (The demands are based on a 15-min. interval of time).

*b*. Determine:

1. The maximum demand on the power plant.
2. The average daily demand in kilowatts of each load.
3. The average yearly demand in kilowatts of each load.
4. The total energy delivered per year in kilowatt-hours.
5. The daily load factor of the system.
6. The yearly load factor of the system.
7. The diversity factor of the two loads.

FIFTEEN-MINUTE DEMANDS IN KILOWATTS

| Hour | Industrial | Lighting | |
|---|---|---|---|
| | | Winter | Summer |
| 12 N.T. | 300 | 240 | 240 |
| 1 A.M. | 230 | 160 | 160 |
| 2 | 205 | 160 | 160 |
| 3 | 200 | 160 | 160 |
| 4 | 210 | 160 | 150 |
| 5 | 250 | 160 | 80 |
| 6 | 310 | 160 | 80 |
| 7 | 1000 | 120 | 80 |
| 8 | 950 | 80 | 80 |
| 9 | 900 | 80 | 80 |
| 10 | 900 | 80 | 80 |
| 11 | 880 | 80 | 80 |
| 12 | 800–400 | 80 | 80 |
| 1 P.M. | 400–800 | 80 | 80 |
| 2 | 960 | 80 | 80 |
| 3 | 930 | 170 | 80 |
| 4 | 900 | 480 | 80 |
| 5 | 900 | 720 | 80 |
| 6 | 800 | 800 | 160 |
| 7 | 370 | 660 | 320 |
| 8 | 330 | 560 | 480 |
| 9 | 330 | 560 | 560 |
| 10 | 330 | 510 | 510 |
| 11 | 320 | 400 | 400 |
| 12 N.T. | 300 | 240 | 240 |
| Daily load factors, per cent......... | 56 | 35 | 32 |
| Annual load factors, per cent......... | 46 | 23 | |

NOTE.—Values for winter and summer must be given for Parts 2 and 5.

*c*. If the demand factor of the system is 60 per cent, what is the total amount of connected load in kilowatts?

*d.* Decide whether the generators shall be alternating current or direct current. Give reasons for your choice. What voltages are best suited for the installation? Give reasons.

### Problem 2

*a. Type of Prime Movers and Generators.*—The generators may be driven by either steam turbines or diesel engines. Determine type of unit, considering *economy*, safety, continuity of service, reliability, floor space required by each unit, weight of each unit, etc. Include in the report all *calculations* and *reasons* that guided you in your choice of the equipment. (For approximate cost of the machinery see "Electrical Equipment" by Brown, Chap. XXIII, page 495.)

*b. Size and Number of Units.*—Having determined which type of prime mover should be used, assume at least four different combinations of different size units and determine which combination will yield the minimum cost per kilowatt-hour. Take into effect the reserve equipment necessary to maintain continuity of service.

*c.* What is the total initial cost of the plant per kilowatt of installed capacity?

Note: In part *a* it is suggested that the computation for cost be carried out for a two-unit power plant, one unit being a spare. In part *b* it should be noticed that the fuel economy for steam plants is increasingly poor, as the size of units is reduced, and also as a particular unit is operated at partial load. The fuel economy of diesel engines may be taken as constant for all sizes considered.

### Problem 3

*a. Wiring Diagram.*—Draw a simple wiring diagram of the generating plant. Include in this diagram the connections of the generator and feeder meters.

*b. Layout.*—Make as many floor-plan layouts and sectional views of the plant as will be necessary to show the location and grouping of the prime movers, generators, exciters, switchboards, etc.

### Problem 4

#### SWITCHBOARD

*a.* Design the switchboard for the station showing the various panels. Locate the meters, switches, circuit breakers, etc., in their respective positions on the board. This should show the front of the board (as represented on blue prints used in assembling a board in a factory).

*b.* Draw in detail a wiring diagram for the panels of Problem 4*a*. This should show the wiring on the back of the panels in such a manner that a wireman could make the required connections, using it as guide. Give explanation and labels where the sketch is not self-explanatory.

## Report 4

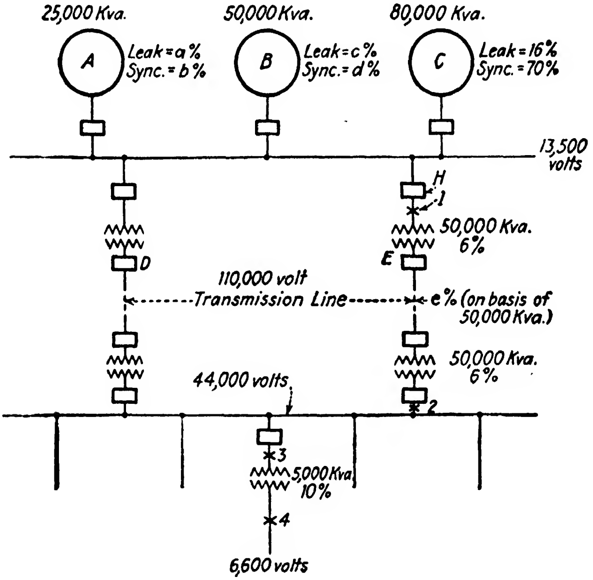
## SHORT-CIRCUIT-CURRENT CALCULATIONS

(Three-phase short circuits assumed)

Given a three-phase power network, as shown in the accompanying diagram.

1. Assuming a symmetrical generator transient, determine the initial effective value of short-circuit current flowing into the short circuit at (1) by each of the following methods:

*a*. Component short-circuit currents, using per cent reactances.
*b* Reactance in ohms.
*c*. Equivalent per cent reactance.



C

2. Solve Problem 1*c* for an asymmetrical generator transient.

3. An overload relay is used to control circuit breaker *H*. If the time setting of this relay is 0.5 sec., determine the interrupting capacity in amperes, the arc kilovolt-amperes, the normal current carrying capacity, and the rated voltage of circuit breaker *H* for a short-circuit at (1). (Use time-decrement curves as given in Chap. XIII.)

4. Transmission line *D open*. Determine the sustained short-circuit current flowing into the short circuit.

*a.* When short circuit occurs at (2).
*b.* When short circuit occurs at (3).
*c.* When short circuit occurs at (4).

5. Solve Problem 4 for the case when both transmission lines *D* and *E* are in service.

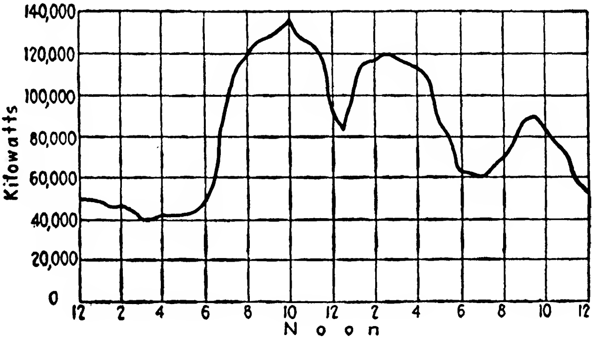
6. Determine the per cent reactance on the basis of 5,000 kva., of a current-limiting reactor to be connected in the circuit at (4), in order that the sustained short-circuit current at that point shall not exceed 2,190 amp. (Both transmission lines are assumed to be in operation.)

7. Determine the current in each line for short circuits corresponding to items 4 and 5.

## Report 5

## ALTERNATING-CURRENT POWER-PLANT PROJECT

A power company proposes to build a power station to supply 60-cycle three-phase power. The estimated average daily load curve shown is based on a survey of the section to be supplied and comparison with similar existing systems. It represents the power demand that is expected at the time when the plant will be ready to deliver power. It is estimated that the peak demand will reach 200,000 kw. within 2 years of the opening of the station and that the shape of the load curve will not change appreciably.



*D*

*Type of Plant.*—There are two possibilities. A steam plant may be constructed at the mouth of a coal mine 30 miles from the load center, or a hydroelectric plant may be built at a place 100 miles away. A certain amount of power, at generator voltage, is required in the vicinity of the power plant.

*Option.*—Each of the two possibilities has its supporters in engineering construction companies that are submitting proposed layouts with their respective bids. (*Choose the option in which you are most interested.*)

References: Consult "Standard Handbook for Electrical Engineers" for text material and additional references.

## Problem 1

*a. General* (Chap. II)[1].

1. The assumption has been made, that a steam plant or a hydro-plant *can be built* to fulfill the requirements of the load given. *State briefly* the important factors that must be considered when making a choice between the two types of plants.

2. What factors influence the choice of location of a power plant: (*a*) for a steam plant, (*b*) for a hydro-plant?

*b. Generators* (Chap. IV).

1. What type of generator is to be used? (Synchronous or induction, horizontal or vertical.) What are the largest sizes of that type available?

2. Decide on the generator voltage. Give reasons.

3. How is reserve capacity provided?

4. Specify the number and kilovolt-ampere ratings of generators to be installed. Give reasons.

*c. Exciters* (Chap. V).

1. What system of excitation are you going to use? Why?

2. Give the number, type, and kilowatt ratings of the exciter units. What is to be the exciter voltage?

3. What provision is to be made for reserve excitation in cases of emergency? Give details.

4 How are the exciters to be driven? Specify ratings of drivers.

## Problem 2

*a Wiring Diagram and Layout* (Chap. VI).

1. Wiring Diagram.—Show by single-line diagram, the connections to be used for the power-plant system (including excitation). (A low-tension busbar is required.) Indicate the rating of power transformers on this diagram.

2. Layout (Appendix I).—Make as many floor-plan layouts and sectional views of the plant as will be necessary to show the location and grouping of the prime movers, generators, exciters, switchboards, oil circuit breakers, transformers, busses, etc.

*b. Instrument Transformers for Generator Panel* (Chap. VII).

1. Specify the rating of a standard-size current transformer to be used in each generator circuit.

2. Give the rating of a standard-size potential transformer that is to be used in the generator circuit.

3. What two causes of errors are present in instrument transformers? Is it, therefore, advisable to connect a number of instruments or relay coils, in addition to the measuring instruments, in the same transformer secondary circuit?

4. For what operating voltages should each of the above instrument transformers be insulated?

5. Will it be necessary to ground the secondaries of the instrument transformers? Why?

---

[1] Chapter references refer to "Electric Power Equipment."

6. How are potential-instrument-transformer circuits protected against damage due to a short circuit on the secondary?

7. Draw a diagram of connections for measuring the three generator line currents using only one ammeter and two current transformers. Is this scheme advisable?

8. Also draw a diagram of connections for measuring the voltage between any pair of generator terminals with only one voltmeter.

### Problem 3

*a. Short-circuit Currents* (Chaps XIII and XIV).

NOTE: Assume that the synchronous generators to be installed in this plant have the following short-circuit characteristics: leakage reactance = 25 per cent, synchronous reactance = 85 per cent. Power transformer may be assumed to have 10 per cent reactance. (The above values are based on the kilovolt-ampere capacity of the equipment to which it refers.)

1. How many times normal full-load current will each generator deliver when short-circuited at its terminals: (*a*) at the instant of short circuit (use Table XIII of text), (*b*) after the current has reached its steady state?

2. Compute the equivalent percent leakage and synchronous reactances between the generators and a possible short circuit on (*a*) the low-tension busbars, (*b*) the high-tension busbars.

3. Determine the sustained short-circuit current that will flow into the short circuits as assumed above.

*b. Reactors* (Chap. XIII).

1. Assuming that it is desirable to limit the sustained short-circuit current delivered by each generator to normal full-load value when short-circuited at its terminals, determine the per cent reactance of the reactors that must be installed in the generator leads.

2. Specify the name-plate ratings of the above reactors as follows: (*a*) frequency; (*b*) voltage drop (percentage reactance times voltage to neutral); (*c*) normal full-load current; (*d*) kilovolt-ampere rating (volt drop times normal full-load current); (*e*) to give ______ per cent reactance drop in a ____ kva. ______ volt three-phase generator circuit.

3. What is the reactance in ohms of each reactor? What is the relative value of the resistance in ohms?

4. What is the maximum short-circuit current in amperes that could flow through this reactor? Of what importance is this?

5. How can reactors be used in this plant to localize troubles? Illustrate by computing the sustained short-circuit current, delivered to a short circuit on one extreme end of the low-tension busbars, when one isolating reactor of 10 per cent reactance based upon 40,000 kva. is used in the center of the low-tension busbar. (Assume all circuit breakers in transformer circuits open.)

*c. Oil Circuit Breakers* (Chap. XI).

NOTE: The time settings of the relays controlling the operation of the oil circuit breakers of such a plant may be assumed as follows:

| Circuit-breaker Location | Time in Seconds from Instant of Short Circuit |
|---|---|
| High-tension transmission line | 0.7 |
| High-tension transformer circuit | 1.00 |
| Low-tension transformer circuit | 1.50 |
| Low-tension local circuits | 0.5 |

1. Specify the ***interrupting capacity in amperes, the arc kilovolt-amperes, the normal current-carrying capacity,*** and the ***rated voltage*** of oil circuit breakers in the four circuits listed above.

NOTE: The capacity of these circuit breakers will be dictated by short circuits occurring on the load side of each breaker.

2. Specify the type of relay control that should be used for the generator oil circuit breakers. Illustrate by means of a sketch.

3. Would the three poles of the above breakers be in the same or in separate compartments? Specify suitable breakers from some trade catalogue.

4. How should these breakers be mounted? Where would they be placed relative to the switchboard?

5. What type of control would you use? (Hand operated, remote mechanical, or remote electrical control.) Why?

6. The time settings of the oil circuit breakers have been given above. Explain what determines the relative time settings used.

## Problem 4

*Switchboard Construction Details* (Chap. IX).

*a.* Is this switchboard to have remote mechanical or remote electrical control? Why?

*b.* Specify the type of board that is to be used in this powerhouse. (Panel board, combination control desk and elevated instrument board, or combination pedestal and instrument post board.) Discuss reasons for choice..

*c.* State what is to be the location of the switchboard, relative to the busbars.

*d.* Of what material is the board to be made, and what type of framework is to be used?

*e.* Is it desirable to have this framework grounded? Why?

*f.* Draw a simple sketch showing a cross-sectional view of the board and the relative locations of the different pieces of apparatus.

*g.* Draw another sketch of the plan view, naming each panel, for example, generator panel, etc.

## Problem 5

*Generator Panel* (Chap. IX).

*a.* Make a list of the motors that are to be used with each generator. Give reasons for your selection. Specify the type and ratings of each of these motors.

*b.* Should the generator oil circuit breakers be provided with reverse-power relays? What better scheme may be used?

*c.* Would it be desirable to connect overload relays in the generator circuits? Discuss the effect of overload relays when synchronizing a generator to the busses.

*d.* What method of synchronizing is to be used in this station. Can a synchroscope alone be depended upon?

*e.* Draw a diagram of connections for synchronizing the generator to the busses. Indicate what portion of the wiring and instruments will be in the control room.

*Voltage Regulation.*

*a.* Is the voltage to be maintained at a constant value at the generator bus, or at the bus at the main distributing point in the city (located at the end of the transmission line), or should the voltage be maintained practically constant at both the generator bus and at the main distributing point at the end of the transmission line? Why? How can this be accomplished?

*b.* What type of regulator is to be installed? How many regulators are required?

## Report 6

## TRANSMISSION-LINE-SAG COMPUTATIONS

NOTE: This report is confined to transmission-line spans having the supports at the same elevation.

1. *Short Span.*

Look up data on commercial cables.

Assuming that the curve formed by the suspended cable is a *parabola*, determine and plot a set of tension-sag curves for loadings $A$, $B$, and $C$ with superimposed temperature lines for 0, 32, 70, and 100°F. (See text for detail of loadings.)

Specify *a.* The maximum tension in cable at 0°F. (The maximum tension should not exceed 80 per cent of the elastic limit.)

*b.* Maximum sag in cable at 100°F.

*c.* The necessary height of point of cable suspension if the minimum clearance required between conductor and ground is 30 ft.

Explain how such a set of curves would be used when stringing the conductor into place.

2. *Long Span of* 4,000-*ft. Length.* (Consider loading $C$.)

For such a long span a special aluminum steel reinforced cable of the following characteristics may be used:

| | |
|---|---|
| Size | 318,000 cir. mils |
| Stranding, aluminum | 24 × 0.1151 in. |
| steel | 43 various sizes |
| Total section of steel ($A$) | 0.3952 sq. in. |
| Diameter of complete cable | 1.036 in. |
| Elastic limit of complete cable | 53,500 lb. |
| Ultimate strength of complete cable | 67,600 lb. |
| Weight of complete cable | 1.684 lb. per ft. |

If the working tension of the cable, at the lowest point of the span, is limited to 33,000 lb., determine:

*a.* The sag, length of cable between supports, and the maximum tension in the cable, by means of the catenary equations.

*b.* The sag, by means of the approximate parabola equations.

*c.* What percentage error is involved in item *b* above.

NOTE: Density of ice = 57.4 lb. per cu. ft.

### Report 7

The following data applies to the Boulder Dam–Los Angeles transmission line.

Length of line = 300 miles
Cross-sectional area of conductor = 512,000 cir. mils
Diameter of conductor = 1.4 in.
Spacing of conductors = 32.5 ft.
Resistance of conductor per 1,000 ft. = 0.0214 ohm
Inductive reactance per 1,000 ft. = 0.1517 ohm
Capacity reactance per 1,000 ft. = 1,025,000 ohms

For a receiver voltage of 159,000 volts per phase and a value of receiver power of 50,000 kw. per phase at power factors of 60 per cent leading, unity, and 60 per cent lagging determine: receiver current, receiver kilovolt-amperes, receiver reactive kilovolt-amperes, sending voltage, sending current, sending kilovolt-amperes, sending power, sending reactive kilovolt-amperes, line power loss, efficiency and torque angle by the following computational circuits:

*a.* Simple series impedance.
*b.* Nominal T circuit.
*c.* Nominal $\pi$ circuit.
*d.* Exact circuit.

### Report 8

Using the line data of Report 7, determine phase voltage and line current at 200-mile intervals for a 2,000-mile line with open-circuited receiver terminals at 159,000 volts. Use exact equations.

### Report 9

The same line of Report 8 operates with receiver open-circuited and with sending voltage held constant at 159,000 volts. Determine phase voltage and line current at 200-mile intervals for a line 2,000 miles long.

### Report 10

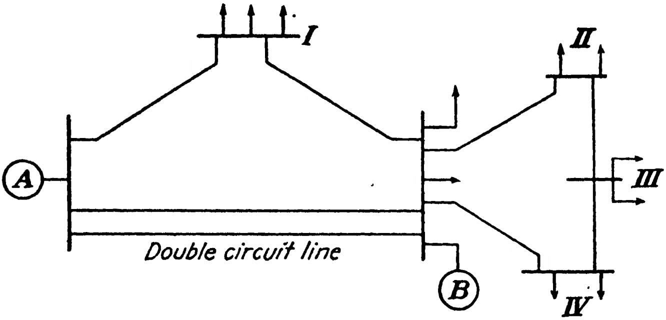
Station *A* has a capacity of 100,000 kw. of hydro-power. Station *B* has a capacity of 50,000 kw. of steam power. The distance between *A* and *B* is 100 miles, between *A* and *I* it is 75 miles, and between *I* and *B* it is 60 miles. Substation I requires 10,000 kw. to be distributed over a wide area. Substations II, III, and IV are in a city of a population of 100,000. Total demand of these substations is 50,000 kw. Both stations *A* and *B* generate power at 13,800 volts. Specify the following items for this system, giving your reasons.

*a.* Transmission-line voltages.

*b.* Transformer installations and connections.

*c.* Type of transmission-line towers, specifying conductor clearances; size and type of conductors; and type, size, and number of insulators.

*d.* Suitable lightning protection to be used throughout system.



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*e.* Complete relay protection throughout including secondary feeder circuits.

*f.* Voltage regulation for generating stations.

## Report 11

Substations II and IV of Report 10 are 10 miles apart. A city electric traction line requires 500 kw. of direct-current power at 600 volts at each station. Station II is to be of the rotary-converter type and station III is to be of the power-rectifier type. Design both stations specifying in detail the following:

*a.* Number of units.

*b.* Number of phases on alternating-current side, and all voltages.

*c.* Complete wiring diagram.

*d.* Transformer connections, including phase shifters if used.

*e.* Methods of starting all equipment.

*f.* Switchboard details.

*g.* Station arrangement.

# APPENDIX III

## EXPERIMENTS

In the experiments listed below, it is suggested that more emphasis be placed on the external operating characteristics and the manipulation of circuits, leaving the internal details of machine or circuit theory for a more suitable course. As indicated, in the preface, the purpose of this volume is to acquaint the student with power equipment from the generator to the customer's premises.

1. *Inspection Trip to Power Plant.*—Inspect the college power plant and report on the following details: generators, exciters, plant layout, general circuit, switchboard, metering, circuit breakers, synchronizing arrangement, voltage regulators and any other details of general interest.

2. *Direct-current Generator Voltage Characteristics.*—Determine generator voltage characteristics similar to Fig. 37. Different degrees of compounding may be obtained by shunting the series field.

3. *Parallel Operation of Direct-current Two-wire Generators.*—(*a*) Parallel two shunt generators, and observe how the load divides between the units. (*b*) Repeat the performance for compound generators. Observe the equalizer current. Investigate possibility of parallel operation without equalizer.

4. *Three-wire Direct-current Generators.*—(*a*) Operate a three-wire generator at no-load. Using an oscillograph, investigate wave shape of voltage between slip rings and also between direct-current line wires. (*b*) Operate generator with unbalanced loads, and investigate current distribution in the three lines. Also check wave shape of current in lines and also between slip rings.

5. *Alternator Armature Connections.*—Using a standard multiphase laboratory alternator, develop all types of multiphase connections, measuring all voltages. Sketch corresponding voltage vector diagram.

6. *Salient-and Nonsalient-pole Alternators* —Inspect a salient and a nonsalient pole machine. Make sketches showing field structures, and indicate magnetic field paths. Also lay out a field flux distribution chart, showing flux densities as ordinates against pole arc in radians as abscissa. A pilot coil in the air gap of a revolving field machine may be used to obtain the wave shape of the air-gap flux distribution.

7. *Load Characteristics of Alternators.*—Operate a three-phase alternator at varying balanced loads at various power factors. Hold the field current constant at the value necessary for rated line voltage. Observe the line voltage for different values of line currents. The results of voltage should be plotted against current.

8. *Parallel Operation of Alternators.*—Using two alternators illustrate several methods of synchronizing. Have each student perform the actual synchronizing. Effects of opposite phase sequence and unequal voltages should be investigated.

9. *Rotary Converters.*—Using a laboratory type of rotary converter, equipped with several alternating-current phase combinations illustrate alternating-current to direct-current conversion and also reverse operation. Investigate several methods of starting and synchronizing. Observe voltage ratios between alternating-current and direct-current sides. Illustrate introduction of neutral direct-current line.

10. *Mercury-arc Rectifiers.*—Make a circuit diagram of various types of rectifiers, including the steel-type tank rectifier. An elementary radio power supply might be wired and studied. Use an oscillograph for voltage and current wave shape studies.

11. *Transformer Connections.*—In the following transformer connections each student should carry out the task of actually wiring up the circuit. Use a voltmeter to check all voltages.

*a.* Single Phase.—Using a transformer with two sets of windings, each set containing two identical windings, work out all possible series and parallel combinations for primary and secondary. Investigate effect of polarity.

*b.* Two Phase.—With a four-wire two-phase system, reproduce the circuits of Figs. 149 to 152.

*c.* Three Phase.—Reproduce and check the voltages of circuits similar to Figs 153 and 154.

*d.* Three-phase Open-delta Connections.—Reproduce and check voltages of Figs. 158 and 159.

*e.* Scott Connection.—Develop and check voltages for the Scott connection.

*f.* Reproduce and check voltages of the connections shown in Figs. 163 to 174.

12. *Transformer Wave Shape.*—Using an oscillograph obtain the exciting current wave of a single-phase transformer. Repeat performance for a Y-connected bank of single-phase units, and illustrate function of delta winding. Using a cathode-ray oscillograph demonstrated hysteresis loop.

13. *Study of Meters.*—Provide as many types of meters and instruments for detailed inspection. If possible remove meters from the cases for best results. Have students sketch the working details and explain the function of each element.

14. *Alternator Short-circuit Current.*—Operating an alternator at partial excitation, measure the current for a balanced three-phase short circuit and each of the types of short circuits indicated in Table XII. Investigate the wave shape of the short-circuit current and also of the voltage across unloaded phases. Check the ratios given in Table XII.

15. *Transmission Lines.*—The following tests are outlined for an artificial line. The voltage and current should be measured at intervals along the line for each of the following cases:

*a.* No-load.

*b.* Loaded with 100 per cent power-factor load.

*c.* Loaded with 80 per cent power-factor leading.

*d.* With constant resistance load and variable parallel capacity at the receiver end.

16. *Substation.*—Inspect a distribution substation, investigating such items as: (*a*) bus structures, (*b*) transformer connections and ratings, (*c*) circuit breakers, (*d*) lightning arresters, (*e*) metering and any other peculiarities. Give a detailed account of such an inspection including a schematic diagram of connections.

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