ELECTRICAL EQUIPMENT

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ITS SELECTION AND ARRANGEMENT

WITH SPECIAL REFERENCE TO FACTORIES, SHOPS AND INDUSTRIAL PLANTS

BY

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INTRODUCTION

A working knowledge of electrical engineering is becoming of greater importance every day as the applications of electrical apparatus increase. The usual course of instruction given to mechanical engineers includes a discussion of the theory of operation of the various electrical machines but goes no further. It is often said in criticism of college instruction that the student learns more of engineering in the first three months of practice than he does during his whole college career. What he really does when he begins his practice is to work on a limited number of problems, to the solution of which he has to bring the sum total of his experience; and thus he gradually gains confidence in himself.

The mechanical engineers at Cornell University cover the usual course on the principles of electrical engineering during their junior year, and it was considered desirable that the work of the senior year include one or two pretentious projects, consisting of the selection and arrangement of all the electrical equipment for an industrial plant, such as a machine shop or a cement plant—problems that require for their solution a comprehensive rather than a detailed knowledge of electrical apparatus. It was soon found, however, that the student lacked the broad point of view that comes from practice. He knew for example that direct-current motors were good for speed adjustment and that alternating-current motors were essentially constant-speed machines, but he was not able to reach the conclusion that therefore direct-current supply was desirable for machine shops with many variable-speed tools.

The set of notes prepared by Mr. Brown to guide the student in his work contained so much useful information not to be found in books that it was considered desirable to offer them to the engineering profession. There are innumerable books for wiremen and for the shop mechanic, but there was no book on the market written specially to guide the mechanical engineer in the selection of his electrical equipment.

While it was considered not only advisable but necessary to give extensive references to the literature of the subject, it was recognized that the mechanical engineer would not have an extensive library of electrical texts, nor would he be familiar with the electrical periodicals. It was therefore decided that, except in rare cases, the references would not go beyond one of the standard texts in addition to the electrical handbooks. If the student can be trained to use the matter contained in the handbooks in an intelligent manner, and also to check up his theory from a reliable text, he will approach the dreaded electrical problems with great confidence. Our experience with this course at Cornell has given us great satisfaction.

ALEXANDER GRAY,
Head of Electrical Engineering Department,
Cornell University.

PREFACE

A great mass of electrical data is now available in the various handbooks, and other technical literature. The engineer must not only have such data at hand—he must know how to use them. The purpose of this book is to show how to apply the available data, and the principles laid down in textbooks, to the equipping of shops, factories and industrial plants. Numerical examples are worked out illustrating these applications; and in addition a progressive series of problems is placed at the end of the book. Both the text and the problems are drawn largely from the author's experience as engineer with the Westinghouse Electric & Manufacturing Co., in the Detail and Switchboard Divisions.

I acknowledge with thanks the privilege extended by the McGraw-Hill Book Co., Inc., publishers, to make use of the material in the Standard Handbook,[1] and a similar privilege extended by John Wiley & Sons, Inc., with reference to the American Handbook.[1] Only condensed data and brief statements of theory are included in the text; references are given throughout the book to fuller data in these two handbooks, and to fuller description and theory as given in Gray's "Principles and Practice of Electrical Engineering".[1]

It gives me pleasure to express my thanks to Professor Alexander Gray, Head of the Department of Electrical Engineering, for suggesting the publication of this material, for painstaking reading of manuscript and proof, and for important suggestions, as to both details and general form of presentation. I am glad to acknowledge also my obligation for valuable suggestions and data, to members of the Engineering and Sales Departments of the Westinghouse Electric & Manufacturing Co.; of the Engineering Department of the National Lamp Works of the General Electric Co.; of the Sales Department of the American Steel and Wire Co.; also to Mr. W. H. Kniskern, General Manager of the Cayuga Cement Corporation; and to Mr. R. A. Hunt, Power and Electrical Engineer at the Sayre Shops of the Lehigh Valley Railroad.

H. W. B.

Cornell University,
January, 1916.

[1] See footnote, page 1.

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CHAPTER I

THE CIRCUITS OF POWER PLANTS AND DISTRIBUTION SYSTEMS[1] [2]

This chapter is intended to give a general survey of the kinds of electric circuits in common use, and the customary ways of representing the circuits by diagrams. In plants of any considerable size, practically every circuit leads to or from a set of buses, as illustrated in Fig. 1. The generators furnish power to the buses, and feeders take it to its destination. Thus it is possible for the generators to operate in parallel, and to share in the fluctuation of the load on any feeder. The circuits most commonly found in practice, feeding to and from these various buses, are:

D.C. generator circuits.
D.C. power and lighting feeders.
A.C. generator circuits.
A.C. power feeders.
A.C. constant-potential lighting feeders.
Series lighting circuits.
Exciter circuits.

[1] Throughout the text the following abbreviations are used in references:

G. = Principles and Practice of Electrical Engineering, by Alexander Gray. The numbers following G. refer to paragraphs. (First Edition, 1914, McGraw-Hill Book Co., Inc.)

S. = Standard Handbook for Electrical Engineers. The numbers preceding colons refer to sections; those following colons refer to paragraphs. In addition to the references cited, a bibliography is given at the end of nearly every section, and at the ends of many of the individual articles. (Fourth Edition, 1915. McGraw-Hill Book Co., Inc.)

A. = American Handbook for Electrical Engineers. The numbers refer to pages. A bibliography is given at the end of nearly every article, and cross references to related subjects are given at the beginning. (First Edition, 1914, John Wiley & Sons., Inc.)

[2] G. 193–197, Parallel operation of D.C. generators.
S. 10 : 765–768, 799–802, D.C. and A.C. switching connections.
A. pp. 1474–1478, 1494, Switchboards and switching connections.

Each of these circuits should be controlled by a switch, and protected if necessary by a fuse or circuit-breaker. In addition, it is necessary, for the intelligent control of the plant, to make

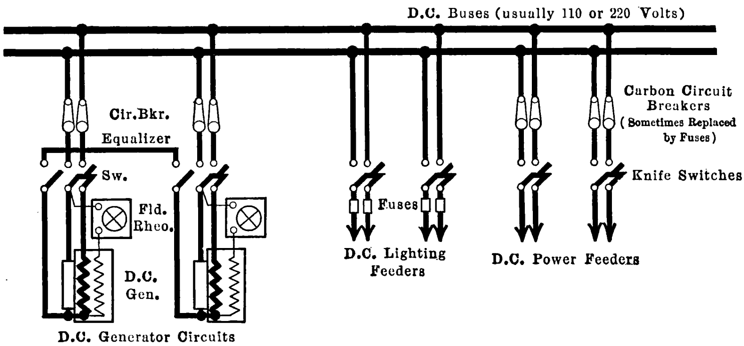

FIG. 1.—D.C. generator circuits, feeders and buses.

Showing how D.C. generators deliver current to the buses, and the buses distribute it to the several feeders.

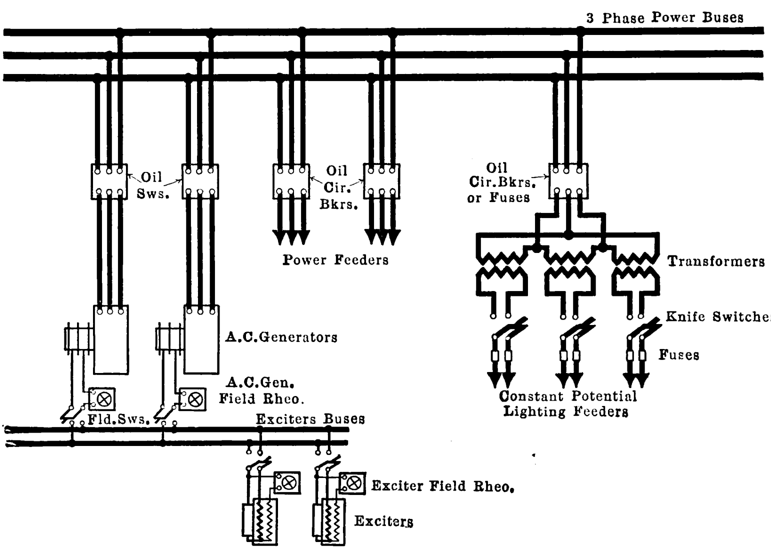

FIG. 2.—A.C. Generator circuits, feeders and buses.

If the exciters are to operate in parallel, an equalizer is to be added as in Fig. 1.

measurements of current, voltage, power, energy, power factor and frequency, or some of them, on some if not all of these circuits. The economic considerations determining the kind of system to be installed are outlined in the next two chapters. In later chapters the equipment is taken up in detail.

D.C. generator and feeder circuits are illustrated in Fig. 1, and A.C. circuits in Fig. 2. In large power plants, the connections become much more complicated, but still the entire arrangement is based on that shown in these simple diagrams. The connections as indicated should be studied in detail. A complete diagram includes not only the power circuits shown here, but

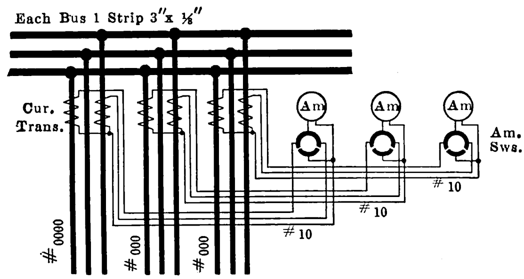

FIG. 3.—Ammeters, ammeter switches and current transformers on three circuits.

Illustrating relative widths of lines, spacing between lines, and between groups, and method of designating size of wire, if necessary. The significance of the various connections will be better understood after a study of Chapter XIX.

also the connections to meters, meter switching devices, and overload trip-coils of circuit-breakers. In many cases this equipment is not connected directly to the line, but to the secondaries of instrument transformers, whose primaries are connected to the line. In Fig. 3 are several current transformers connected to ammeters. The switching arrangement shown is discussed further in Chapter XIX.

DIAGRAMS OF ELECTRICAL CONNECTIONS

A good diagram of connections is important, from the beginning to the end of the development of a power system. Conventional forms and methods are adopted, which represent the apparatus and connections in one way or another. In some cases the apparatus should be represented more as it appears to the eye, and in others it is better to emphasize theoretical relationships. We consider three features of diagrams; namely: (*a*) rules for representing wiring; (*b*) conventions for representing apparatus; and (*c*) notes and labels.

(*a*) **Rules for Representing Wiring.**—The following rules for drawing lines that represent wiring will be found conducive to clearness and compactness of the diagram, and ease of drawing:

1. Lines are to be drawn with no more turns (angles) than are necessary; they are to be drawn vertically and horizontally, except that short lines may be made slanting, where it is particularly advantageous, as in one of the diagrams of the three-phase generator, Fig. 4*c*.

2. Lines must not cross other lines more than is necessary.

3. The width of each line is to indicate what is the general use of the conductor (see Table I). It is not always practicable to represent all the various sizes of wire by widths of lines, because only a few widths of lines can be distinguished clearly in the ordinary diagram. If the sizes of wire are to be given on the diagram, they may be put in a table, or marked alongside the line, as in Fig. 3.

TABLE I.—WIDTHS AND SPACING OF LINES.

The dimensions given are suitable for drawings. They may be varied somewhat, depending on the nature of the diagram. For diagrams printed from plates, each dimension may be divided by 2.

Lines representing	Width of ink line (inches)	Spacing, center to center, between lines	
		Of the same group (inches)	Of consecutive groups (inches)
Small wiring for meters, instrument transformers, relays, trip-coils, D.C. generator and motor fields (usually about No. 10 B. & S. wire).	0.005	1/16	1/8
Outlines of all apparatus (not used for wires)	0.01		
Leads for exciter armatures, A.C. generator and motor fields; also buses for auxiliary circuits	0.02	1/8	1/4
Leads for power circuits (*i.e.*, generator and motor armatures, transformers, feeders, etc.); also exciter buses	0.035	3/16	3/8
Ordinary power buses	0.05	1/4	1/2

4. The space from the middle of one line to the middle of the next should be from two to ten times the width of the line. The wider the line and the more accurate the drawing, the less relative spacing is required.

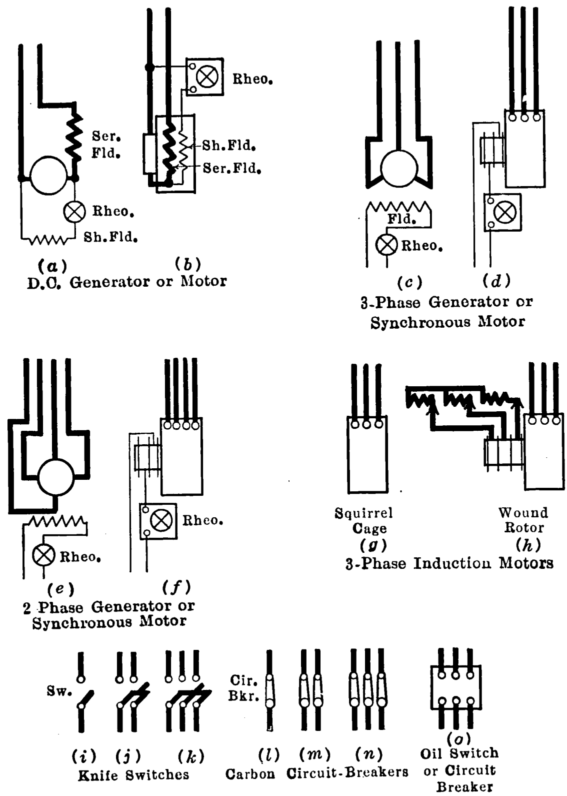

FIG. 4.—Conventional representations of several kinds of electrical equipment.

(*a*) and (*b*) show two ways of representing D.C. machines, (*a*) shows the theoretical relationships and (*b*) is nearer the actual appearance. (*c*) and (*e*) correspond to (*a*), and (*d*) and (*f*) to (*b*), representing A.C. machines. (*g*) and (*h*) differ in that the squirrel-cage motor (*g*) has no rheostat connected to the rotor, such as the machine with a wound rotor has, as shown in (*h*).

5. Not more than three or four lines should be drawn in a group. (Usually a group consists of one circuit. See Fig. 3.) Spacing between groups should be at least twice the spacing between lines in a group.

6. A dot is used to indicate where one conductor is connected electrically to another, as in Fig. 3. If the dot is so used,

semicircular curves or "jumpers" should *not* be used to indicate that wires are not connected.

(*b*) **Conventions for Representing Apparatus.**—Several useful conventions are given in Fig. 4. Such conventional forms must sometimes be modified on account of changes in apparatus or in the purpose of the diagram.

(*c*) **Notes and labels** should be added wherever they make the diagram easier to understand, or easier to draw.

1. Conventional forms should be labelled wherever there can be any doubt as to their meaning. Sometimes they are labelled by abbreviations, and a list of abbreviations is appended to the diagram.

2. It is well to label circuits—*e.g.*, "Lighting Feeder," "Power Feeder to Woodshop," "Feeder to XYZ Substation."

3. Notes can be added in many cases, to save drawing several duplications of circuits, as:

"Total of 5 Generator Circuits Like This."

"2 Such Feeders to Woodshop and 1 to Paint Shop."

4. Reference notes should be given, indicating where detail diagrams, and diagrams of related installations can be found, as:

"See p. 47 for Details of Motor-starter Connections."

"See Dwg. 2,732 for Diagram of Connections of Machine Shop."

CHAPTER II

THE REQUISITES OF POWER PLANTS AND DISTRIBUTION SYSTEMS[1]

Whether a power plant is part of an industrial establishment or is a commercial plant furnishing power to customers, the requisites for a good stable investment are as indicated in the following outline, which is put in convenient form for ready reference. The reference letters and Roman numerals refer to the fuller discussion, which begins on the next page.

I. **Safety to operators and equipment,** which requires:
- (*a*) Voltage not unnecessarily high.
- (*b*) Adequate insulation of lines and equipment.
- (*c*) Protection against lightning and other excessive voltages.
- (*d*) Automatic protection against grounds, short-circuits, and overloads.

II. **Continuity of service,** which requires:
- (*a*) All that is required for safety.
- (*b*) Duplication of all essential equipment.
- (*c*) Circuit-breakers that do not operate instantly, and some interlocking arrangement that keeps one breaker in when another goes out.

III. **Small first cost, fixed charges and operating cost,** which require:
- (*a*) All that is required for safety.
- (*b*) Voltage neither too high nor too low.
- (*c*) Labor-saving apparatus without unnecessary complications.
- (*d*) Installation of no unnecessary equipment.
- (*e*) Generating and other units neither too large nor too small.

[1] S. Sections 10 to 13; Power Plants, Distribution and Wiring.
A. pp. 1087, 1089, 1119, 1462, 1463; Power Stations and Substations.
A. pp. 251, 352, 363, 1657, 1891, Distribution and Wiring.

(*f*) Units of high efficiency, operating at about their maximum efficiency.
(*g*) Equipment having little depreciation.
(*h*) Equipment requiring little outlay for upkeep and repairs.
(*i*) Conditions of low interest, insurance, and taxes.

IV. Small per cent. voltage variation, which requires:
(*a*), (*b*) High line voltage or large line wires for small per cent. drop.
(*c*), (*d*) Suitable compounding or voltage regulation of D.C. generators, voltage regulation of A.C. generators, or regulation of feeder voltage, or any combination of these methods of regulation.
(*e*) Power factor of the A.C. load as high as possible.

V. Adaptability to all required loads, which requires:
(*a*) Sufficient total capacity of generating units.
(*b*) Capacities of some or all the units not much in excess of the minimum load.
(*c*) Allowance for expansion.
(*d*) Ammeters and wattmeters whose full-scale indications are sufficient for all ordinary overloads, and whose indications at customary loads are readable with fair accuracy.

VI. Good appearance, which encourages keeping the plant in good condition, and requires:
(*a*) Consideration of appearance in selecting equipment.
(*b*) Orderly layout of switchboard and machines.
(*c*) Good building.
(*d*) Well-arranged natural and artificial lighting.

I. SAFETY TO OPERATORS AND EQUIPMENT

(*a*) **High voltages** are undesirable if the employees working around the circuits are not familiar with electricity. Usually there is no advantage that would warrant a voltage much above 550, in a plant employing non-electrical men (see Chapter III, p. 19, for customary voltages).

(*b*) **Insulation.**—All parts of the system should be insulated well enough so that there is no danger of breakdown to ground, nor from one wire to another. For all inside wiring, the insulation should be in accordance with the rules of the National Electrical Code,[1] together with city ordinances, power company requirements and local insurance rulings, if there are such.

(*c*) **Lightning Arresters.**—When lightning strikes a line, the danger is on account of the excessively high voltage that may occur between the line and ground. If this voltage due to the lightning is high enough, the insulation breaks down at the weakest point, and the lightning discharges to ground. A lightning arrester provides a direct and easy path to ground, thereby reducing the strain on the insulation. This easy path is made operative the instant the lightning strikes, but is made inoperative as soon as the strain due to the lightning is past (see Chapter XVIII).

Lightning arresters serve as a protection against other high voltages on the line, as well as against lightning. This is a matter of considerable importance in case of some high-tension lines in which the voltage surges that are liable to occur in the operation of the system become excessive.

(*d*) **Automatic Protection against Grounds, Short-circuits, and Overloads.**—If a system is already grounded at one point, the result of another ground, on another phase or polarity, is equivalent to a short-circuit. Such a ground or a short-circuit is very much like a heavy overload, and is to be treated accordingly. A circuit-breaker can be set to operate when the current in the line exceeds the maximum safe value, thereby protecting against all these troubles (see Chapter XVII).

II. CONTINUITY OF SERVICE

(*a*) **Safety Requirements.**—Whatever is required for safety is also important for continuity of service, because a breakdown is likely to interrupt the service.

(*b*) **Duplicate Equipment.**—As far as practicable, the plant should be laid out so that if any one part is disabled it need not interrupt the entire plant. By providing at least one more of every piece of equipment than is required for normal operation, such danger of interruption is largely avoided. The emergency equipment should be available on an instant's notice, for use wherever required, if it is not actually in service. Consider two

[1] Rules and Requirements of the National Board of Fire Underwriters for Electric Wiring and Apparatus; revised every 2 years. These rules can be obtained from any local insurance inspection office, or from the headquarters in Philadelphia.

cases: (1) A spare generator takes its turn at lying idle, but it should be driven by an engine or other prime mover that can be started without delay (see Chapter XII, p. 97). (2) In case of transmission lines and distribution systems, two lines are kept in continuous service, in parallel. Either line may then drop out of service on account of some fault; the other line then carries the entire load (see Chapter XVII, p. 140). For economic reasons this duplication of equipment cannot be carried to an extreme, and those responsible for laying out the plant must decide to what extent they are willing to sacrifice continuity of service in case of emergency, in order to reduce the first cost of the plant.

(*c*) **Restricted Operation of Circuit-breakers.**—Unnecessary opening of the circuit-breaker is to be avoided whenever possible, so that the circuit-breaker should be set for as large a current as is safe; and usually it is better for the sake of continuity of service, to allow some time to elapse, so that if possible the trouble will clear itself without opening the breaker. This time element is introduced in many cases by means of a small relay which determines the time when the circuit-breaker is to open (see Chapter XVII, p. 137).

In many cases it is necessary to lay out the wiring so that a single short-circuit tends to open two circuit-breakers. It is desirable that the breaker nearer the seat of trouble should open, but that the other should remain closed, because opening it usually affects some other machines. In such a case the circuit-breakers are made to operate "selectively;" that is, there is a mechanical or electrical interlock that prevents the one trouble from tripping more than one breaker.

III. FIRST COST, FIXED CHARGES, AND OPERATING COST

The first cost is the cost of equipment, including transportation and installation. The building, steam plant, electric plant, and wiring naturally come under this head. Fixed charges are for annual depreciation, interest on the investment, insurance, and taxes. Operating cost includes labor, fuel, supplies, upkeep and repairs.

(*a*) **Safety.**—Whatever makes for safety reduces one element of the operating cost, by saving in repairs.

(*b*) **Voltage.**—The voltage best adapted to any particular circuit depends on the extent of the system. A high-voltage installation may cost more for protection and insulation than one of low voltage, but on long lines the saving in copper by increasing the voltage is so great as to make the higher voltage more economical (see Chapter III).

(*c*) **Labor-saving Apparatus.**—Under this head is included whatever saves time or special attention, such as meters, instrument transformers, meter-switching devices, and indicating lamps (see Chapters XV and XIX).

(*d*) **Unnecessary Equipment.**—The dividing line between necessary and unnecessary equipment is not always easy to draw; but unless every $100 invested brings $10 or $15 return every year, in profit, labor-saving, or protection, it is not usually a very good investment. Sometimes meters can be omitted, and perhaps even more often they can be replaced by switching devices to shift an ammeter and voltmeter from one phase to another, and to shift a voltmeter from one circuit to another (see Chapter XIX).

(*e*) **Size of Generators and Other Units.**—Large generators and transformers cost less per kilowatt capacity than small ones; but the investment in spare machines becomes excessive if all the units are of too large capacity. Both the first cost of the entire plant and the operating cost must be considered in determining the most economical size of machines (see Chapters VII, XII and XIII).

(*f*) **High efficiency operation** is desirable, not only because the cost of operation is less, but also because the machine runs cooler at high efficiency.

(*g*) **Depreciation.**—The total amount annually chargeable to depreciation is proportional to the investment, except that some equipment depreciates less rapidly than other. On account of the smaller depreciation, apparatus having the larger first cost is frequently the more economical.

(*h*) **Upkeep and Repairs.**—Some apparatus rarely requires any attention to keep it in perfect condition. Other apparatus is laid up for repairs an appreciable part of the time. The loss is twofold: The cost for making the repairs, and the loss of the use of the apparatus during the time of repairs.

(*i*) **Interest, Taxes, Insurance.**—Interest and taxes are essentially proportional to the total investment, except as better rates of interest are obtainable for a plant that is better protected and more durable. Insurance depends on the quality of the building to such an extent that, considering the small cost of the building, the saving in insurance usually warrants construction that is at least approximately fireproof.

IV. VOLTAGE VARIATION

Except series lighting circuits, practically all power and lighting apparatus operates from nominally constant-potential systems. Only a small percentage variation from constant potential is allowable in motor circuits, and on incandescent lighting circuits it should be still smaller. Excessive variation of voltage with load on account of line drop is avoided by adopting a suitable line voltage, and suitable size and spacing of conductors.

(*a*) **Line Voltage.**—If the amount of power transmitted, and the length of line remain constant, the higher the voltage the less is the per cent. voltage drop. The voltage must, therefore, be high enough so that a line can be designed whose voltage drop is not excessive, with reasonable sizes of wire (see Chapter III).

In case of A.C. circuits it is good practice to use one voltage for transmission over considerable distances, and another voltage for local distribution.

(*b*) **Size of Conductors.**—After the voltage of transmission and distribution has been fixed, the conductors must be of such size and spacing that the drop does not exceed a prescribed maximum. On A.C. circuits, line reactance as well as resistance produces voltage drop, but of course on D.C. circuits only resistance is to be considered (see Chapters X and XI).

(*c*) **Compounding D.C. Generators.**—The voltage of small shunt generators decreases so much with load that if constant potential is at all important on D.C. circuits, small generators are compound-wound. If all the power is used so near the bus that there is no considerable line drop, the generator may be flat-compounded—that is, compounded so that its voltage at full-load is the same as at no-load. But if all the power is transmitted to a distant point, such that the per cent. line drop is large, the machine may be overcompounded—that is, compounded so that the generator voltage at full-load is higher than at no-load, thereby compensating for the line drop and maintaining constant voltage at the load (see Chapter XII).

(*d*) **Voltage Regulation.**—It is necessary, in many cases, to provide, external to the generator, some means of voltage regulation. This is of less importance on D.C. than on A.C. circuits, because A.C. machines are not generally self-regulating. If all the feeders are short, the voltage of the entire system can be kept constant by a device called a voltage regulator, applied to the generators; but if some feeders are very long, each one may require additional individual regulation (see Chapters XIV and XVI).

(*e*) **Control of Power Factor.**—The greatest voltage drop due to line reactance occurs in case of a lagging current at low power factor. With current at 100 per cent. power factor, the reactance has no appreciable effect on the terminal voltage, and with a leading current the reactance tends to increase the terminal voltage (see Chapter XI, p 87). Where it is feasible, the load should be so arranged that the power factor is about 100 per cent., thereby eliminating reactance drop.

V. ADAPTABILITY TO ALL REQUIRED LOADS

(*a*) **The total capacity of the generating units** must be large enough to carry all ordinary loads with good efficiency, and without excessive heating, sparking, voltage drop, or other harmful effect of overload. The capacity should be such that if any one unit is disabled, the remaining machines can carry the load without seriously crippling the plant or endangering the remaining generators (see Chapters XII and XIII).

(*b*) **Units for Light Load.**—It should be possible to run the plant at good efficiency, at the lightest load that the plant is likely to carry for any considerable time. If the plant has a large number of machines, they should all be of the same size; in case of a small plant, having only two or three generators, and operating for long periods at a very light load, it may be advantageous to have one of the units of about one-half the size of the others.

(*c*) **Allowance for Expansion.**—If the plant is of such a nature that the demand for power is likely to increase, the plant should be large enough to anticipate the increase, or provision should be made for one or more additional generators and related equipment, to be installed later.

(*d*) **Meter Capacity.**—Ammeters and wattmeters should be of such capacity that they will indicate the largest load that the line is likely to carry for any appreciable time; but the meters should not have *too* large capacity, because in that case the deflection is very small under normal and light-load conditions, and it is not possible to take accurate readings.

VI. GENERAL APPEARANCE AND ENVIRONMENT

This does not necessarily refer to ornamentation, but the plant should give the appearance of being adapted to its purpose. It should of course satisfy stockholders and directors and the general public, but it should also be so designed that it appeals to those who are operating the plant, as being worthy of the best of care. An operator takes pride in keeping a plant in perfect condition, if he believes it to be the best of its kind in the vicinity.

(*a*) **Consideration of Appearance in Selecting Equipment.**—The best manufacturers of electrical equipment take pride in their products, and are not willing to send them out poorly finished. It requires only a small additional expense to make a good piece of apparatus appear well, and to some extent the appearance serves as a guarantee of good workmanship and materials. For this reason, and because apparatus that is well-finished is easier to keep in order, it pays to consider appearance in selecting it.

(*b*) **Layout of Switchboard and Machines.**—Switchboard panels should be grouped, so that as far as possible all A.C. generator panels are in one group, all A.C. feeder panels in another, lighting feeders in another, etc. This plan is frequently carried so far as to leave blank panels for future additions, rather than to install the additions out of order. The machines should, if possible, be in essentially the same order as the switchboard panels. It is easier for the operator to act quickly in an emergency, and easier to give proper care at all times, if the entire layout is so rational that the operator has it perfectly in mind.

(*c*) **The Building.**—The cost of the building is small compared with the cost of equipment, but the convenience, safety and durability of the building play no small part in the safe and economical operation of the plant.

(*d*) **Natural and Artificial Lighting.**—The lighting of the power plant should be good: first, because every operation is performed more safely and easily with good light; and second, because if any part of the plant is in disorder good lighting reveals the fact. Good lighting, whether natural or artificial, includes (1) plenty of light, (2) uniform distribution, and (3) light so placed that there is no glare or blinding effect, due to strong direct or reflected light in the field of vision (see Chapter IX).

CHAPTER III

CHOICE OF SYSTEM

The first things to be decided in arranging for an electrical installation are:

(1) Whether it is to be an A.C. or a D.C. system;

(2) If A.C., whether a one-, two-, or three-phase system;

(3) Whether the frequency is to be 25 cycles, 60 cycles, or some frequency that is not standard;

(4) What the line voltage or voltages are to be.

1. A.C. versus D.C. Systems.—If a storage battery or any other electrolytic equipment is to be connected to the system, obviously a D.C. system must be employed. Otherwise, the decision must be based on the relative merits in the individual case, because either A.C. or D.C. can be used for both lighting and power. For incandescent lighting, either an A.C. or a D.C. system is satisfactory if the voltage can be maintained constant. For arc lighting, the D.C. has some advantages, but not enough to warrant its use if there are many motors connected to the circuit which operate better on A.C.

It is possible to use either an A.C. or a D.C. motor at will for every motor application; but there are some cases, for example, in a powder mill, where D.C. is very undesirable; and others, for example, where there are cranes and many variable speed machine tools, where A.C. would be objectionable. In each plant where a choice is possible, the advantages of the two systems must be balanced against each other. The chief advantages in using A.C. motors for industrial applications are:

(*a*) The possibility of A.C. transmission and distribution at higher voltages, and stepping down to motor voltages.

(*b*) The possibility of stepping down from the voltage of motor feeders to that of lighting feeders without a lower voltage generator or its equivalent.

(*c*) The possibility of using induction motors which are rugged, and have no commutator to wear out or introduce fire hazards.

The chief advantages in D.C. motors are:

(*a*) The possibility of automatic speed variation of series and compound motors, without excessive power lost in rheostats.

(*b*) The possibility of speed adjustment in shunt motors by field rheostat, thereby obtaining at high efficiency any number of speeds that remain constant at the required values, at all loads.

(*c*) The absence of reactance in line drop.

(*d*) The possibility of connecting motors to the same circuit as storage batteries or other electrolytic apparatus.

In Table XIII, p. 167 is a list of machine tools and other industrial motor applications, indicating the motors that are usually preferable, and others that are sometimes satisfactory.

2. Number of Phases.—The only systems in general use are single-phase, two-phase four-wire, two-phase three-wire, and

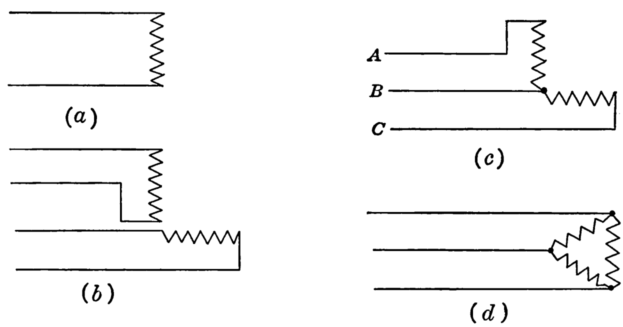

FIG. 5.—Comparison of distributing systems.
(*a*) Single-phase. (*b*) 2-phase 4-wire. The two voltages are equal. (*c*) 2-phase 3-wire. The CA voltage is $\sqrt{2}$ times BA or CB. (*d*) 3-phase. The three voltages are equal.

three-phase. These are illustrated in Fig. 5. The zigzag lines may be taken to represent transformers or any other source of power. Their angular positions indicate the phase relations of the several circuits.

The principle advantage of a single-phase circuit is its simplicity. It requires only two wires for transmission, and the connections and equipment are sometimes a little simpler than for a polyphase circuit. The chief advantages of a polyphase system are that the size and cost of motors and generators are less, and that motor starting is easier. The advantages of the polyphase system far outweigh those of the single-phase, for ordinary industrial-motor applications. The only extensive single-phase application is to railway motors, which operate from only one trolley line and the ground return. There is but little choice between single-phase and polyphase systems for lighting circuits. For small currents, the use of only two wires is an advantage; for large currents, the polyphase system offers a small saving in copper.

After it has been decided to use a polyphase system, there is but little choice between two- and three-phase. The small advantages of the several systems are as follows:

The two-phase four-wire system has the advantage over the three-phase, in requiring only two transformers, and in having two phases that are insulated from each other and independent in their operation.

The two-phase three-wire system has the advantage over the four-wire system, that the wiring is simplified, and there is a small saving in copper.

The three-phase system has the advantage over the two-phase three-wire, that the three voltages between lines are equal, and all conductors are of the same size.

Where a generating station is to be installed, the advantages of a three-phase system usually outweigh those of two-phase; but if there is a power company from which power can be obtained in an emergency, the system used by that company should be considered. Transformers are used to step the power company's voltage down to that required by the industrial plant, and even in case the power company should have a two-phase system, the transformers could be Scott-connected (see Chapter VII, page 48), so that three-phase could still be used in the industrial plant. However, if two-phase emergency power could be obtained without stepping down the voltage, it might be well to introduce two-phase in the industrial plant, and save the transformers.

It should be remembered that in transforming it is always possible to change not only from two-phase to three-phase, but also from three-phase to two-phase, and from two-phase three-wire to two-phase four-wire.

3. Frequency.—In the choice of the frequency of an alternating-current system, some considerations make a low frequency advantageous, and others a high frequency.

Transformers, generators, synchronous motors, and induction motors can be made smaller, and at less cost, if they are to operate on a high than if on a low frequency. But very slow-speed induction motors are more satisfactory on 25 than on 60 cycles, on account of the higher power factor that can be obtained on 25 cycles. The cost of a 25-cycle transformer or induction motor is usually from 25 to 50 per cent. higher than a corresponding 60-cycle equipment, and a 25-cycle generator or synchronous motor sometimes costs 20 per cent. more than a corresponding 60-cycle machine.

Alternating-current commutating motors, used on electric railways, operate at a higher power factor on low frequency. For this reason they are preferably designed for about 25 cycles.

Arc and tungsten lamps flicker visibly on very low-frequency circuits. It is better not to use them on less than 50 or 60 cycles, on account of the resulting eye-strain.

Transmission and Distribution Wiring.—The voltage drop due to inductive reactance of the line is greater at high than at low frequency; it is entirely negligible at any ordinary frequency if the load current is at 100 per cent. power factor, but may be very large with load at low power factor.

The desirable frequency to be adopted on any system depends on what equipment predominates. Alternating-current commutating motors are used on electric railways, but very little elsewhere; slow-speed induction motors are used only in steel rolling mills, and for other rather rare applications. For these motors a low frequency is better; but for all others the frequency should be higher. The reactance drop in the various machines, as well as in the line, would be excessive if the frequency were *too* high, but it is found in practice that at 25 to 60 cycles this drop need not be excessive, either in the machines or in the line. In the United States, 25 and 60 cycles are used in practice almost exclusively, for ordinary industrial purposes. Of the two, 60 cycles is far more common than 25, especially where slow-speed induction motors and alternating-current commutating motors are not employed. Besides these frequencies, 15, 30, 50, 133, and a few others are found occasionally. It is of advantage to use 25 or 60 cycles wherever possible, because standard equipment is made for these frequencies. If any other frequency is adopted, the delivery of equipment may be delayed, and the cost may be higher.

4. The voltage of a so-called "constant-potential" system, or of any circuit in such a system, depends, chiefly, on (1) the length of the system, (2) the kind of apparatus that it feeds, and (3) the danger to life or apparatus. All of these should be considered with reference to every circuit.

Standard Voltages.—The voltages in common use at the present time are 110, 220, 440, 550, 1,100, 2,200, 4,400, 6,600, 11,000, 13,200, 16,500, 22,000, 33,000, 44,000, 66,000, 88,000, and 110,000. All of these are derived from 110 volts, by multiplying by the factors 2, 3 and 5, as many times as necessary. Various other voltages, as high as 165,000 are in less common use. On account of line drop, the voltage cannot be standard along the entire length of the line. Either the beginning or the end of the line is usually kept at or near the standard voltage.

Voltage of Distribution System.—There is no simple, universal rule for the relation between voltage and length of line; but in practice, where transformers are necessary, the line voltage is nearly always between 500 and 2,000 volts per mile, and is ordinarily about 1,000 volts per mile. Thus a line 10 miles long usually has a voltage of about 10,000. The choice would be between 6,600 and 11,000, which are standard voltages. It would be decided by considerations of cost, safety, and voltage regulation (see Chapter X). However, if some other line in this same system would dictate a higher voltage, sometimes it is of advantage to have the entire system at that higher voltage.

If transformers are installed at the end of the line, it is usual practice to have a line voltage of at least 2,200, which is very common as a transmission and distribution voltage. Wherever it is possible to use 2,200 volts, it is better to adhere to this standard than to adopt the higher voltages which introduce added risks, especially in populous districts.

Tungsten lamps connected in multiple are usually used on about 110 volts. (Lamps are also made for 220 volts, but in most cases, at present prices, the 220-volt lamps of a given wattage cost 20 per cent. more, and produce only 90 per cent. as much light.) In a plant of any considerable size, if only a 220-volt D.C. circuit is available, some convenient means can be provided, so as to have a 110- and 220-volt three-wire system. Various other arrangements can be employed at other voltages, to obtain a suitable lighting system. In case alternating current is available, transformers may be employed to provide the desired voltage for the lighting circuit.

Arc lamps connected in multiple on a D.C. circuit operate efficiently and satisfactorily on about 110 volts. (A little lower voltage could be used if there were a standard of about 70 volts, but the gain would not be very large.) When higher D.C. voltages than 110 are employed, a relatively large series resistance is used to cut down the voltage across the arc, and the efficiency is very much reduced. For A.C. circuits, however, arc lamps are regularly made for 110, 220 and 440 volts. For voltages above 110, a transformer accompanies the lamp, and a good electrical efficiency is obtained, even on 440 volts. Special lamps can be obtained, also, to operate at still higher voltages.

D.C. motors usually operate on 110 or 220 volts in industrial plants. Line drop is unnecessarily large in a large plant at 110 volts, but 220 volts is satisfactory if the motors are within 500 or 1000 feet of the power plant. A 550-volt system in an industrial plant has two disadvantages: that it is approaching a dangerous condition if it is a plant in which non-electrical men are regularly at work; and that some provision must be made for lighting, other than the customary three-wire system.

A.C. motors may operate at any desired voltage, without regard to the lighting circuit, because transformers can be employed for the lighting voltage. It is rarely desirable to operate the motors on less than 220 volts. A 440-volt system is more common in any plant requiring power several hundred feet from the generator; and even a 550-volt system is sometimes used.

A motor-generator set has no electrical connections between the motor and the generator, so that the voltage of each machine may be whatever is required to adapt it to its circuit. The same fact holds for a dynamotor (see Chapter VI, p. 42).

A synchronous converter, used to convert either from A.C. to D.C., or from D.C. to A.C., has only one winding for the A.C. and D.C. circuits, and there is a very nearly constant ratio between the A.C. and D.C. voltages. This ratio depends on the A.C. connections to the converter, and is as follows:

A.C. connection to converter	Ratio $\frac{\text{A.C. voltage}}{\text{D.C. voltage}}$
Single-phase	0.707
Two-phase	0.707
Three-phase	0.612
Six-phase, double-delta	0.612
Six-phase, diametrical	0.707

The ratio given is for ordinary connections. Special connections may be employed to obtain other ratios in case of the two- and six-phase connection.

A storage battery, with or without a booster, has a voltage on discharge that is the same as the line voltage. The charging voltage depends on what method of charging is employed. If the storage battery is connected across only one side of a three-wire system, its discharge voltage is only the lamp-line voltage —that is, one-half the motor voltage.

CHAPTER IV

D.C. MOTORS[1]

In specifying the motor and its controlling apparatus for any given kind of service it is necessary to determine what kind of D.C. circuit is available, and what is required of the motor. We should know in particular:

(1) What D.C. voltage is available, and whether it is a two-wire or a three-wire system;

(2) Where the motor is located;

(3) What is the maximum load on the motor, and how the load varies;

(4) What automatic variation of speed with load is desired or allowable; and

(5) What speed adjustment is required to be made by hand at the will of the operator, under various conditions.

1. The voltage of the motor and of the line must be adapted to each other. The best voltage for industrial plants is generally 220 volts; but if no motors are over a few hundred feet from the generator, 110 volts may be used.[2]

2. Locations Requiring an Enclosed Motor.—The motor should be enclosed, if it is in a place where dust would injure the commutator or interfere with commutation, where shavings might catch fire from the commutator, or where water might injure or short-circuit the machine. The motor may be semi-enclosed or entirely enclosed to keep flying objects from the moving parts of the machine. A semi-enclosed machine may also be used in some cases where there is slight trouble from dust, shavings or water, but not enough to require that the machine be entirely

[1] G. Chapter XV, Characteristics; Chapter XVII, Applications; Chapter XVIII, Speed Control.

S. 8: 157–180, 200–205, Characteristics, weights and costs; Section 15, Applications.

A. pp. 957–971, Characteristics, weights and costs; pp. 892–896, 972–982 (also see references, p. 972), Applications.

[2] See Chapter III, p. 20.

enclosed. Enclosing a motor increases its cost per horse-power, because it reduces the horsepower, that can be delivered continuously without overheating. See Chapter XX, p. 183, as to the effect of enclosing on the motor rating.

3. Motor Rating and Allowable Overload.—The motor rating given by manufacturers is usually based on the horsepower that the machine will deliver without causing excessive heating of any part[1] or excessive sparking at the commutator. Usually the rating is based on continuous duty (8 hr. or more), but sometimes on 1-hr. duty, or even a shorter time. On the short-time basis the rating is much higher than on continuous duty (see page 183 for increase of rating). For example, the ordinary crane motor does not operate more than a few minutes at a time, and a ½-hr. or a 1-hr. rating is sufficient; so that the motor size, weight, and cost can be much less than if it were driving a lathe for 8 hr. If the load is intermittent or variable, having maximum values of several times the average, it is well to specify that the motor is to deliver power according to a given time-load curve. The ratio of starting torque to full-load running torque should also be specified, especially if the motor is expected to exert a very great starting torque.

After the full-load rating has been determined, in terms of either horsepower, or torque and speed, the full-load current can be found directly:

$$2\pi NT/33{,}000 = \text{h.p.} = EI \times \text{efficiency}/746$$

where T is the full-load torque in pound-feet and N is the speed in r.p.m.

Table II gives reasonable figures for efficiency and rated speeds. If the motor is well-constructed mechanically, and commutation is good, the speed may be increased in each case by field control, to double the rated speed. If the torque is one-half as great at double the speed, the power delivered is the same as before, and the current input is practically the same. The ventilation is so much better at higher speeds that most motors running at double the normal speed will stand 120 per cent. of the rated armature current; so that the torque on continuous duty at double the rated speed may be as much as 60 per cent. of that at rated speed.

[1] For A.I.E.E. standard of allowable temperature rise see footnote, p. 94.

TABLE II.—D.C. MOTOR DATA FOR CONTINUOUS DUTY AT FULL-LOAD

Rating in horsepower	Efficiency, per cent.	R.p.m.[1]
2	80	1,000
5	83	800
10	85	600
20	88	500
40	89	400
100	90	300
300	93	200
1,000	95	100

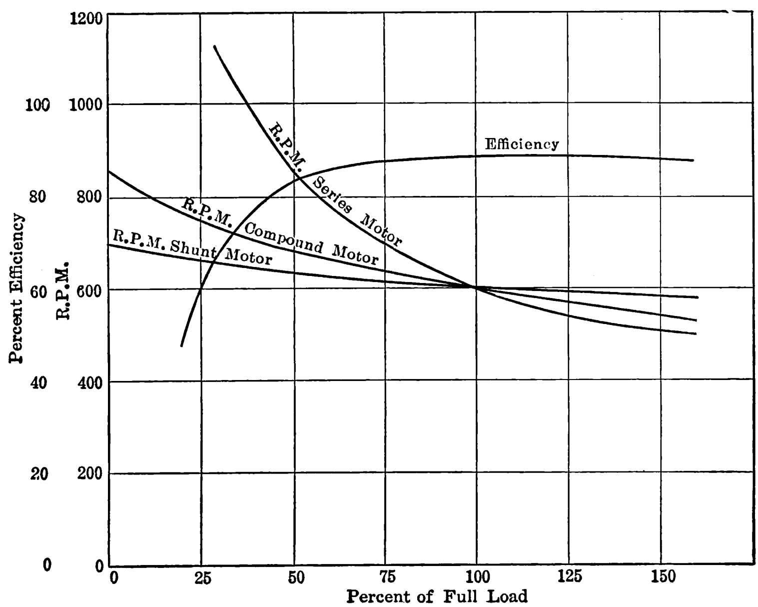

FIG. 6.—Typical efficiency and speed curves of D.C. motors.

4. Speed Regulation.—Fig. 6 shows the comparative regulation (automatic variation of speed with load) of shunt, compound and series motors. The large majority of industrial applications

[1] There are no definite limitations of rated speeds of D.C. as there are of A.C. motors. The speeds given in this table are in common use. The chief disadvantage of lower speeds is the increased cost of the motor. The chief disadvantages of higher speeds are commutation difficulties, and the extra gear reduction that is necessary.

require that motor speeds remain approximately constant under all conditions of loading. A lathe is an example. See also the table of motor applications in Chapter XX, page 167. *Shunt motors* satisfy the requirement of constant speed so well that they are used in all such cases. (For extremely constant speed the motor may be differentially compounded, but at the present time the differential motor is almost obsolete.)

A compound motor is adapted for operating such machines as shears, punches and crushers, which require a heavy torque intermittently. The kinetic energy of the rotating armature is utilized when the machine slows down at the instant of heavy torque. If a flywheel is on the motor shaft, the available kinetic energy is still greater. The compound motor is also adapted to certain hoists and pumps, and similar applications, in which the speed should be less at heavy than at light loads.

A series motor has a still greater speed variation with load than a compound motor; it is in danger of running away at very light loads. Its speed regulation is adapted to hoisting and conveying, where it cannot run away; because it is always under the control of the operator, even if it is not always loaded. There are in use three methods of protection against overspeed of a series motor:

(*a*) Gearing or other positive connection to a load that cannot be less than a safe minimum.

(*b*) An operator who is present, controlling the speed whenever the motor is running.

(*c*) Sufficient resistance in the motor circuit to keep down the back e.m.f., and therefore the speed of the machine. This makes the machine inefficient and the speed less, especially at heavy loads. It is only suited to very small motors.

5. Speed adjustment refers to changes made at the will of the operator, whereas speed regulation refers to the automatic change in speed due to change in torque.

Speed Adjustment by Rheostats.—The most common method of speed adjustment is by a rheostat in either the field or the armature circuit or one in each circuit.[1] The effects of these rheostats are shown very clearly by the expression for speed of a D.C. motor,

$$\text{r.p.m.} = k\,(E_a - I_aR_a)/\phi$$

[1] See Chapter XVI, for points to be considered in specifying rheostats.

Where E_a is the applied voltage.

I_a is armature current in amperes.

R_a is resistance of armature circuit in ohms.

ϕ is the flux in lines per pole.

The *armature rheostat* is a part of the resistance R_a; when the resistance in the rheostat is increased, the speed decreases, until when $R_aI_a = E_a$ the speed is zero. It should be noted that *when R_a is large, the regulation is poor;* the variation of speed with load is excessive, because R_aI_a varies with I_a, and therefore with the torque. The RI^2 power loss is also large, so that this method of regulation is very inefficient.

Compare with the foregoing the effect of the *field rheostat.* An increase of its resistance decreases the field current, and so the flux, ϕ; and the speed variation is in inverse proportion to the flux. Since R_a is now only the small armature resistance, its effect on the speed is negligible under all ordinary conditions. There is no large RI^2 power loss, so that this is an efficient method of speed control. An excessive resistance weakens the field so much that commutation is bad, unless the motor has a commutating field. Motors can be built having speed adjustment by field rheostat, by which the speed can be increased from normal to twice the normal speed.

The effect of an armature rheostat with any given current and resistance is calculated readily from the speed formula given above; but the effect of the field rheostat cannot be determined accurately without knowing how much the field is saturated. As an approximate guide, it may be assumed that for every 2 per cent. increase in field circuit resistance the speed is increased 1 per cent.

Speed control by armature rheostat can be applied to shunt, compound and series motors. A field rheostat can be used on the shunt field of either a shunt or a compound motor. A similar field control of a series motor is accomplished by connecting a rheostat in *parallel* with the series field. Increasing the resistance of such a rheostat increases the field strength, by sending more of the current through the field winding.

Multiple-voltage Speed Control.—The difficulties of speed control by armature rheostat are overcome by the multiple-voltage system. For slower than normal speed the armature is connected across a lower voltage, while the field remains unchanged. The motor runs at essentially the same reduced speed at light load as at full load, and has a reasonably good efficiency. The difficulty with this arrangement is that some form of motor-generator set must be provided to obtain the additional voltages, and additional wiring is necessary wherever the multiple voltage is required. The only multiple voltage in general use at the present time is the three-wire system having equal voltages on the two sides. For example, on a 110- and 220-volt three-wire system, if a motor armature is connected across 110 volts, the speed is one-half of the normal speed which the motor has when across 220 volts. Intermediate speeds are obtained by connecting the armature to 110 volts and weakening the field by a rheostat. Still higher speeds, as high as double the normal, are obtained by connecting the armature across 220 volts and weakening the field by the rheostat.

CHAPTER V

A.C. MOTORS[1]

Types Available.—Of all A.C. motors, the squirrel-cage and phase-wound[2] induction motors are the ones used most extensively for industrial purposes at the present time. Synchronous motors and various forms of commutating motors are used to a limited extent for power-factor adjustment, but the simplicity and ruggedness of the induction motors make them desirable wherever it is practicable to use them. The present discussion will be limited to the two kinds of induction motors. In providing A.C. motors, the following should be considered:

(1) The voltage, frequency and number of phases;

(2) Where the motor is located;

(3) What the maximum load is on the motor, and how the load varies;

(4) What starting torque is required, compared with full-load torque;

(5) Whether it is necessary that the speed at full-load be appreciably less than at no-load, and if so how much; and

(6) Whether any speed adjustment is required to be made by the operator, and if so how much.

1. Voltage, Frequency and Phases.—The motor should be designed for the same number of phases, the same voltage and the same frequency as the supply.

If applied voltage $>$ motor voltage If applied frequency $<$ motor frequency	iron loss is excessive.
If applied voltage $<$ motor voltage If applied frequency $>$ motor frequency	maximum torque is too low.

Single-phase induction motors are of value where it is important to use only two wires for distribution of power; but polyphase motors are to be preferred, particularly on account of

[1] G. Chapter XXXVI, Theory and Characteristics; Chapter XXXVII, Applications; Chapter XXXVIII, Single-phase motors.

S. 7:205, 215–221, 271–285, Characteristics; Section 15, Applications.

A. pp. 983–988, 1005, 1007–1013, Characteristics, Costs and Weights; pp. 892–896, 972–982, also references on p. 972, Applications.

[2] Otherwise known as "wound-rotor" or "slip-ring" motors.

special arrangements that are necessary for a good starting torque of the single-phase motors.

There is no essential difference in operation between two-phase and three-phase motors. If it is necessary to operate a two-phase motor on three-phase, the Scott connection of transformers, or preferably auto-transformers, should be employed (see Fig. 23 *h* and *i*, p. 49 for the Scott connection, and Chapter VII, p. 46 for the advantage of using auto-transformers instead of transformers).

2. The location has less effect on the kind of induction motor than of a D.C. motor, because the induction motor has no commutator; and therefore no commutator trouble due to dust, and no fire hazard due to ignition from commutator sparking. The frame of the motor surrounds the winding to such an extent that injury from water or flying objects is almost impossible. If the motor is subjected to continued dampness or acid fumes, the coils should be treated with a special varnish. A phase-wound motor with external starting resistance requires slip-rings, which should be enclosed if the machine is in a very dusty location. The bearings of any induction motor in a dusty place should also be well protected from dust.

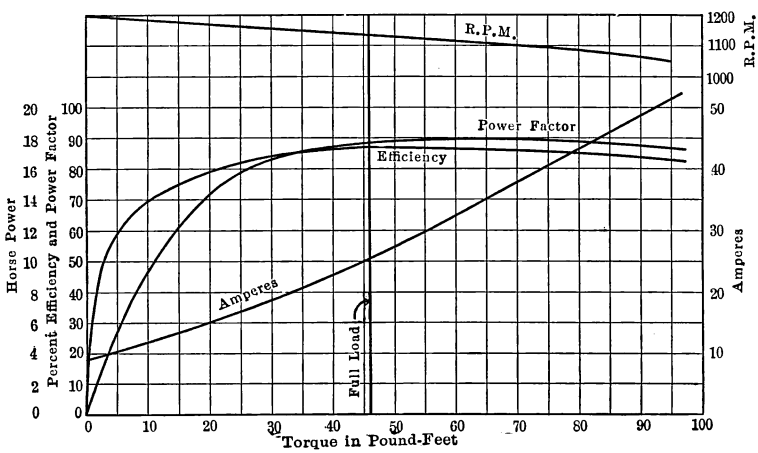

FIG. 7.—Charactistic curves of a 10-hp., 3-phase, 220-volt, 60-cycle induction motor.

3. Operation at Various Loads.—Increasing the load applied to an induction motor affects the motor operation, as to speed, power factor, efficiency and current. Referring to Fig. 7, it will be seen that for the highest efficiency and power factor, the load should be neither very large nor very small. The speed decreases gradually with increase of load until a certain maximum horsepower output is reached. The motor would stop if a torque were applied much beyond the value for maximum horsepower. Usually the motor is made large enough so that the maximum possible torque is 100 per cent. more than the motor will be required to deliver.

The full-load current of a three-phase induction motor is obtained directly from the expression,

$$2\pi NT/33{,}000 = \text{h.p.} = \sqrt{3}EI \cos\theta \times \text{efficiency}/746 \quad (1)$$

where N is the speed in r.p.m., T is the torque in pound-feet, $\cos\theta$ is the power factor, E is the voltage between lines and I the amperes per motor lead. Equation (1) holds for single-phase and two-phase motors, if the constant, $\sqrt{3}$, is replaced by 1 and 2, respectively. Table III gives reasonable values for full-load efficiency and power factor, no-load and full-load speeds and per cent. slip, for typical 60-cycle and 25-cycle motors.

TABLE III.—TYPICAL DATA AT FULL-LOAD AND NO-LOAD, ON SQUIRREL-CAGE AND PHASE-WOUND INDUCTION MOTORS[1]

Horsepower Rating	Per cent. efficiency at full-load	Per cent. power factor at full-load	Per cent. slip at full-load	60-cycle motor		25-cycle motor	
				No-load or synchronous r.p.m.	Full-load r.p.m.	No-load or synchronous r.p.m.	Full-load r.p.m.
1	82	78	5.5	1,800 (1,800–600)	1,700		
5	85	86	5.5	1,800 (1,800–600)	1,700		
10	87	88	5.0	1,200 (1,800–600)	1,140	750	712
25	89	89	4.0	1,200 (1,800–600)	1,150	750	720
50	89	89	3.5	900 (1,800–600)	870	750	725
100	90	90	3.5	600 (1,800–514)	580	500	485
500	91	91	3.0	600	582	375	365
1,000	92	92	2.5	450	440	250	244

[1] The speeds given in parentheses are the highest and lowest for which the sizes given are ordinarily made.

Both the *usual* load and the *maximum* must be considered, with reference to all the operating characteristics, in specifying a motor. Also the heating on short-time overloads must not be excessive (see Chapter XX, p. 183, for allowable short-time overloads).

4. Starting Torque.—Induction motors are made with two kinds of rotating elements, or rotors. One of these, the *wound rotor*, has a winding in the rotor slots, with leads brought out to slip-rings. A rheostat connected to the slip-rings as in Fig. 8, is mounted outside the motor. It is used to insert resistance in the rotor winding when the motor is being started. The effect of the resistance is to reduce the current, and to increase the power factor. Such an increase of power factor is important, because otherwise it is very low at starting, and the necessary starting current is very high. Where a rheostat in the motor secondary controls the starting current, the relation between torque and current is the same as at full speed (see Fig. 7).

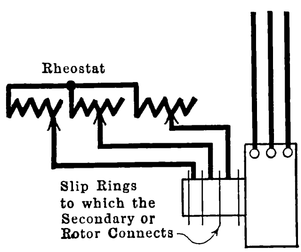

FIG. 8.—Induction motor with wound rotor connected to a rheostat.

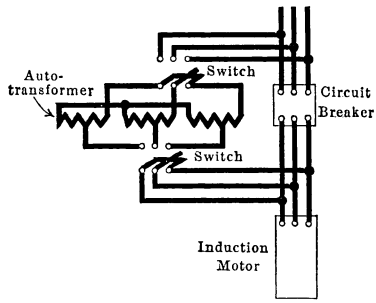

FIG. 9.—Squirrel-cage induction motor with auto-transformers and switches for starting on low voltage.

The diagram shows the theoretical connections. The circuit-breaker is opened by hand before the motor is started. Usually the switches and circuit-breaker are combined so that the change from starting to running position is made by a single switching operation.

The other type of rotor is called a *squirrel-cage.* It has heavy conductors, short-circuited on themselves. If the motor were started at full voltage, the current in the rotor (and also in the stator) would be excessive. The starting voltage is stepped down by auto-transformers as in Fig. 9 (see Chapter VII, page

46; also G. 307, 332). The smaller the starting voltage, the smaller is the starting current. If the voltage is too low, the motor will not start. Table IV gives the starting voltages and the resulting currents that produce certain starting torques. The voltage should be sufficient for starting under the worst conditions; but if it is kept as small as practicable it prevents excessively large starting currents. For example, if in starting, a motor requires 1.1 times its full-load torque, then we find the starting voltage must be 80 per cent. of the full voltage, and the primary of the auto-transformer must take from the line 3.85 times the motor full-load current. In a motor with a wound rotor the current above full-load is nearly proportional to the torque, as shown by Fig. 7, so that it would have started with about 1.1 times full-load current.

Table IV.—Current and Voltage Required for Starting Typical Squirrel-cage Induction Motors at Various Starting Torques

(These figures are subject to some variations, depending on the purpose for which the motor is designed)

Per cent. of full-load torque	Per cent. of full line voltage	Per cent. of full-load current in motor	Per cent. of full-load current in primary leads to auto-transformer
27	40	240	100
60	60	360	220
110	80	480	385
170	100	600	600

5. Speed Regulation.—Ordinary induction motors, whether squirrel-cage or phase-wound, correspond approximately to shunt motors in their speed regulation. This is in accordance with the usual requirements for industrial applications; but as applied to a punch press, for example, there is an advantage in decreasing the speed when the torque is very great. This is accomplished by permanently inserting resistance in the secondary of either a squirrel-cage or a phase-wound motor, as mentioned in a preceding paragraph. This produces a speed characteristic similar to that of a D.C. compound motor, but it is obtained at the expense of efficiency. The more resistance in the secondary, the greater the speed reduction and the less the efficiency.

6. Speed adjustment requires either a special motor whose synchronous speed can be changed (A. p. 977, Multi-speed Induction Motors), or a phase-wound motor with a rheostat to be inserted in the secondary, just as is done in motor starting. The first of these is not used so extensively as the second, although by changing the synchronous speed a high efficiency is maintained, and the speed is very nearly constant. Where the speed adjustment is by the phase-wound motor, the rheostat carries the secondary current continuously—or for as long a time as the reduced speed is required. Such a rheostat must, therefore, have a heavier conductor than one used only for starting. If the rheostat is used for both starting and speed adjustment, the first few steps, which are necessary for a speed adjustment, may be heavy enough for continuous use; but more resistance is required for starting, and the additional steps need only be heavy enough for short-time use.

Motor Applications.—Some of the customary applications of induction motors are listed in Chapter XX, page 167. Table V reviews the special advantage of each motor.

TABLE V.—THE KINDS OF SERVICE FOR WHICH THE SEVERAL A.C. MOTORS ARE PARTICULARLY ADAPTED

Kind of motor	Specially adapted for	Example of application
Phase-wound.....	Large starting torque.	Tube mill in cement plant.
	Hand control of speed.	Elevator.
Squirrel-cage.....	Applications where phase-wound is not necessary.	Wood-working machinery that starts without load.
Synchronous.....	Control of power factor.	Motor-generator set.
	Small starting torque.	Motor-generator set.
	Very constant speed.	Frequency-changing motor-generator set.
Single-phase induction.......	Where only single-phase circuit is available.	Small fans.
25-cycle.........	Very slow speed.	Steel rolling mill.
60-cycle.........	Applications where 25 cycles is not necessary.	Nearly everywhere.

CHAPTER VI

MOTOR-GENERATORS, CONVERTERS AND RECTIFIERS

Electricity appearing in one form is converted to another in a variety of ways:

1. *A.C. is converted from one voltage to another* by an ordinary transformer (see Chapter VII).

2. *A.C. is converted from constant potential to constant current* by a constant-current regulating transformer (see Chapter XIV).

3. *A.C. is converted from one number of phases to another* by a suitable combination of transformers, such as the Scott connection (see Chapter VII).

4. *A.C. is converted from one frequency to another* by a motor-generator set called a frequency changer, in which the generator has not the same number of poles as the synchronous or induction motor, so that the frequency of the generator is different from that of the motor circuit; for example, if a 25-cycle supply is available and a 60-cycle system is desired, a 25-cycle motor is used to drive a 60-cycle generator.

5. *D.C. is changed to A.C.* (*a*) by a shunt motor driving an A.C. generator, or (*b*) by an inverted synchronous converter.

6. *A.C. is changed to D.C.* (*a*) by a synchronous or induction motor driving a shunt or compound generator, (*b*) by a synchronous converter, (*c*) by a mercury rectifier, or (*d*) by a vibrating rectifier.

7. *D.C. is changed from one voltage to another* (*a*) by two machines comprising a balancer-set, connected in series across the higher voltage, with a neutral or low-voltage lead brought out from the connection between machines; (*b*) by a three-wire generator which is provided with one or two coils by which the neutral voltage of a three-wire system is established; (*c*) by a motor-generator set in which the motor and generator are designed for different voltages; or (*d*) by a dynamotor consisting of a machine having two distinct circuits—one for the higher and one for the lower voltage, each circuit having its own complete winding and commutator.

This list includes only the conversions that are most frequently seen in industrial plants, and only the means most frequently employed for making them. The first three of the conversions listed are accomplished by transformers, and are discussed in Chapter VII. The fourth, frequency changing,[1] and the fifth, converting D.C. into A.C.,[2] are not discussed further, because they are comparatively rare. We shall consider the sixth and seventh in this chapter.

6. Converting A.C. to D.C. is most often desirable where a relatively long line requires A.C. transmission, and a storage battery or a number of variable-speed motors call for D.C. applications. Each of the means of conversion has its advantage, and is the best to use in certain cases.

(*a*) *A motor-generator set* may consist of either a self-starting synchronous or an induction motor, and either a shunt or a

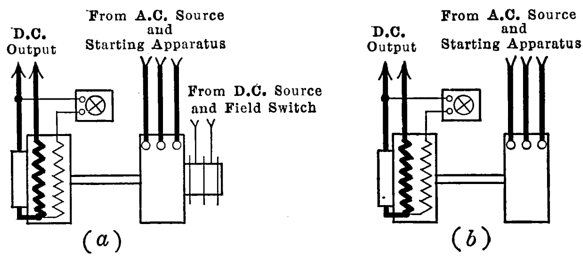

FIG. 10.—Motor-generator sets.

(*a*) Synchronous motor-generator set, requiring connection to D.C. for field excitation. It may be started by an additional induction motor winding. (*b*) Induction motor-generator set, having a squirrel-cage motor, which requires no connections to the rotor.

compound generator.[3] The induction motor is more rugged and more easily started, and does not require synchronizing nor D.C. field excitation. The synchronous motor can be operated at unity power factor or with a leading current, and has no speed variation between no-load and full-load. Large motors of either kind, with suitable windings, can be connected to the line without transformers, if the line voltage is not over 13,200. For small motors the voltage must be lower. Self-starting synchronous motors are usually used in motor-generator sets of 500 kw. or more; induction motors are ordinarily used for 100 kw. or less on account of their simplicity; and between 100 and 500

[1] S. 7 : 346–369; A. pp. 951, 952.

[2] S. 9 : 95–102 A. p. 280.

[3] Chapters V and XII; also G. Chapter XXXIX; S. 7 : 335–345; A. p. 950.

kw. either motor may be used, depending on conditions under which it is used. Diagrams of the connections of the two kinds of motor-generator sets are given in Fig. 10.

(*b*) *A synchronous converter* has advantages over a motor-generator set, in that the cost is less and the efficiency higher, especially if transformers are used in both cases.[1] It has the disadvantages of inflexibility: the ratio of D.C. to A.C. voltage is nearly constant (see Chapter III), and the power factor cannot be varied through any considerable range.[2] To overcome these difficulties, the synchronous booster-converter has been developed.[3] It con-

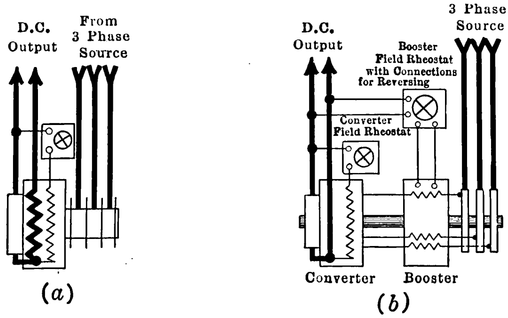

FIG. 11.—Synchronous converter with and without a booster.

(*a*) Three-phase synchronous converter. With this connection it can be started from the D.C. end. Special field connections are necessary for self-starting from the A.C. end. (*b*) Three-phase synchronous booster converter, showing A.C. connections from the three-phase source through the booster, to the converter. The rheostat can be manipulated so that the field current flows in either direction, and the boosting is either positive or negative.

sists of a synchronous converter direct-connected to an A.C. generator which is used as a booster. This combination costs somewhat more than the synchronous converter alone, but less than the motor-generator set. Its efficiency is nearly as high as that of the synchronous converter, and it has the voltage flexibility of the motor-generator set. The external connections of these machines and some of the internal connections of a synchronous booster-converter are shown in Fig. 11.

[1] For data, applications and operation see G. Chapter XXXIX; S. 9: 38–84; A. pp. 279, 280, 290, 291.

[2] A. p. 950: Induction motor driving D.C. generator.
p. 279: Synchronous converter *versus* motor-generator.
S. 9: 55–61 Comparison of motor-generator sets and synchronous converters.
7: 332 Flexibility of motor-generator.
12: 63 Efficiencies, costs and floor space.

[3] S. 9: 20 The synchronous booster-converter.

(*c*) *A mercury vapor rectifier* consists essentially of a receptacle containing mercury vapor, connected to a single-phase or polyphase source, from which the mercury vapor causes the selection of a current flowing in only one direction.[1] Its best application at the present time is to circuits of 110 volts or more, and relatively small currents. Rectifiers are made for use in connection with series lighting circuits, for as many as seventy-five 6.6 amp. arc lamps, but they are more often made to be connected to 110- or 220-volt A.C. circuits, for charging batteries at D.C. voltages from 2 to 120, and currents from 5 to 50 amp. A simple diagram of a mercury vapor rectifier is shown in Fig. 12.

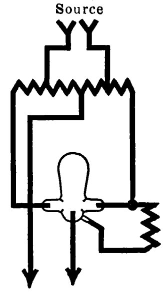

FIG. 12.—Mercury vapor rectifier.

The A.C. source connects through an auto-transformer to the rectifier. The zig-zag line in the lower right-hand corner of the diagram represents a resistance leading to a starting terminal.

(*d*) *A vibrating rectifier* accomplishes mechanically what the mercury vapor does by other means—it has a vibrating contact that closes, at such times that the current can flow in only one direction.[2] This rectifier is made for low voltage only, at which the efficiency of the mercury vapor rectifier is very low. It is connected to a 110- or 220-volt single-phase circuit, and delivers as much as 8 amp. to three lead storage cells in series. The external connections of a vibrating rectifier may be represented as in Fig. 13.

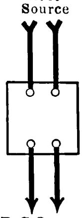

FIG. 13.—Vibrating rectifier.

While there is some overlapping in the application of these converting devices, each has certain features peculiar to itself that adapt it to certain kinds of service: (1) If a transmission line has a large voltage drop, a motor-generator set or a synchronous booster-converter will probably be the best choice, because the D.C. voltage can be maintained constant with fluctuating A.C. terminal voltage. If the power factor of the line current is low, the motor field of the synchronous motor-generator set can be over-excited, to produce a leading current, and raise the power factor. (2) Where line drop is low and power factor high, the ordinary synchronous converter can be used to advantage, because it

[1] G. 388; S. 6 : 269–281; A. pp. 1209, 1210.
[2] S. 6 : 289–295; A. p. 1211.

is more efficient and a little less expensive, especially if it requires no additional transformers. (3) For smaller currents, the rectifiers have their field of usefulness, the mercury vapor rectifier being suited to all voltages above the 8 or 10 volts required for charging three lead storage cells. Table VI. shows the efficiency of the various means for converting, under the conditions for which they are adapted.

TABLE. VI.—COMPARISON OF EFFICIENCIES OF THE SEVERAL KINDS OF CONVERTING AND RECTIFYING APPARATUS.

Apparatus	Kw.	Amperes in D.C. circuit	D. C. voltage	Approximate efficiency at full-load (per cent.)
Motor generator set..........	2 to 10 15 to 300			70 80
Synchronous converter or synchronous booster converter.......	2 to 10 15 to 300			85 90
Mercury vapor rectifier, constant potential		5 to 50 5 to 50 5 to 50 5 to 50	15 50 110 220	50 75 85 90
Mercury vapor rectifier For constant current circuits...		4 6.6	Up to 5500 Up to 4000	Up to 95 Up to 95
Vibrating rectifier......		8	5 to 10	55

7. Raising or Lowering D.C. Voltage.—There are several conditions requiring a change of D.C. voltage. Those most frequently found in practice, on constant potential circuits, and the means employed in producing the change are as follows:

Three-wire System for Lighting Circuit.[1]—The most satisfactory voltage for arc and tungsten lighting is 110 volts. This voltage is too low for satisfactory distribution in a large industrial plant, in which the motors are usually operated on 220 volts. The

[1] G. 368; S. 13: 82, 83; A. p. 366.

generators furnish power at the motor voltage, and some means is to be provided for furnishing the lower voltage to the lamps. If the lamps are adapted to one-half the motor voltage, they may be connected from one of the lines to neutral. A *balancer-set* may be installed as indicated in Fig. 14, to keep this voltage actually neutral—that is, midway between positive and negative.[1] This set consists of two shunt or compound machines that are exactly alike, direct-connected mechanically, and connected electrically in series across the outside lines. The neutral line connects to a point between the two armatures.

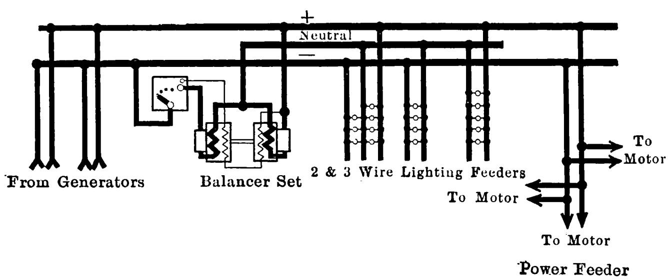

FIG. 14.—Balancer set on D.C. 3-wire system.

When the lamp load is exactly balanced—that is, when the current flowing from the positive line is the same as that flowing to the negative—there is no current flowing back in the neutral wire, and the two machines of the balancer-set float on the line as idle motors. But if more or larger lamps are on one side of the line than on the other, the joint resistance of lamps on that side is less. As a result, the voltage across that side would drop, and that across the other side would increase, except for the balancer-set, which keeps the neutral wire at or near actual neutral voltage, allowing the unbalanced portion of the current to return through the neutral and the balancer-set, instead of flowing through the lamps. With this unbalanced condition of the load, the machines are running, one as a generator furnishing the unbalanced current to the side requiring more; and the other as a motor driving the generator. If each of the machines has a series winding, the connections can be made as shown, so that the current of the neutral wire flows in such directions through the series fields as to decrease the voltage on one side and to increase

[1] G. 347; S. 8: 224, 225; A. p. 375.

it on the other, compensating for *RI* drop in the neutral line and armature.

Instead of the balancer-set, a *three-wire generator* may be employed, as in Fig. 15.[1] The generator itself is essentially a two-phase synchronous converter. Each balance coil is simply a coil of large reactance connected by slip-rings across one of the phases. On account of the high reactance, the alternating current flowing through the coil from one slip ring to the other is negligibly small. The middle points of the two coils are at neutral voltage; they are connected together, and to the neutral line. Since direct current is not affected by reactance, it can flow readily in the neutral line, either to or from the generator. Sometimes only a single balance coil is used, and is connected to single-phase slip-rings. In Fig. 15 the slip-rings and the commutator are shown at opposite ends of the armature. Frequently the two are at the same end, but the operation is unchanged.

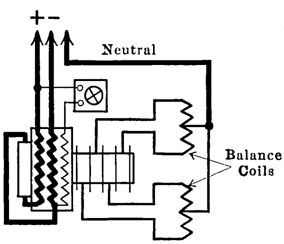

Fig. 15.—Three-wire D.C. generator and balance coils.

Multiple Voltage for Motor-speed Adjustment.[2]—A three-wire circuit such as has just been described for lighting purposes can be used for motor-speed adjustment. When the armature is connected from one line to neutral the speed is practically one-half that when it is across the outside lines. Further speed control is obtained by a field rheostat, as stated in Chapter IV, page 25.

Ward Leonard and Ilgner Systems for Motor-speed Adjustment.[3]—The Ward Leonard system may be considered as a refinement of the multiple-voltage system. It is limited to the few cases where the fine adjustment obtained is worth the cost. The motor whose speed is to be adjusted has its field excited from a constant-potential source, and its armature is connected to the generator armature of a motor-generator set. Thus in Fig. 16, motor *A*, which is connected to the constant-potential source, drives generator *B* at constant speed. Rheostat *R* controls the voltage of the generator. Motor *C*, whose speed is to be adjusted, has a constant current in its field, and a variable

[1] G. 348; S. 8: 190-199.
[2] G. 129; S. 15: 448; A. p. 966.
[3] G. 130; S. 7: 341–345; S. 15:99–107; A. p. 976.

voltage across the armature, depending on how much of the resistance of rheostat *R* is in the circuit. The motor speed depends on its armature voltage and is thus controlled by the generator field rheostat. The direction of rotation of the motor is reversed by reversing the field connections to the generator. Sometimes motor *A* is an induction motor, but motor *C* and generator *B* are always D.C. machines.

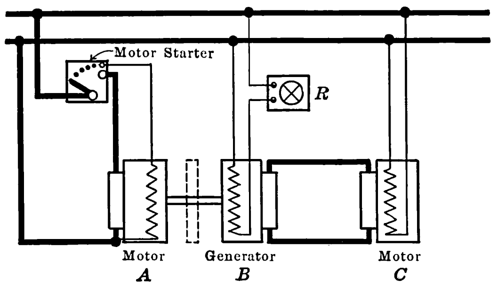

FIG. 16.—Ward Leonard system of motor speed control.
Motor *A* is sometimes an A.C. motor. The Ilgner system is similar to this, having a fly-wheel, as shown dotted, driven by motor *A*, which is usually an A.C. motor.

The Ilgner system is similar to the Ward Leonard; in addition there is put on the shaft of the motor-generator set a flywheel that gives up its energy when the motor-generator set slows down. This system is used for hoisting, and is subject to short, heavy peak loads. As usually installed, motor *A* is a slip-ring induction motor, and *B* and *C* are D.C. machines. The speed of motor *A* is controlled by an automatic device to utilize the energy in the flywheel when the peak loads come; and the speed of hoisting by motor *C* is controlled by the generator field rheostat.

Boosters for Battery Control, and Line-drop Compensation.[1]—A booster is merely a generator used to raise or lower the line or other voltage when it is necessary. It is used to raise or lower the voltage of a battery circuit, so as to make the battery charge or discharge more strongly than it would if it were floating on the line without the booster. A booster is also used to raise the voltage on a long feeder, in which the voltage drop would otherwise be excessive.

[1] G. 204–209, 346; S. 8: 184; S. 12:86; S. 20:147–160, 165, 166; A. pp. 97-100.

The voltage of the booster, which is superposed on the battery or line voltage, may be regulated either by hand or automatically. If it is regulated by hand, the field circuit is connected through a field rheostat, across the line. The machine is then called a shunt booster. If the operation is to be automatic, at least one winding of the booster is in series with the circuit that controls the booster voltage. For example, for compensating for line drop the field coil of the booster is in series with the line; and for maintaining approximately constant current in the generator, a booster field winding is in series with the generator. There are a number of ingenious arrangements used in connection with battery charging and discharging, that make the battery take a part or practically all the fluctuation of the load on the line, so that the load on the generator can be made to remain practically constant.

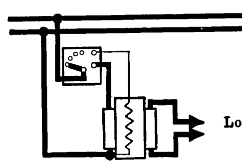

Fig. 17.—Dynamotor for delivering very low voltage.

Very Low D.C. Voltage.—A dynamotor[1] is especially suited for supplying a heavy current at a very few volts; for example, for some electrolytic work. As shown in Fig. 17, a commutator at one end connects to the higher D.C. voltage—usually 110 or 220 volts. This commutator and the corresponding winding serve as a motor element, driving the machine at constant speed. Another commutator at the other end, and its low-voltage winding, serve as the generator element. The high- and low-voltage windings are entirely distinct, but are laid in the same slots and revolve in the same field.

[1] S. 9: 126–133; A. p. 382.

CHAPTER VII

TRANSFORMERS[1] AND AUTO-TRANSFORMERS

The original use of transformers was to step the A.C. voltage up at the beginning, and down at the end of a transmission line. Since the original applications, new applications of that type of transformer have been made, and various other kinds of transformers have been applied to new uses. We shall consider several of the more important applications, beginning with the original step-up and step-down transformers.

Applications and Operation of Transformers.—Transformers for stepping up the voltage are unnecessary if the generator voltage is high enough; but it pays to build small generators for relatively low voltage and to step the voltage up, rather than to build small generators for very high voltage.

Voltage and Ratio.—A transformer should not be put across a voltage much above its rated voltage, because if the amount of iron has not been generous, the resulting magnetizing current may be excessive. Too high voltage also endangers the insulation; but the magnetizing current, rather than the insulation, usually limits the voltage. If the line voltage is lower than the transformer rated voltage, no harm is done except that in extreme cases the voltage regulation and efficiency are poor, and the kva. capacity goes down with voltage.

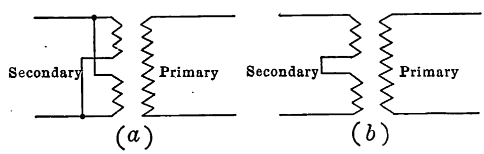

FIG. 18.—Transformer with the secondary winding in two equal sections. In (a) the sections are in parallel, and in (b) in series. Sometimes the primary winding is also in sections, which may be either in parallel or in series.

[1] G. Chapter XXXIV, Characteristics; XXXV, Connections.

S. 6:85–126; 133–135; 137–145; 147–149; 155–161, Characteristics, data and connections. S. 10: 837–849, Applications.

A. pp. 1606–1610, Classification and Theory. 1612–1617, Connections. 1632–1637, Applications, weights and costs.

See Chapters XIV and XV, Regulating and Instrument Transformers.

To guard against applying to wrong voltages, it is well to express the ratio in actual volts, as 2,200/110, rather than to make the numerator or the denominator unity, as 20/1 or 1/20. If a 2,200-volt transformer be put on a 2,500-volt circuit the operator will then know that the magnetizing current will be excessive.

Some transformers are provided with voltage adjustment, which is in one or more of four ways: (*a*) The secondary is divided into two or more equal parts, which are to be connected either in parallel, as in Fig. 18*a*, or in series, as in Fig. 18*b*, depending on the required secondary voltage. (*b*) Several leads are brought out from points a few per cent. from one end of the secondary winding, as in Fig. 19. Of course the methods of Fig. 18 and Fig. 19 cannot be combined, unless *both* windings in Fig. 18 are provided with additional leads shown in Fig. 19. (*c*) The primary is divided into equal parts, as the secondary is divided in Fig. 18. (*d*) Primary leads are brought out as in Fig. 19.

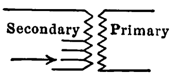

FIG. 19.—Transformer with several secondary leads brought out for adjustment of voltage.

Similar leads are sometimes brought out from the primary.

The application of transformers with extra leads, such as the foregoing, must be with due care. Unless there is definite information to the contrary, the transformer should not be put on a line of the highest rated primary voltage, unless the primaries are in series, and all or nearly all the end turns are in circuit; it should be assumed that primary end turns are intended for adjusting for low primary voltage.

Capacity in Kva.—The product of the voltage times the current in a single-phase circuit is called the *apparent power*, and is expressed in volt-amperes.[1] This is the same as the power in watts, if the power factor is at 100 per cent., but at lower power factors the number of volt-amperes is greater than the number of watts. This unit and the *kilovolt-ampere* (= 1,000 volt-amp.) are used to designate the capacity of A. C. apparatus to transform or deliver current at a given voltage. Transformers and A.C. generators are regularly rated in kilovolt-amperes (abbreviated to kva.), rather than in kilowatts, because a kilowatt rating has no definite significance unless the power factor is given. If the current is balanced on a polyphase circuit, the

[1] G. 246; S. 24:27; A. p. 1298.

same relation exists as on single-phase, between watts and volt-amperes. Thus, we have,

On a single-phase circuit kva. = kw./$P.F.$ = $EI/1{,}000$
On a two-phase circuit kva. = kw./$P.F.$ = $2EI/1{,}000$
On a three-phase circuit kva. = kw./$P.F.$ = $\sqrt{3}EI/1{,}000$

where E is the voltage between lines and I is the current per line leading to the transformer or group of transformers. It is at once evident that to get the maximum power from transformers and other similar equipment, they should deliver power at as high a power factor as possible.

If a transformer is used only intermittently, it will deliver safely much more than the rated kva. output, for the short time (see Chapter XX, p. 183).

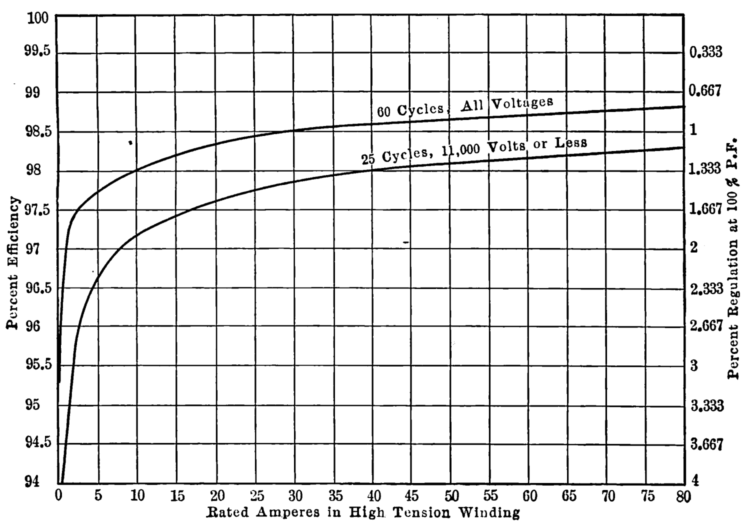

FIG. 20.—Curves showing full-load efficiency and regulation of typical transformers.

Efficiency.—Fig. 20 shows how transformer full-load efficiency depends on the current capacity of the high-tension winding. These curves are based on data on about 100 typical transformers of voltages from 2,200 to 110,000, and are correct in most cases within 0.1 per cent. or 0.2 per cent. It will be seen that the losses in transformers made for 25 cycles are nearly 1.5 times those for 60 cycles. The variation of efficiency with load in a typical transformer is illustrated in Fig. 21. In some transformers full-load is a little nearer the point of maximum efficiency than is indicated on this curve.

Regulation.—The per cent. regulation is the per cent. ratio of the change in secondary voltage between no-load and full-load to the transformer rated secondary voltage.[1] Fig. 20 shows the regulation, as well as the efficiencies of typical transformers, when the load is at 100 per cent. power factor. At other power factors the regulation is poorer than at 100 per cent. In a transformer having a high-tension voltage of 13,200 or less, with

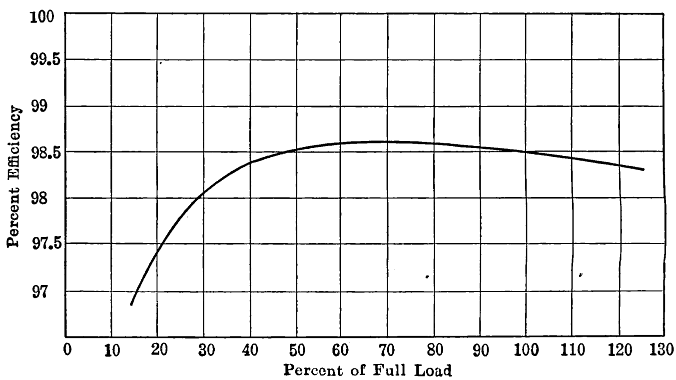

FIG. 21.—Curve showing variation of efficiency with load in a typical power or lighting transformer.

a lagging current, the regulation at 80 per cent. power factor is usually between 2 and 3 per cent. With a leading current at 80 per cent. power factor, the regulation is not far from zero.

Frequency.—The weight and cost of a transformer are greater for low than for high frequencies (see Chapter III, p. 17). A transformer designed for a given frequency can be used on a circuit of a higher, but not of a lower frequency, at the same voltage.

An auto-transformer[2] is a transformer in which the primary and secondary are combined in a single circuit, as in Fig. 22*a*, where the primary is connected across *AB* and the secondary across *AC*, or *vice versa*. The winding from *A* to *C* is common

[1] S. 24:560, 565; A. pp. 1327, 1328.

[2] G. 307, 332, 333.
S. 6:173–178, 180, 181.
A. pp. 63–65.

to both primary and secondary and that from C to B is in only the circuit of the higher voltage—which we will call the primary.

The advantage of an auto-transformer over a transformer is seen by comparing Fig. 22*a* with *b*. Neglecting all losses and the reactance drop, the apparent watts input equal the output. If the *auto-transformer* is used to step down from 110 to 100 volts, and is to deliver 11 amp., the current taken from the primary line must be 10 amp. Winding CB must carry 10 amp., and winding CA must furnish the other 1 amp. Thus, winding CB is for 10 volts $\times$ 10 amp., or 100 volt-amp., and winding CA

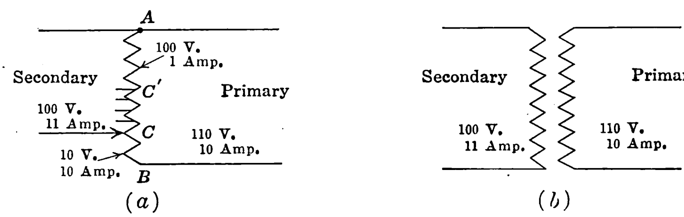

FIG. 22.—Auto-transformer and transformer, with primary voltage higher than the secondary.

If the contact at C is movable, and leads are brought out from suitable points in the winding, any desired secondary voltage can be obtained, between the primary voltage and zero. If the primary and secondary are interchanged, the secondary voltage is higher than the primary. Such a connection must be made with care, to avoid too high a voltage for the shorter winding.

is for 100 volts $\times$ 1 amp. or 100 volt-amp. But each winding of a *transformer*, as in Fig. 22*b*, must be for 1,100 volt-amp.; so that the required size of the auto-transformer is only one-eleventh that of the transformer to do the same work.

One can readily see also that the efficiency of transformation is much higher in the auto-transformer than in the transformer, because the losses are very small—in the case above, corresponding to the losses in a transformer of one-eleventh the size that would be required for ordinary transformation.

The advantage in size and efficiency is less marked, when the ratio is farther from unity. In the case of Fig. 22, with the same primary voltage, if the output were at 11 volts, instead of 100, the volt-ampere capacity of the auto-transformer windings would be nine-tenths of that of the corresponding transformer.

One of the most important applications of auto-transformers is to starting squirrel-cage induction motors. This is better than to use rheostats, because less power is wasted. It is better than to use ordinary transformers, because the auto-transformers are smaller and less expensive.

3. Grouping of Transformers.—The only groupings of transformers that we shall consider are some of those on three-phase circuits. Two-phase combinations are omitted because they are comparatively simple, and require no explanation except what is given in this chapter with reference to the Scott connection. Six-phase connections are important for those who have to do with large synchronous-converter substations; but they are little used elsewhere.

Several of the more usual groupings of transformers are illustrated in Fig. 23. Of these, the *delta connection*, Fig. 23*a*, is used more than any other,[1] for ordinary transformation.

Perhaps the greatest advantage of having a delta connection in both primary and secondary is that in case of breakdown of one transformer, it can be removed, and the group can continue to operate with a *V-connection.* The two remaining transformers will be carrying a 73 per cent. overload, if they deliver the same power as was required of the three at full-load, but if the load is cut down to 58 per cent. of the original full-load, the two are only carrying normal load. This fact holds true, not only for a group of three single-phase transformers, but also for a three-phase transformer, if one phase is out of commission. In a three-phase core-type transformer care must be observed that there are no dangerous loose ends in the broken-down phase of the transformer; for there is full voltage in all phases, even though both primary and secondary of one phase are entirely disconnected from the system. The voltages are not as well balanced, and the efficiency of transformation is lower with the V than with the delta connection.

The Scott connection is illustrated in Fig. 23*h*. Two transformers are T-connected to a three-phase circuit; and the other windings of the transformers are connected to a two-phase circuit. This connection is suitable for transforming either from three- to two-phase or from two- to three-phase.

To appreciate the importance of this somewhat familiar connection, imagine a machine shop in a city such as Philadelphia or New York, in which two-phase power has been obtainable for

[1] Except on very high voltages where the Y-connection is used on the high-tension side; the low-tension side may even then be delta-connected. See Fig. 23*b* and *d*.

a long time. Suppose that a change in management of the electric power company results in changing from a two-phase to a three-phase system. It is only necessary to install a pair of Scott-connected transformers, to continue the two-phase system

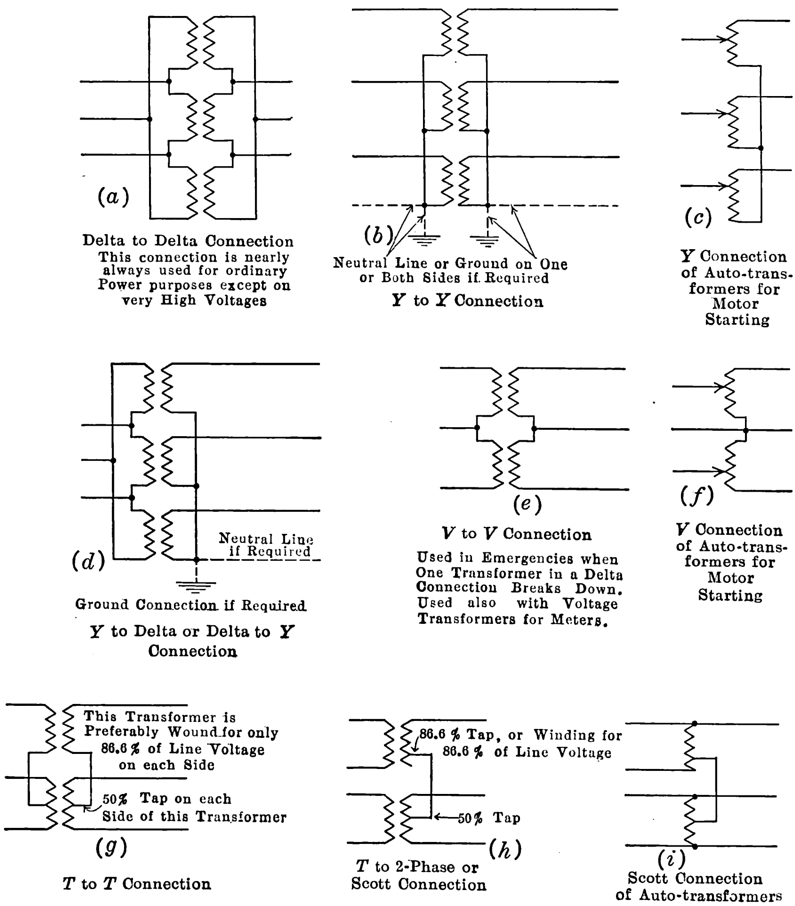

FIG. 23.—Transformer grouping.

in the shop; whereas without this connection or its equivalent, it would be necessary to take out every two-phase motor in the shop and replace it by a three-phase motor, costing from $100 to $1,000 for every motor changed.

The Scott connection may be employed to step the voltage up or down, or to transform with no change in voltage. If the two voltages are the same, or nearly the same, auto-transformers may be used; there must then be no other electrical connection between the two phases of the two-phase circuit. The auto-transformer connections for equal two-phase and three-phase voltages are shown in Fig. 23*i*.

CHAPTER VIII

STORAGE BATTERIES[1]

COMPARISON OF TYPES OF STORAGE BATTERIES

The storage cells used in practice are of two kinds. One of these is the lead cell, whose electrodes are lead and lead peroxide, and whose electrolyte is dilute sulphuric acid. One form of lead cell has "*pasted*" plates, in which the active material is added in the form of a paste. Another has "*Planté*" plates which are formed electrochemically by putting them in the electrolyte and passing a current repeatedly first in one direction and then in the other. A third form of lead cell is the "*Ironclad*," whose positive plates are made up of a series of hard-rubber slotted tubes containing the active material. Besides these lead cells are the alkaline cells. The Edison storage battery is of this type, and is the alkaline battery in most general use; it has caustic potash for the electrolyte, and nickel peroxide and iron for the electrodes. So much depends on the size and kind of installation, and the treatment the battery receives, that the following information must be taken only as a general guide, subject to large corrections in individual cases. Among the more important considerations are the following:

Cost.—Alkaline batteries cost about $80 per kw.-hr. capacity; portable lead batteries with pasted plates cost $30 to $55 per kw.-hr. capacity. The cost of stationary batteries with Planté plates is 1.5 to 2 times that for pasted plates, depending on size, liberality of construction and various other details. It is not enough higher to warrant the use of pasted plates where the more

[1] G. Chapter XXIII, Characteristics; Chapter XXV, Applications; Chapter XXVI, Train Lighting.

S. 20: 43–233, Characteristics and Applications; 10: 898, 900 Depreciation; 12: 77–79 Stationary Installations; 17: 62–84; 22: 67–85 Vehicle Batteries and Charging; 22: 292–298 Train Lighting Systems.

A. Lead Batteries pp. 103–119; Alkaline Batteries pp. 77–86; Applications pp. 87–102.

durable Planté plates can be put in small enough compass, except for "stand-by" batteries, and others used infrequently.

Space Occupied and Weight.—The net space occupied by an Edison battery is about 0.7 cu. ft. per kw.-hr. of energy to be stored. That of a portable lead cell with pasted plates is from 0.5 to 0.7 cu. ft., and that of a lead cell with Planté plates about 1.5 cu. ft. per kw.-hr. The weight of the Edison battery is about 75 lb. per kw.-hr., the lead battery with pasted plates 65 to 125 lb. and with Planté plates about 200 lb. The volume and weight of lead cells varies considerably depending on liberality of design, kilowatt-hour capacity, and kind of retainer, as well as on kind of plates.

Durability and Repairs.—The Edison battery is thoroughly guaranteed by the manufacturers, for a length of time depending on the conditions under which it is to operate. The time of this guarantee is usually 4 or 5 years. Lead cells with pasted plates for portable service are much less rugged: their life depends on how much their durability has been sacrificed to make them light, as well as on the kind of treatment they have. With reasonable care they can be fully charged and discharged from 300 to 500 times. Cells with Planté plates for stationary service, on account of more rugged construction, more liberal design, and more favorable conditions of operation, last with good care from 5 to 10 years. Pasted plates, under similar conditions, need not be very much shorter lived. Planté plates are used in train lighting, which is between the portable and stationary installations as to favorable conditions. Their life is about 40 per cent. of that of the stationary batteries.

Annual cost for maintenance and repairs of portable batteries (not including cost of charging) is $10 to $20 per kw-hr. capacity for Edison batteries and about $25 for lead cells with pasted plates. Train-lighting batteries are so well constructed that maintenance and repairs need not be over 10 to 20 per cent. of that of other portable batteries. Stationary batteries, well-installed and properly cared for, require no allowance for maintenance and repairs that cannot be included in ordinary attendance, together with the allowance for replacing them.

The current-discharging rate of a *Planté lead cell* for stationary use is usually such that the battery discharges in 8 hr.; that is, a 600-amp.-hr. battery would normally deliver 75 amp. for 8 hr. If such a battery is called upon for more than 75 amp., the time is so much reduced that the total ampere-hour capacity is less. Table VII shows the maximum time of discharging, and the ampere-hour capacity, at various currents.

TABLE VII.—AMPERES AND AMPERE-HOURS OF PLANTÉ LEAD STORAGE BATTERIES ON HEAVY DISCHARGE

When the discharge rate is	The battery will deliver that current for	That is, at that current it is capable of delivering per cent. of rated ampere-hours
1 × normal amp.	8 hr.	100
2 × normal amp.	3 hr.	75
3 × normal amp.	1 hr. 35 min.	60
4 × normal amp.	1 hr.	50
6 × normal amp.	30 min.	37
8 × normal amp.	20 min.	33

It should be noted that these percentages indicate the relative *capacity* of the battery at various currents. They are not the same as efficiency, although the efficiency does drop off very much with increase of current.

For *pasted lead cells* with thin plates, suitable for vehicle use, the decrease in capacity on overload is not so great as with Planté plates. If they are discharged in 1 hr., their capacity is 60 per cent. of that in 8 hr.; if discharged in 2 hr. the capacity is 75 per cent. of that in 8 hr. For other times of discharge the percentage is correspondingly higher than in the table. Pasted cells for portable use are not always rated on an 8-hr., but frequently on a 5- or 6-hr. basis.

For *Edison cells* the ampere-hour capacity is practically the same at all rates of discharge. Their current rating is regularly based on discharging in 5 hr.; *i.e.*, the ampere-hour capacity divided by 5.

The Current-charging Rate.—The most approved method of charging *lead cells* is to give the battery a "tapering charge"—that is, starting the charging at a high rate and gradually reducing the current. The charging rate starts at from 1 to 2 times the normal discharge rate, and finishes at ½ to ¾ of the normal discharge rate. The best charging of *Edison cells* is at a steady rate, equal to the normal discharge rate.

Voltage.—The discharge voltage of a lead cell is about 2 volts, and that of an Edison cell about 1.2 volts, when the cells are discharged at their normal rates. Fig. 24 shows how the voltage drops off during discharge at normal current, and also during discharge that is so rapid that the cell is discharged in 1 hr. It also shows the voltage required for charging at the normal rate. At higher rates of charging, the voltage is a little higher; but if the generator voltage is high enough for the final charge at the normal rate, it will be ample for the initial charge at a

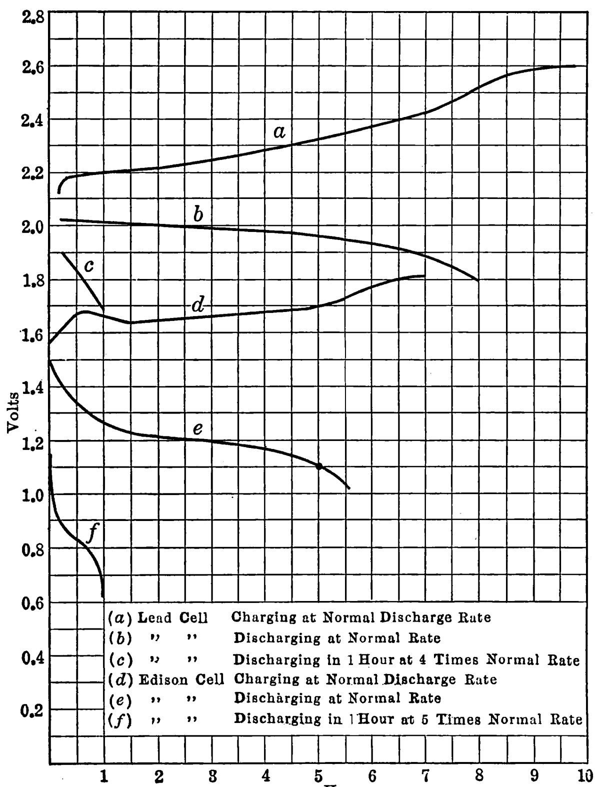

FIG. 24.—Voltages of storage cells during charging and discharging.

higher rate. The lead-cell voltages in Fig. 24 refer primarily to cells of the Planté type, but they apply rather closely to all kinds of lead cells, if the discharge rate is on the 8-hr. basis.

Efficiency.—The efficiency of a storage battery varies greatly with the rate of charging and discharging. In ordinary service, portable Edison batteries have a watt-hour efficiency of 40 to 50 per cent., and portable lead batteries 65 to 75 per cent. The ampere-hour efficiencies of the same batteries are 60 to 70 per cent. for Edison, and 80 to 90 per cent. for lead batteries. On very heavy loads, the watt-hour efficiency drops even lower than the lowest values given, and on very slow discharge rate it rises even higher than the high values.

APPLICATIONS TO STATIONARY SERVICE

Since space and weight are not of vital importance, it is not necessary to sacrifice ruggedness. The combined qualities of durability, high efficiency and relatively low cost of the Planté

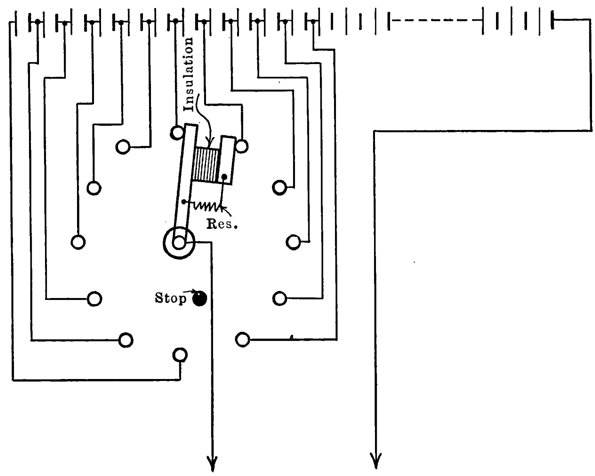

FIG. 25.—End-cell switch connected to storage battery.

cell gives it first place in common use for stationary service, although pasted plates also prove satisfactory. However, if a battery is to be discharged infrequently, even at very high rates, it is more economical to install pasted plates, as their life compared with that of Planté plates is a matter of discharges, and not of time. Several of the more common applications of batteries may be mentioned:

In the generating station a battery may be installed in parallel with the generators. Its main purpose is to relieve the generators at certain times, but it may also serve to maintain constant voltage. Such a battery may take the instantaneous fluctuations in the load current; or it may furnish a part of the steady power output of the plant when the station is overloaded, or when one generator may thereby be shut down; or it may furnish all the power in an emergency or when the load on the plant is light enough to shut down all the generators.[1]

The internal drop in the battery is so great that it will not of its own accord furnish current for the instantaneous fluctuations, but an automatic booster in series with the battery may be excited by a field winding in series with the generator, in such a way that practically all the fluctuations in line current come from the battery.

For taking a steady load, it is not necessary that the battery be provided with an automatic booster. A shunt booster may be used whose field rheostat is operated manually; or an end-cell switch such as is illustrated in Fig. 25 may be operated manually or by an automatic device, to make the battery carry the fluctuations of the load.

In a battery substation, if the voltage drop on a feeder is excessive, a battery may be connected to the feeder near its end, to keep the voltage more nearly constant. A study of the battery characteristics at various charging and discharging currents will show how great voltage variation exists when the battery is doing its part to maintain a constant voltage. If closer regulation is required, a booster or an end-cell switch may be employed. The battery should be located far enough out on the feeder to keep up the voltage at the end; but the drop at intermediate points should not be excessive on account of having the battery too far out on the feeder. A study of the distribution of the load, and the characteristics of the battery, will indicate the most desirable location.

On circuits that are entirely distinct, or connected through resistance, batteries are used for various purposes. If there are wide fluctuations of the voltage on the power circuit, a storage battery may be first charged and then used for lighting, or for laboratory or other *purposes requiring a more constant voltage.* This requires a separate period of charging, and perhaps some attention to voltage regulation. To avoid these difficulties the battery may be connected to the line through a rheostat. The higher the resistance of the rheostat, the less effect will fluctuations of line voltage have on battery voltage, but the resistance and the number of cells must be small enough to keep the battery charged.

Besides use for obtaining very constant voltage, such a battery

[1] For connections see footnote, p. 51.

may be used *to insure a voltage when there is no generator voltage.* For example, a circuit-breaker should operate without fail when an accident reduces bus and line voltage to approximately zero, but this is just the condition under which it cannot operate if it has a trip-coil (see Chapter XVII, p. 135, Fig. 65), operating on generator voltage. Another important application is to lighting and other circuits that require power, 24 hr. per day, where the generator runs only during the daytime.

Still another important application is to apparatus requiring *small amounts of power at low voltage.* Small motors, bells and other small equipment are sometimes better adapted to a few storage cells than to higher voltages. Even the three-wire system for lighting may be included in the same class. The neutral voltage can be established by the middle point of a battery that connects across the entire line.

APPLICATIONS TO PORTABLE SERVICE

Batteries used for portable service should be as light and compact as possible, and at the same time they should be as efficient and durable as possible, and they should not be unnecessarily expensive. Obviously not all these conditions are obtainable to the fullest extent in any one kind of battery. Referring to the advantages of the various kinds of batteries; as already stated, we find that an Edison battery is light and durable, but is not quite so compact as the most compact lead cells, nor so efficient as lead cells, and it is more expensive. The several advantages and disadvantages must be weighed in each case, and those that are most important will usually dictate the battery to be used. Lead cells with Planté plates are little used for portable service, because their only claim of great advantage over the pasted plates is in durability; durability must be sacrificed in portable batteries, in favor of less bulk and weight. The exception is in train-lighting batteries, which are not subject to these restrictions to the same extent.

The voltage of portable batteries is usually less than 110 volts and depends on the amount of power to be delivered. There are no standards of voltage that are now in universal use, but the following have been found satisfactory in a great many cases, and are gradually being adopted as standards:

	Volts
Automobile ignition, lighting and starting	6
Electric automobiles	60 to 85
Battery locomotives	80 to 240
Battery trucks	24 to 60
Car lighting (batteries fully charged, 32 and 64 volts) nominal voltage	30 and 60

The amount of power required for each purpose varies somewhat, but not greatly, from the following:

	Watts
Automobile lighting:	
Headlights, two to be provided	each, 15
Side lamps, two to be provided	each, 3
Tail lamp, one to be provided	each, 3
Other lighting, if desired, need not exceed	15
Gas engine ignition	3
Automobile electric starting, small automobile	500
Average automobile	600 to 700
Large automobile	1,000
Railway car lighting:	
Pullman sleeper, 16 section	1,600
Coach	500
Mail car, 60-ft	650
Baggage car	300
Dining car	1,600

Automobile Lighting, Ignition and Starting Power.—Automobiles that are not self-starting require very small battery power for lighting and ignition. For self-starting, according to the above table, much more power is required, but even in that case the three-cell battery is sufficient. The large amount of power required for starting is used for only a very short time, so that it is allowable to overload the battery. It is accepted practice to furnish a battery of such size that it will deliver the required power for starting for a period of 20 min. A lead battery made for this purpose, with thin pasted plates, will deliver for 20 min. six or seven times the current that it will for 5 hr., at an average of 85 per cent. of the *initial* voltage that it would have at normal load. An Edison battery will deliver for 20 min. six times the current that it would for 5 hr., at about 70 per cent. of the initial voltage that it would have at normal load.

Electric automobiles, battery trucks and battery locomotives are driven by motors operated from storage batteries.[1] For

[1] See *Proc. A. I. E. E.*, 1916, A. E. Kennelly and O. R. Schurig, "Tractive Resistances to a Motor Delivery Wagon on Different Roads and at Different Speeds."

battery trucks, less power is required than for automobiles and locomotives, and the customary voltage is less, as indicated above. The resistance to rolling on a floor or track depends on the kind of tire, the kind of floor or track, and the speed. As the speeds are not over 12 miles per hr., if we have wheels with solid or pneumatic tires, the total resistance, including chain and bearing friction, windage, and tire friction, is about 25 lb. per ton weight of truck and load, on a good level floor. With wheels having steel tires, on good rails, the total resistance of a locomotive is about 20 lb. per ton. If the floor or track is inclined in any part of the travel, the grade must be considered in addition to these figures. The weight of a battery truck or locomotive varies considerably, but values near enough for estimating the loads to be carried by the battery are the following: For battery trucks, up to 10 tons capacity, 1,000 lb. + 30 per cent. of the weight of the load to be carried; and for locomotives with drawbar pull up to 2,400 lb., 4,000 lb. + 4 times the drawbar pull. The efficiency of the motor is about 80 per cent. at any ordinary load. This does not take into account losses due to speed adjustment by gear reduction or by controller series resistance; but it does permit speed variation with a ratio of about 3:4, by series and parallel connection of two sections of the series field.

Train lighting is done in three different ways, each requiring the use of storage batteries:

1. *The straight storage system.* This requires a sufficient battery capacity on each car for all demands for light, to last until the car is brought again to a charging station. Usually it is not so satisfactory as one of the other systems. It is proposed to standardize on a nominal voltage of 60 (32 lead cells) for this system. A number of roads are still using voltages ranging from 30 to 110, but new installations should be at 60 volts if possible, for the sake of uniformity. The size of cell most commonly used has a capacity of 300 amp.-hr. It is better to use this standard size if it is large enough, and not very much too large.

2. *The head-end system* has a generator, in the baggage car or on the locomotive, large enough to light the whole train. The battery need not be so large in this case as in the straight storage system, because it is only required to furnish lights during stops and for a time at the beginning and end of the run, for cleaning and other work about the cars. Some cars require light for longer times before and after the run than others. Thus, mail cars are

required to have sufficient battery capacity to light them for 12 hr. without recharging the batteries; diners require lights for laying in supplies, cleaning and other operations; Pullman cars require lights for cleaning, and for occupancy at the beginning of the run, before the car starts. One difficulty of the head-end system is that these several cars cannot be charged up in advance so readily as if each were handled independently. In some cases, but not all, the rule can be followed of making the total ampere-hour capacity of the battery one-half of what it would be if there were no generator on the train. This system has another disadvantage where the train is broken up at junction points. If some cars are run on branch lines there must be some provision for lighting those that are so switched off. It is proposed to standardize the battery voltage for head-end systems on 60 volts. In a few cases 110-volt systems are in use at present, but new systems should conform to the standard. Cells of 300 amp.-hr. capacity should be used wherever practicable, but others may be used if necessary.

3. *The axle-generator system* has both a generator and a battery on each car, and is therefore the most flexible of all systems. The proposed standard for this system is 30 volts. At present dining cars and a few others commonly use 60 volts. Cells of 300 amp.-hr. capacity should be used if practicable. The same provision must be made as before indicated, for additional time of lighting mail cars, diners and Pullman sleepers.

CHAPTER IX

ILLUMINATION[1]

THE ESSENTIALS

It requires the application of only a few principles, in making the necessary computations for illumination. We shall consider enough of these principles to lay out the equipment for good industrial illumination.

Illumination intensity refers to the strength of light on the object that is observed. If it comes from a single lamp, it varies as the candlepower and inversely as the square of the distance of the lamp from the surface (G. 398, 399). The candlepower is usually different in different directions, and the value used in computing should be found for the required direction, from a curve that shows the variation of candlepower with direction. In Fig. 28 are four such curves, showing the candlepower of a 100-watt lamp without a reflector, and with three different kinds of reflectors. Illumination intensity is expressed in *foot-candles*, and a surface is said to have one foot-candle of illumination when the light is from a one-candlepower lamp, one foot from the surface, if the beam of light is normal to the surface. The illumination intensity due to any lamp at any distance, with the light striking the surface at any angle, is

$$I = C \cos \theta / D^2$$

where C is the candlepower in the particular direction, D the distance in feet-between the lamp and the object, and θ the angle between the light beam and the normal to the surface. If the

[1] G. Chapter XLII.

S. Section 14; also see list of references, paragraph 250.

A. Theory, pp. 764–771; Interior Illumination, pp. 756–763; Street Illumination, pp. 772–778.

Bulletins of Engineering Department, National Lamp Works of General Electric Co., Cleveland, O. In particular, *Bulletin* 20, Industrial Lighting.

Chapters X and XI, D.C. and A.C. Lighting Circuits.

Chapter VIII and references, p. 51, Train and Vehicle Lighting.

surface is lighted by several sources, the total intensity is the sum of the intensities from the several sources.

The total amount of light, striking any surface, is the product of average intensity of illumination times the area. If the intensity is in foot-candles, and the area in square feet, the total light, or the *light flux*, is expressed in *lumens*. Consider a sphere, Fig. 26, of radius D, with a lamp at the center having a candlepower C, in all directions. The illumination intensity on the inside of the sphere is C/D^2, and the total light flux in lumens on the inner surface of the sphere is $4\pi D^2C/D^2$ or $4\pi C$. That is, the total light in lumens emanating from any lamp of uniform candlepower is 4π times the candlepower. If the candlepower is not the same in all directions, the total light is 4π times the "mean spherical candlepower." Incandescent lamps are now rated in mean spherical candlepower. Up to the present time they have been rated in "horizontal candlepower," which is the candlepower in a horizontal direction when the tip points straight down. This is about 1.25 times the spherical candlepower, but this ratio differs in different lamps. At present, lamps are also rated in lumens or in watts or both. A 100-cp. (spherical) lamp produces $4\pi \times 100$, or 1,257 lumens.

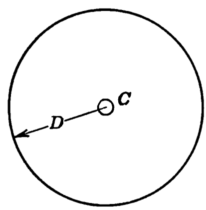

FIG. 26.—Lamp of C candle-power, at the center of a sphere having a radius of D feet.

The effect of *reflectors* is to change the direction of light, and to absorb a small amount of it. The light actually reaching the working plane is increased by the use of reflectors, and light that would be annoying, by shining in the eyes, is cut off. The distribution of the light depends on the kind of reflector that is used. Reflectors are classified, with reference to distribution, as extensive, intensive, and focusing. An *extensive reflector* throws a large part of the light out toward the horizontal, and is suitable for use in lighting streets and large areas. An *intensive reflector* throws the light on an area that is less extended; it is suitable for ordinary industrial lighting, especially for purposes of general interior illumination. A *focusing reflector* concentrates the light on a relatively small spot, immediately below the lamp. It is not suitable for general lighting unless the lamps are placed close together, but it is especially good for spot lighting, where that is required.

The shapes of several of these reflectors are illustrated in Fig. 27, and the distribution of light is shown in Figs. 28 to 30.

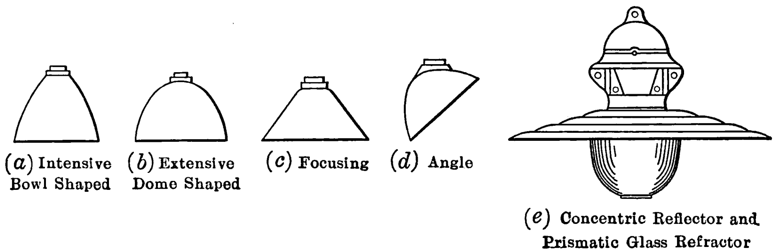

FIG. 27.—Typical reflectors.

(a), (b) and (c) are made of steel, covered with porcelain or other reflecting material. They are suitable for in-door and industrial use. Extensive reflectors are usually dome-shaped. Intensive reflectors are either bowl- or dome-shaped; the dome-shaped are preferable on accout of high efficiency, and because they cast softer (less sharp) shadows. The chief disadvantage of dome reflectors is that they do not conceal the lamp filaments from view. See Fig. 28 for photometric curves of these reflectors. (d) is suitable for certain cases of special lighting. (See Fig. 29.) (e) is a combination reflector and refractor. It is suitable for out-door lighting. (See Fig. 30.)

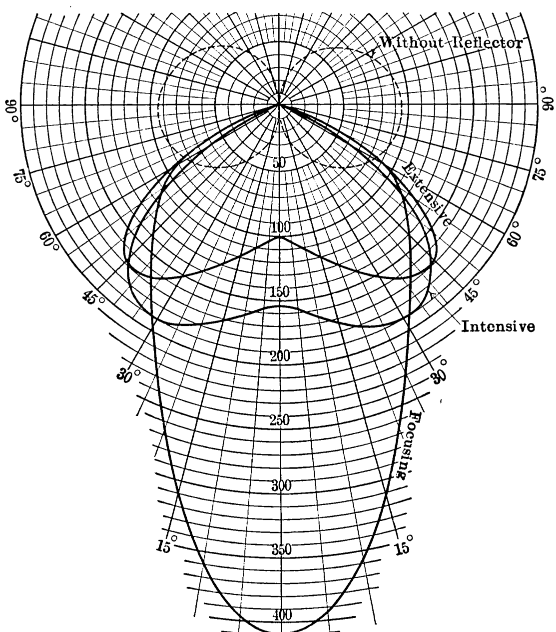

FIG. 28.—Curves showing the distribution of light from a clear Mazda lamp, without a reflector, and with three kinds of steel reflectors.

Radii are candle-power. This was a 100-watt lamp, operating at 9.1 lumens per watt, or 1.38 watts per spherical candle-power.

The dotted line in Fig. 28 illustrates the fact that the candle-power of a Mazda lamp is relatively high in a horizontal direc-

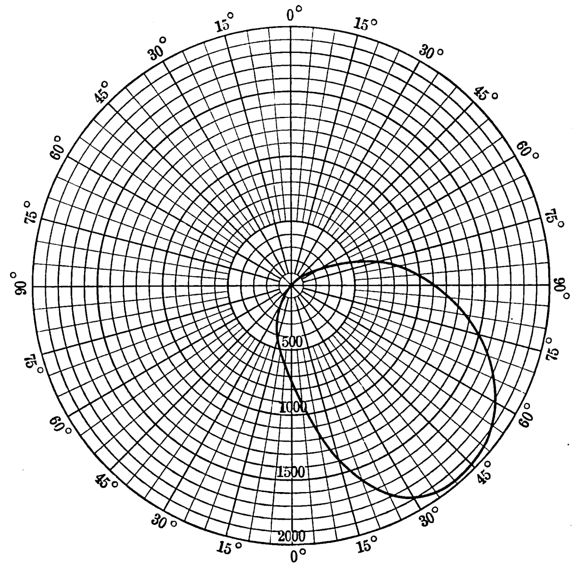

FIG. 29.—Curve of distribution of light from a 100-watt lamp (9.1 lumens per watt) with an angle-type reflector.

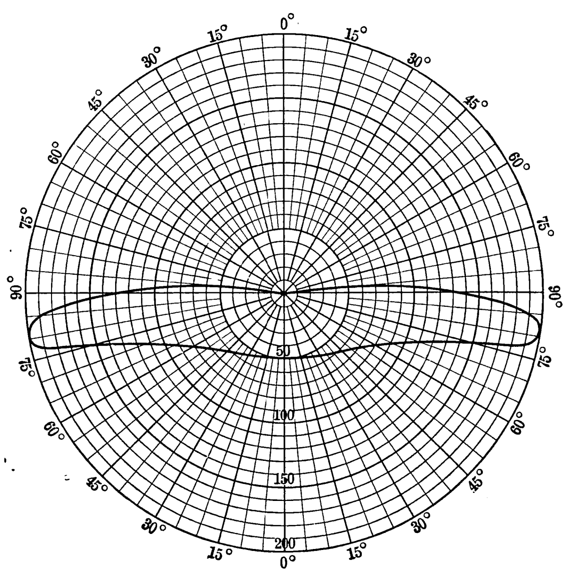

FIG. 30.—Curve of distribution from an 85 spherical candle-power series Mazda lamp.

The power required varies somewhat, depending on the current for which the lamp is rated. It is about 0.8 watt per spherical candle.

tion, and that it is very low directly downward. The extensive reflector throws a stronger light than the intensive, at angles of more than 45° from the vertical, and the focusing reflector throws more than either of the others at less than 30°. The first impression in comparing these curves would be that the total amount of light is several times as great with the focusing reflector as with the others. This is not the case, because the *solid* angle is so small in which the light from the focusing reflector is very strong.

As the light leaves the lamp and reflector, a large part of it is thrown directly on the *working plane.*[1] The rest falls on the walls, ceiling and other surfaces, and a part is reflected from there to the working plane. The *utilization efficiency* is the ratio of the light flux finally reaching the working plane to the total light produced. Thus, if 1,000 lumens are produced by the lamp, and the average illumination intensity is 3 foot-candles on an area of 100 sq. ft., the utilization efficiency for that area is 30 per cent. The efficiencies in Table IX are given by the National Lamp Works of the General Electric Co.; they show that in a large room having several rows of units in each direction, two or three times as much of the light reaches the working plane as in a very small room having only a single lamp.

Table IX.—Utilization Efficiencies of Illumination

Installation—units spaced 1.5 to 1.6 times height above work	Reflector	
	Enameled steel dome, per cent.	Enameled steel or pyro glass bowl, per cent.
1 unit	28	24
1 row of 5 units	42	36
2 rows of 2 units	48	41
2 rows of 3 units	52	44
3 rows of 3 units	56	47
3 rows of 4 units	60	49
4 rows of 4 units	63	51
4 rows of 8 units	67	54
8 rows of 8 units	71	57

The intensity of illumination that is suitable for industrial purposes depends on considerations mentioned later—particu-

[1] That is, the horizontal plane at the average height of the work—usually 30 to 40 in. above the floor.

larly on glare. It is sometimes easier to see in a room that has an illumination intensity of 1 or 1.5 foot-candles, produced by indirect lighting, than in a room having 3 foot-candles produced by direct lighting in which the lamp filaments are in the range of vision. If the filaments are concealed, and the lamps are placed as much as possible out of the field of vision, the intensities given in Table X should be sufficient, for ordinary cases; but special conditions may call for either higher or lower values.

TABLE X.—ILLUMINATION INTENSITIES

Purpose of illumination	Average values for well-placed lamps with suitable reflectors, foot-candles
Desk work	4–6
Fine machine work	5–10
Rough machine work	3–5
Storage	1
Passageways	1–2

The *effect of dust and aging of lamps* must be taken into account in providing for the illumination of a room or other space. The values of illumination intensity given in Table X refer to conditions that should be found in service, after dust has accumulated on the lamps and reflectors, and the lamps have become somewhat dimmed with age. *The effect of dust* depends on the frequency of cleaning the lamps, the location of lamps, general conditions as to dust, and the kind of reflectors used. An average dimming on account of dust, with the kind of reflectors commonly used in industrial plants, is 1 per cent. per week for the first 2 months, and a further dimming of 0.5 per cent. per week for the next 4 months.[1] *The aging* of a Mazda (tungsten) lamp, during a period of 1,000 hr. of use which is considered the normal length of life of the lamp, produces a decrease in lumens to 87 per cent.[2] of the initial value, at the end of the life of the lamp. The average during the life of the lamp is 94.5 per cent.[2] of the initial value. If we are willing to accept average illumination during the

[1] These figures are for ordinary conditions. Under very bad conditions there may be a dimming of 50 per cent. in 1 month.

[2] These figures show the decrease in useful, as well as in total light, if dome reflectors are used; but with bowl reflectors, the useful light drops in 1,000 hr. to 82 per cent. of the initial value, and the average during the life of the lamp is 92 per cent.

1,000 hr., we shall allow for the average effect of dust and aging; but if the minimum illumination intensity is not to fall below the specified value, it is necessary to allow for the accumulation of dust during the full period between cleanings, and the effect of aging in the full 1,000 hr.

If the lamps are not spaced too far apart, and suitable reflectors are used, the illumination is practically uniform over the entire area. The distances given in Table XI should not be exceeded, if uniform illumination is required.

TABLE XI.—MAXIMUM SPACING DISTANCES FOR UNIFORM ILLUMINATION
(H is the height of the lamps above the working plane)

Kind of reflector	Distance between rows
Extensive	$2.0H$
Intensive	$1.25H$
Focusing	$0.75H$

Glare.—The purpose of light is to make objects visible, and we should consider not only what intensity of light is produced, but also whether anything reduces the usefulness of the light. If the eye is accustomed to a very bright light, it is not in condition to see very well on a moderately lighted surface. Any such interference with clear vision is called glare. There are several cases to consider: (1) Bright spot-lighting contracts the pupil of the eye, and makes it difficult to see objects in the vicinity, even if they are fairly well lighted. (2) A reflecting surface sometimes produces glare, if the light strikes it at such an angle as to be reflected to the eye. (3) The intensely bright filament of a tungsten lamp, or the arc of an arc lamp, if not covered, produces glare when it is seen in looking less than about 20° above the horizontal. (4) A flickering light is similar to the other cases, and in addition the continuous changing tires the eye.

Color of light has a considerable effect on its usefulness; for most industrial purposes the colors of tungsten and arc lighting are satisfactory. If the work requires careful color observations a test should be made before the installation is completed, to ascertain what type of lamp is most effective, and causes the least eye-strain.

Shadows.—If an object is so perfectly lighted that there are no shadows, the details of the object are not so plainly visible as if there are moderate shadows, showing by contrast where the depressions and projections are. On the other hand, if shadows are too intense, the part in the shadow is entirely invisible. The best effect is obtained if the light comes from at least two or three directions. For drafting, and similar work on a plane surface, the less shadows there are, the better is the effect.

THREE KINDS OF ILLUMINATION

We have found that sufficient intensity, avoidance of glare, and moderate shadows are essential to good lighting. Each of these is obtained to a greater or less degree by each kind of illumination:

Direct lighting has the advantage over indirect, that the light is used more efficiently. It has the disadvantage that the source of light is visible, and may produce glare. For the best results the lamps must be out of the field of vision, and close enough together so that the working plane is uniformly lighted and so that several lights from different directions show the form of every object by the shadows.

Indirect lighting is more expensive on account of inefficiency. The surfaces lighted should be large enough to reflect sufficient light without producing glare. For even moderate efficiency, the lighted surfaces should be of a very light color.

Semi-indirect lighting is produced by lamps, at least part of which are used for direct lighting, whereas some or all throw their light also on walls, ceilings or other surfaces, for indirect lighting. If the lamps are screened from the eye by an adequate diffusing medium, this kind of light may be very nearly as soft and free from glare, as indirect lighting, and it is less expensive.

COMPUTATIONS

There are two methods of finding the number, size and arrangement of lamps, to produce the required illumination. The *point-by-point* method is very tedious, and is as follows: a trial layout is made, of lamps and reflectors such as would be expected to give the necessary illumination intensity in all parts of the room or space. The intensity at a certain point is then computed by using the formula on page 61; it is the sum of all the intensities at that point from all the sources in the vicinity. There may be a dozen lamps whose effect at that point is to be computed. Then all these computations must be repeated at a large number of points, so that the illumination in every part of the room is known. If a part or all the illumination is unsatisfactory, it must be changed, and new computations made.

A much simpler, and quite satisfactory method is that of obtaining the *average illumination intensity*. Reflectors have been so well developed that where proper spacing is not exceeded the illumination is practically uniform. If we assume a convenient height of lamps, the table of spacing distances on page 67 gives us the maximum allowable spacing between rows, and from that we know the area to be lighted by each lamp. The product of area and illumination intensity gives lumens per lamp. Or, if we assume a convenient size of lamp, we know the spacing and the minimum allowable height of lamps. The problem is one of finding consistent values of height, spacing and lumens of each lamp. If a satisfactory solution is not obtained directly, it may be desirable (1) to specify a spacing that is less than the maximum allowable, (2) to provide an illumination of higher intensity, or possibly *slightly* lower than was originally required, or (3) to provide general illumination that is considerably too weak, but is supplemented in certain localities by any method that is indicated below for special lighting. In any case computations are made for average illumination on the working plane, taking into account the effect of dust and aging of lamps and the utilization efficiency.

In laying out the positions of the lamps, the scheme can sometimes be modified to adapt it to the shape of the room and the location of machines, preventing dark corners and edges of the room, if good light is required in these places. The distance from the wall to the first row of lamps should not be more than one-half the distance between rows, unless good illumination is unnecessary near the wall. Even if the distance between the first row and the wall is as little as one-half the spacing between rows, the illumination is appreciably less near the wall, unless the wall is of a very light color, and serves as a good reflector.

The provision thus far is for general illumination. If this is not sufficient for all parts of the room, *special lighting* may be introduced to increase the illumination in certain sections (1) by increasing the size of lamps; (2) by reducing the spacing between lamps, (3) by using focusing reflectors, or (4) by providing additional hand or stationary lamps. The use of stationary lamps probably gives the most satisfactory lighting for a small amount of power used.[1] In a shop or factory, the lamp should then be placed where it lights the work to the best advantage. In general, a good rule is to place the lamp so that when the operator is at work, it is just to the right and in front of his right shoulder, and just above his head. The best height of the lamp is from 4 to 7 ft. above the floor, depending on whether the operator is seated or standing. It must be placed where no shadow is cast on the work.

[1] Any such localized lighting is rarely necessary. It nearly always produces glare in some form, and should be avoided if possible.

CHAPTER X

D.C. TRANSMISSION AND DISTRIBUTION SYSTEMS[1]

This chapter applies very largely to A.C. as well as to D.C. systems; some further points are brought out in the next chapter, with reference to A.C. circuits. It is assumed that the kind of system has been chosen in accordance with Chapter III; we now proceed to find the size of wire, which must be large enough so that the current does not produce (1) excessive voltage drop, (2) excessive power loss in the line, nor (3) excessive heating of the conductor. It must also be large enough for mechanical strength, but not so large that the investment is unnecessarily large.

VOLTAGE DROP

Motor Circuits.—When the voltage of a system drops, the motor current must increase, if the motor is to do the same work as at full voltage; also, the operating characteristics of some motors are impaired. A drop of 5 per cent. is satisfactory in motor circuits under practically all conditions, and usually 10 per cent. is not excessive. Still greater voltage drop may be necessary in extreme cases, but should not be allowed without careful consideration of the extra cost and the advantage of keeping it within 10 per cent.[2]

Lighting Circuits.—The voltage drop should be even smaller for lighting circuits than for motors, because every 1 per cent. decrease in voltage causes from 3 to 4 per cent. decrease in the

[1] G. Chapter XLI.
S. Section 11; High-tension long-distance transmission.
Section 12; Distribution systems and short transmission lines.
Section 13; Interior wiring and local distribution.
A. pp. 352–376, 1657–1707.

[2] Overcompounded generators, voltage regulators, or boosters can be employed to maintain a steady voltage, but none of these will keep the voltage constant on all parts of the system without a large investment in equipment. If possible, the line drop, independent of automatic regulating devices, should not be excessive.

amount of light produced. For example, if the voltage drops 5 per cent., the candlepower of a tungsten lamp decreases about 16 per cent. For this reason, the voltage drop on a lighting circuit should not ordinarily exceed 3 per cent., and it is better not to exceed 2 per cent.

There are three cases of voltage drop to be considered, for D.C. motor and lighting circuits: (1) The two-wire system, in which all the current flowing out on one wire necessarily returns on the other; (2) the ground- or rail-return system, in which the current flowing out on the copper wire returns through the ground, or over rails, or both; and (3) the three-wire and other multiple-voltage systems, in which at least one additional conductor at an intermediate voltage is provided for lighting, or for motor-speed adjustment.

Two-wire System.—If a feeder is very long and has branches taking considerable parts of the total current, the conductor need not be so large at the end as at the beginning of the feeder.[1] Ordinarily, however, it does not pay to make the joints and to change sizes; a size is selected which is large enough for safety and economy, and which distributes the current to its various destinations without producing a drop at any destination, exceeding the allowable maximum. The total RI drop in a D.C. line is computed by adding together the RI drops in the various parts that are in series.

Example.—A feeder of 500,000 circ. mil cable furnishes power to three motors, at distances along the feeder of 50, 100 and 200 ft. from the busbars. The motors take, respectively, 100, 200 and 250 amp. It is required to find the voltage drop. From Table XII, p. 80, the resistances of the three lengths are respectively 0.00216, 0.00216, and 0.00432 ohms. The total drop is $550 \times 0.00216 + 450 \times 0.00216 + 250 \times 0.00432$ or 3.24 volts. It is sometimes simpler to compute the drop due to the individual currents by multiplying each by the total resistance through which it flows. The total drop, computed by that method, is $0.00216 \times 100 + 0.00432 \times 200 + 0.00864 \times 250$, which agrees with the other computations.

The voltage drop may be computed without the use of the table, as equal to kLI/A, where k is the resistance of a circular-

[1] In such a case it can be shown that the most economical distribution of copper for minimum line drop is obtained if the sectional area of each length of conductor is proportional to the square root of the current in that length. Thus, if the first 100 ft. carries nine times as much current as the second, and we consider minimum line drop and nothing else, the sectional area of the first 100 ft. should be three times as great as that of the second.

mil-foot (10.6 ohms, for annealed copper at 25°C.), L is the length of conductor in feet, I the current in amperes, and A the area in circular mils. It is simpler to use the table than to make this computation to find the voltage drop, but if the voltage drop is given, and the size of conductor is to be found, it may be simpler to use this formula than to try the various sizes of wire until the one is found that gives the right voltage drop.[1] Where it is specified that the voltage drop shall not exceed a certain maximum, of course the full-load value of the current is to be substituted in the expression for voltage drop, even though the average current is much smaller. However, this maximum drop does not *necessarily* refer to the period of heavy currents for motor starting, lasting for a fraction of a minute; for even if such currents cause an excessive drop for a very short time, they need not interfere with satisfactory operation of other machines.

Example.—If the total full-load current taken by all the motors on a feeder is 500 amp., the motors are 200 ft. from the power-station buses, and the maximum allowable drop is 15 volts, the required area of the wire is $10.6 \times 2 \times 200 \times 500/15$ or 141,000 circ. mils. From the table we find that No. 000 wire is the size to use.

Ground or Rail Return.—In a circuit having a rail or other return path, if the drop in the return circuit is appreciable, the resistance of the return circuit, and the current (if it is different from that of the wire) must be determined. The total drop is, then, the resistance of only *one* wire times its current, plus the resistance of the return circuit (if appreciable) times its current. If the return circuit is through a rail, the drop in the rail is usually small; the resistance of two 60-lb. rails in parallel is about 0.0083 ohm per 1,000 ft. The resistance of other weights of rail is very nearly inversely as the weight.

[1] For rapid calculation of wire resistances without reference to tables, the following rules are convenient to memorize. At 20°C. (68°F.), for ordinary commercial copper wire of sizes from No. 0000 to 10, A.W.G., they are correct within 2 per cent. The errors are slightly larger for smaller wires.

Rule 1.—The resistance of No. 10 wire is 1 ohm per 1,000 ft.; adding 3 to the number of any wire doubles the resistance; and subtracting 3 from the number halves the resistance. That is, changing the number by 1 multiplies or divides the resistance by $\sqrt[3]{2}$ or 1.26.

Rule 2. Adding 10 to the number of any wire multiplies the resistance by 10, and subtracting 10 divides it by 10.

Thus the drop in the rail return 1 mile long, consisting of two 40-lb. rails in parallel, when carrying 150 amp., is $150 \times 0.0083 \times 5.28 \times 40 \times 60$ or 4.4 volts. If only one rail is used as the return circuit, of course the drop is twice as great.

Multiple-voltage Systems.—A direct-current three-wire circuit should be treated the same as a two-wire circuit, if the circuit is balanced. The current in one line and the voltage between outside lines should be used in computing per cent. voltage drop.

Example.—If 100 lamps each taking 1 amp. at 110 volts are balanced on a 110- and 220-volt three-wire circuit, there are 50 lamps on each side, and the per cent. line drop is the same as for 50 amp. on a 220-volt circuit.

If a three-wire circuit is unbalanced, the voltage on either side of the system may be either too high or too low. (See the three-wire feeder in Fig. 14.) If there is a larger current on the positive than on the negative side, a part of the current returns through the neutral. Designating the positive, neutral and negative currents by I_+, I_n, and I_-, and the resistances of the outside and neutral wires by R_o and R_n, the drop in the positive line is $R_oI_+ + R_nI_n$. I_n is usually a small fraction of I_+, but R_n may be larger than R_o. A numerical example will illustrate:

Assume that on a 110- and 220-volt system the maximum current that will flow in an outside line is 50 amp. and at least 80 per cent. of this current is balanced by a current returning in the other outside line. If the resistance of the outside line is 0.04 ohm, and the neutral 0.08 ohm, the maximum voltage drop with balanced load is 0.04×50, which amounts to 2 volts on each side, or 4 volts on both sides. This is a drop of 1.8 per cent. The maximum drop with unbalanced load is $0.04 \times 50 + 0.08 \times 10$ or 2.8 volts on one side. This is a drop of 2.5 per cent. Note that if I_n is reversed, the second term of the voltage drop is negative.

ECONOMICAL SIZE OF WIRE

Even if a large conductor is not required for any other reason, it may be required for economy. Evidently a very small conductor is not economical, because the annual power lost is proportional to the resistance, or inversely proportional to the sectional area of the wire. On the other hand, a very large conductor costs so much that there is an excessive annual outlay for interest and other fixed charges—that is, for charges that exist whether the conductors are carrying current or not. There is an intermediate size of wire that is most economical, whose exact size would be dependent on the cost per kilowatt-hour for energy, and on the necessary allowance for fixed charges, which include interest, taxes, insurance and depreciation.

Some of the items of cost in installing a transmission or distribution system are the same for any ordinary size of wire. Other items are about proportional to the weight, and therefore to the sectional area of the wire. Since the fixed charges are a certain per cent. of the first cost, some fixed charges are constant, whereas others are proportional to area of conductor. Thus the total annual outlay on account of the line includes the fixed charges, in two parts, and the cost of energy. It may be expressed as

$$C = K_1 + K_2A + K_3/A$$

where A is the area, K_1 the invariable fixed charges, K_2A the annual fixed charges proportional to the area, and K_3/A the cost of energy lost on the line per year. Differentiating the annual outlay, with respect to area, and setting the first derivative equal to zero, to find the area for minimum cost, we have

$$dC/dA = K_2 - K_3/A^2 = 0$$

from which we have $K_2A = K_3/A$.
That is, *the annual fixed charges that are proportional to the area should equal the cost of energy lost on the line per year.*

The cost of energy lost is $RI^2tC_e/1{,}000$, where t is the number of hours per year that the current flows, and C_e is the cost of energy in cents per kilowatt-hour. If the line is of annealed copper, the resistance is $10.6L/A$ where L is the length in feet and A the area in circular mils; and the cost of energy lost is $10.6LI^2tC_e/1{,}000A$.

The fixed charges are $3.03 \times 10^{-6} LAC_cF$, where 3.03×10^{-6} is the weight of a circular-mil-foot of copper, C_c the cost of copper, installed, in cents per pound, and F the fraction to be allowed annually for fixed charges. Equating the fixed charges to the cost of energy, and solving for area, if t is 365×24 hr.,

$$^1A = 5{,}500I\sqrt{\frac{C_e}{C_cF}} \qquad (2)$$

When, as is usually the case, the value of A is not a commercial size of wire, the nearest size should be selected—not necessarily

[1] See S. 13: 75, 76 for a similar statement, based as this is on Kelvin's law.

the next larger size. If the time of operation per year is not 365 days of 24 hr., the area is proportional to the square root of the time.

Thus, if a line is in service only 8 hr. per day, 300 days per year, expression (2) becomes

$$A = 5{,}500 \times \sqrt{8 \times 300/(24 \times 365)} \times \sqrt{C_e/(C_cF)}.$$

The cost of energy per kilowatt-hour, C_e, is usually between 1 and 10 cts. if purchased from a power company. If not purchased, but generated in a plant of 2,000-kw. capacity or more, it should ordinarily cost from 0.5 to 1 ct. per kw.-hr., depending largely on the size of the plant and the cost of coal.

The cost of copper per pound, installed, C_c, including insulated wire, supplies and the labor of wiring, depends on the prevailing base on which wire costs are computed, size of wire, the kind of wire insulation, discounts obtainable, cost of labor, and kind of wiring system—that is, whether an out-of-doors pole line, an in-doors conduit system, or some other kind of installation. This total cost may be as low as 25 cts. per lb. of copper installed, or as high as 75 cts., for such sizes as are used for power purposes. To find this total cost, proceed as follows:

1. Knowing from market quotations the base on which the required wire is sold, find from the price list in Table XII the list price of the wire per 1,000 ft., and take off whatever discount is allowed.
2. Add to this the cost per 1,000 ft. for conduits or other supplies, and labor.
3. Divide by the weight of bare wire, in pounds per 1,000 ft.

It is required to find the total cost of a pole line, not including poles, per pound of copper. Market quotations for the required wire are on the 15-ct. base, and a discount of 45 per cent. is obtainable. The line is to be of No. 4 stranded conductor.

List price of wire per 1,000 ft. is	\$122.00
Taking off the discount, 122 × 0.55 is	67.10
Labor and supplies cost, per 1000 ft.	25.00
Total cost per 1000 ft.	\$92.10
Dividing by the weight in pounds, the cost per pound of copper is	0.71

The rate of interest is usually about 5 or 6 per cent., depending on financial condition.

Taxes, of course, depend on the locality. An allowance of 1.5 per cent. is reasonable.

Fire insurance is placed on buildings and their contents, and other equipment that may be destroyed by fire; but it is not customary to insure transmission and distribution lines that are outside of buildings. Insurance on power stations and other equipment ranges from practically zero to 1.5 per cent. In a well-constructed building it is not far from 0.5 per cent.

Depreciation is an allowance for a decrease in value, due to ordinary wear and tear, effect of the weather, and being displaced by equipment better adapted to the requirements. (Scrap value of old equipment reduces the necessary allowance for depreciation.) It is not customary to charge maintenance and repairs to depreciation, but these charges should be included here if they are not elsewhere. Allowance for depreciation ranges in most cases from 5 to 10 per cent., but in a few cases it goes much higher or lower. For ordinary wires and wiring equipment (not including trolley wires) it is about 7 per cent. This brings the total fixed charges for an out-of-doors circuit to about 14 per cent. (It usually ranges between 12 and 16 per cent.) This percentage allowed for fixed charges is to be substituted for F in equation (2). It is to be written as a decimal fraction, *e.g.*, 0.14, not as a whole number, as 14 per cent.

A good check on the results of equation (2) may be made by comparing the total annual cost for the chosen size with that for the next sizes above and below.

Example.—Let us apply the formula and then check it, to find the most economical size of triple-braid weatherproof wire to carry 300 amp., 9 hr. per day, 295 days per year, over an out-of-door pole line, if this wire is sold on the 20 ct. base, there is a discount of 53 per cent., fixed charges are 14 per cent. and energy costs 1 ct. per kw.-hr.

Usually results come out at about 1,000 to 2,000 circ. mils per amp., so we shall look for a conductor of 300,000 to 600,000 circ. mils. Let us work the problem, using the data for 500,000 circ. mils. From Table XII and Note 9 of that table, we find that:

Cost of the conductor per 1,000 ft. is	$604
Cost of labor and supplies per 1,000 ft. is	$28
Total cost per 1,000 ft. is	$632
Weight in pounds per 1,000 ft. is	1,540
Cost per pound is	$0.41

Substituting this value for C_c, in equation (2), we have

$$A = 5{,}500 \times 300 \sqrt{\frac{1}{41 \times 0.14} \times \frac{9 \times 295}{24 \times 365}} = 379{,}000 \text{ circ. mils.}$$

The best commercial size is 400,000 circ. mils.

This solution was obtained, by finding the value of C_c for a 500,000-circ. mil conductor. This would be so nearly the same for 400,000 circ. mils that usually no further computations are necessary. As an extra precaution, the solution can be repeated, after finding C_c for 400,000 circ. mils.

Checking the foregoing by comparing costs for 400,000 circ. mils with those for 350,000 and 450,000, we find:

Area in circular mils	350,000	400,000	450,000
Cost of insulated wire	\$442.00	\$496.00	\$549.00
Labor and supplies	23.80	25.50	27.00
Total first cost	\$465.80	\$521.50	\$576.00
14 per cent. fixed charges	\$65.20	\$73.10	\$80.60
Cost of energy lost at 21°C.	72.40	63.40	56.30
Total annual outlay	\$137.60	\$136.50	\$136.90

These results agree with those obtained by the formula, in indicating that 400,000 circ. mils is the most economical size. There is a small theoretical error in using the formula, because in deriving it we assumed that the cost of copper per pound is constant, whereas it is slightly less for large sizes than for small sizes of wire. For this reason, results obtained by the formula are usually about 3 per cent. too low.

Variable Current.—If the current is not steady, but has values I_1, I_2, I_3, . . . respectively, for t_1, t_2, t_3, . . . hr. per year, the value of I to use in equation (2) is equal to

$$\sqrt{I_1^2 t_1 + I_2^2 t_2 + I_3^2 t_3 + \ . \ . \ . \ /24 \times 365}.$$

Center of Distribution for Branched Circuits.—If the circuit branches near the outer end, so that the current in the main feeder is smaller at the end than at the beginning, it is allowable to make computations as if the feeder carried all the current to a center of distribution, whose distance from the power buses is less than that of the farthest load, but more than that of the nearest load. A large error may be introduced, however, if the current branches at a point near the power station.

SAFE SIZE OF WIRE

The wire must be safeguarded against mechanical strain and electrical heating. The National Electrical Code lists the carrying capacities allowed by the National Board of Fire Underwriters. This list (see Table XII, page 80) is generally accepted as in accordance with good practice. Smaller than No. 14 wire is not permitted for any power or lighting current, except in special cases. The carrying capacity of a triple-braid covered or other wire without rubber is greater than that of a rubber-covered wire, on account of deterioration of the rubber with heat. However, rubber-covered wire is required by the Underwriters in certain cases.

Overhead wiring out of doors should be strong enough to withstand wind and sleet, and good practice calls for a No. 6 wire as the smallest to be used as a pole line. Larger sizes should be used for larger currents, in at least approximate conformity to the ratings of the National Code, even though it be where the Fire Underwriters have no jurisdiction. Underground circuits, in cables and conduits, should usually have not smaller than No. 8 wire, and should conform at least approximately to the National Code.

CONCLUSIONS

After finding the size of wire required for allowable line drop, economy and safety, the largest of the three is to be selected—for obviously we cannot exceed the maximum voltage drop, just because it is safe and economical; nor can the other limitations be disregarded. If the requirements for voltage drop or safety call for an excessively large wire, it may be possible to obtain special concessions from the proper authorities. If the size required for economy is very large, it may not be possible to tie up extra capital, even if it is economical to do so. In any of these cases it is well to consider whether a higher line voltage can be used, thereby reducing the line current.

Table XII.—Data on Wires

Size of wire or cable				Weight of copper[3] wire or cable in pounds per 1,000 ft.		Safe carrying capacity of copper[5] wire or cable in amperes (National Elec. Code)	
B. & S. or A. W. G. No.	Area in circular mils[1]	Outside diameter in mils[1]					
		Bare	Triple braid[2]	Bare	Triple braid weatherproof[4]	Rubber insulation	Other insulations
Stranded	conductors						
	1,000,000	1,152	1,451	3,090.	3,478	650	1,000
	950,000	1,123	.....	2,930.			
	900,000	1,093	.....	2,780.	.....	600	920
	850,000	1,062	.....	2,620.			
	800,000	1,031	.....	2,470.	.....	550	840
	750,000	998	1,300	2,320.	2,615		
	700,000	964	.....	2,160.	.....	500	760
	650,000	929	.....	2,010.			
	600,000	893	1,190	1,850.	2,113	450	680
	550,000	855	.....	1,700.			
	500,000	814	1,108	1,540.	1,781	400	600
	450,000	772	.....	1,390.			
	400,000	728	1,020	1,240.	1,445	325	500
	350,000	681	.....	1,080.			
	300,000	630	930	926.	1,126	275	400
	250,000	575	862	772.	937		
0000	212,000	528	785	653.	806	225	325
000	168,000	470	728	518.	655	175	275
00	133,000	418	662	411.	515	150	225
0	106,000	373	605	326.	420	125	200
1	83,700	332	518	258.	328	100	150
2	66,400	292	440	205.	267	90	125
3	52,600	260	...	163.	...	80	100
4	41,700	232	379	129.	173	70	90
5	33,100	206	...	102.	...	55	80
6	26,300	184	327	81.00	117	50	70
7	20,800	164	...	64.30			
8	16,500	146	290	51.00	75	35	50
Solid	conductors						
0000	212,000	460	660	641.	758	225	325
000	168,000	410	610	508.	616	175	275
00	133,000	365	560	403.	485	150	225
0	106,000	325	510	319.	396	125	200
1	83,700	289	445	253.	310	100	150
2	66,400	258	400	201.	255	90	125
3	52,600	229	...	159.	...	80	100
4	41,700	204	346	126.	164	70	90
5	33,100	182	...	100.	...	55	80
6	26,300	162	303	79.50	112	50	70
7	20,800	144	...	63.00			
8	16,500	128	264	50.00	75	35	50
9	13,100	114	...	39.60			
10	10,400	102	221	31.40	53	25	30
11	8,230	91	...	24.90			
12	6,530	81	200	19.80	35	20	25
13	5,180	72	...	15.70			
14	4,110	64	182	12.40	25	15	20
15	3,260	57	...	9.86			
16	2,580	51	169	7.82	19	6	10
17	2,050	45	...	6.20			
18	1,620	40	...	4.92		3	5

FOR ELECTRICAL CONDUCTORS

Resistance of annealed copper[6] wire or cable in ohms per 1,000 ft. of single conductor at		Reactance on 60 cycles,[8] in ohms per 1,000 ft.[8] of single conductor, with spacing of		List price[9] of copper wires and cables per per 1,000 ft., on the		Size
25°C.[7] (= 77°F.)	50°C. (= 122°F.)	1 in.	12 in.	15-ct.[9] base	20-ct. base	In circular mils, or in A. W. G. No.
						Stranded
0.01077	0.01181	0.0206	0.0776	1,945.	2,418.	1,000,000
0.01134	0.01243	......	......	1,860.	2,310.	950,000
0.01197	0.01312	0.0216	0.0786	1,773.	2,198.	900,000
0.01267	0.01389	......	......	1,688.	2,090.	850,000
0.01346	0.01475	0.0230	0.0800	1,602.	1,980.	800,000
0.01437	0.01575	......	......	1,513.	1,867.	750,000
0.01539	0.01687	0.0245	0.0815	1,427.	1,758.	700,000
0.01658	0.01817	......	......	1,340.	1,648.	650,000
0.01795	0.01967	0.0264	0.0834	1,256.	1,539.	600,000
0.0196	0.0215	......	......	1,170.	1,429.	550,000
0.0216	0.0237	0.0289	0.0859	1,047.	1,284.	500,000
0.0240	0.0263	0.0300	0.0870	956.	1,169.	450,000
0.0270	0.0296	0.0312	0.0882	867.	1,056.	400,000
0.0308	0.0338	0.0327	0.0897	775.	942.	350,000
0.0360	0.0395	0.0345	0.0915	686.	827.	300,000
0.0431	0.0472	0.0365	0.0935	593.	712.	250,000
0.0509	0.0558	0.0384	0.0954	492.	591.	A.W.G. 0000
0.0642	0.0704	0.0411	0.0981	412.	492.	000
0.0811	0.0889	0.0436	0.1006	344.	407.	00
0.1021	0.1119	0.0464	0.1034	289.	338.	0
0.1288	0.1412	0.0491	0.1061	227.	267.	1
0.1625	0.1781	0.0518	0.1088	170.	202.	2
0.205	0.225	0.0542	0.1112	144.	168.	3
0.259	0.274	0.0571	0.1141	122.	141.70	4
0.326	0.357	......	......	103.80	119.40	5
0.410	0.449	0.0624	0.1194	90.10	102.70	6
0.519	0.569	......	......	....	....	7
0.654	0.717	0.0677	0.1247	57.80	65.60	8
						Solid
0.0500	0.0548	0.0394	0.0964	492.00	591.00	0000
0.0630	0.0691	0.0421	0.0991	412.00	492.00	000
0.0795	0.0871	0.0447	0.1017	344.00	407.00	00
0.1001	0.1099	0.0474	0.1043	289.00	338.00	0
0.1263	0.1385	0.0501	0.1070	199.00	237.00	1
0.1593	0.1747	0.0527	0.1097	149.00	179.00	2
0.201	0.220	......	......	124.00	148.00	3
0.253	0.278	0.0580	0.1150	102.70	121.80	4
0.319	0.350	......	......	88.70	103.70	5
0.403	0.442	0.0633	0.1203	75.60	87.50	6
0.508	0.557	......	......	.....	.....	7
0.641	0.702	0.0686	0.1256	47.70	55.20	8
0.808	0.885	......	......	41.40	47.10	9
1.018	1.117	0.0739	0.1309	35.70	40.50	10
1.284	1.408	......	......	.....	.....	11
1.619	1.775	0.0792	0.1362	27.30	30.30	12
2.04	2.24	......	......	.....	.....	13
2.58	2.82	0.0846	0.1416	21.70	23.50	14
3.25	3.56	......	......	.....	.....	15
4.09	4.49	......	......	16.00	17.20	16
5.16	5.66	......	......	.....	.....	17
6.51	7.14	......	......	13.80	14.60	18

NOTES ON TABLE XII

Note 1. Units.—The area of any wire, expressed in square mils, is 0.7854 times the area in circular mils. The area expressed in square inches is $0.7854 \times 10^{-6} \times$ area in circular mils.

Diameter expressed in inches is diameter in mils $\times 10^{-3}$.

Example.—The area of No. 0000 bare wire in square inches is $0.7854 \times 10^{-6} \times 212{,}000 = 0.1665$ sq. in. Its diameter is 0.46 in.

Note 2. Outside Diameter of Insulated Wire.—These diameters are only approximate, because different manufacturers provide different thicknesses of insulation. They are nearly correct also for slow-burning weatherproof, and slow-burning Underwriters' wires. Single- and double-braid weatherproof wires are a little smaller.

Note 3. The weight of hard-drawn bare aluminum wire is 30.4 per cent. of that of the same size of annealed copper wire. (Aluminum, as used in American practice, is nearly always hard drawn.)

Example.—No. 00 bare stranded aluminum conductor weighs 30.4×411, or 125 lb. per 1,000 ft.

Note 4. Weight of Insulated Wire.—The weights given for triple-braid weatherproof wire are only approximate. For a first approximation the weights of wires with other kinds of insulation can be found from the following relations:

The weight of the insulating covering of	Equals the weight of the covering of triple-braid weatherproof wire, multiplied by
Double-braid weatherproof	⅔
Slow-burning weatherproof	2.0
Underwriters' weatherproof	1.5
Single-braid rubber-covered	1.5
Double-braid rubber-covered	2.0

Example.—

	Pounds per 1,000 ft.
No. 4 triple-braid weatherproof stranded copper conductor weighs	173
No. 4 bare stranded copper conductor weighs	129
Insulation of this conductor weighs	44
If the same conductor has a slow-burning weatherproof covering, the insulation weighs approximately 2×44 or	88
As before, the copper weighs	129
And the total weight is approximately	217

Note 5. Safe carrying capacity of insulated aluminum wire is 84 per

cent. of the safe carrying capacity of the same size of copper wire, with the same insulation.

Example.—A 500,000-circ. mil rubber-covered copper conductor has a safe carrying capacity of 400 amp. A corresponding aluminum conductor will carry safely 0.84 × 400, or 336 amp.

Note 6. Resistance of Copper and Aluminum.—The resistance of a hard-drawn copper or hard-drawn aluminum conductor can be found by comparing with that of an annealed copper conductor. The resistance of

Hard-drawn copper is 1.02 to 1.03 }
Hard-drawn aluminum is 1.64 } times that of an annealed copper conductor of the same dimensions, at the same temperature.

Example.—A 1,000,000-circ. mil hard-drawn aluminum stranded conductor has 1.64 × 0.01077 or 0.0176 ohm per 1,000 ft. at 25°C.

Note 7. Resistance at Other Temperatures.—The table gives resistances at 25° and 50°C. By interpolation or extrapolation, resistances at other temperatures can be obtained.

Example.—The resistance of 1,000 ft. of No. 10 annealed copper wire (not stranded) at 40°C. is $1.018 + \frac{40 - 25}{50 - 25}(1.117 - 1.018)$ or 1.077 ohms. A hard-drawn aluminum wire of the same dimensions and temperature is 1.077 × 1.64, or 1.76 ohms.

Note 8. Line reactance is proportional to the frequency and to the length of line. It also depends on the diameter of the conductor and the spacing between conductors.

Example.—A transmission line of 300,000-circ. mil stranded conductors is 3,000 ft. long; the distance between centers of conductors is 12 in., and the frequency is 25 cycles. The reactance given in the table, for 12-in. spacing, is 0.0915, and therefore for the required length and frequency it is $\frac{3,000}{1,000} \times \frac{25}{60} \times 0.0915$, or 0.114 ohm.

The reactance for other distances between conductors is obtained from that given in the table for 1-in. spacing, which we shall call X_0.

Distance, center to center, between conductors, in inches	Reactance per 1,000 ft. on 60-cycles, in ohms	Distance, center to center, between conductors, in inches	Reactance per 1,000 ft. on 60-cycles, in ohms
1	X_0	15	$0.0621 + X_0$
1½	$0.0093 + X_0$	18	$0.0663 + X_0$
2	$0.0159 + X_0$	24	$0.0729 + X_0$
3	$0.0252 + X_0$	30	$0.0780 + X_0$
4	$0.0318 + X_0$	36	$0.0822 + X_0$
6	$0.0411 + X_0$	48	$0.0887 + X_0$
9	$0.0504 + X_0$	60	$0.0939 + X_0$
12	$0.0570 + X_0$		

Example.—To find the reactance of a No. 00 stranded conductor 1 mile long, on 25 cycles, where the distance between centers of conductors is 15 in. The order of procedures is (1) to look up X_0 for the given size, (2) to add the term for spacing, and (3) to multiply by factors for frequency and length of line.

X_0 for 00 stranded conductor is.................... 0.0436 ohm.
Spacing term for 15 in. is.......................... 0.0621 ohm.

Reactance per 1,000 ft. on 60 cycles is............... 0.1057 ohm.

$$\text{Required reactance is } \frac{5,280}{1,000} \times \frac{25}{60} \times 0.1057 = 0.232 \text{ ohm.}$$

Note 9. (*a*) **Cost of Copper Wire.**—The list price is subject to a discount of about 50 per cent., depending on the quantity of wire that is purchased. List prices fluctuate with the market, and quotations are made at some particular base price, which is arbitrarily known as a 15-ct., 16-ct., or other base. The table gives the 15-ct. and 20-ct. base price list. List prices on any other base can be found approximately by interpolating.

Example.—To find the list price of No. 10 solid conductor, per 1,000 ft., on the 18-ct. base. The prices on the 15-ct. and 20-ct. bases are \$35.70 and \$40.50 respectively. On the 18 ct. base it is $\$35.70 + \frac{18 - 15}{20 - 15}(\$40.50 - \$35.70)$, or \$38.58. If there is a discount of 45 per cent., the cost for 3,000 ft. is $\$38.58 \times (1.00 - 0.45) \times 3$, or \$63.66.

(*b*) **The cost of labor and supplies for installing** varies over a wide range, depending on the labor market and the kind of installation. The following give only a first approximation of the cost in dollars per 1000 ft. of wire. (D = diam. of bare wire in mils.)

For pole lines, not including poles............ $0.035\,D$
For interior knob and tube work............. $10 + 0.035\,D$
For conduit work, not including conduits..... $15 + 0.05\,D$

CHAPTER XI

A.C. TRANSMISSION AND DISTRIBUTION[1]

The treatment of D.C. transmission and distribution systems applies as well to A.C. systems in many respects. Certain points are taken up in this chapter which apply only to A.C. circuits, and therefore are not dealt with in Chapter X.

VOLTAGE DROP

The voltage drop in an A.C. circuit is computed as in D.C., except for three considerations: (1) the effect of line reactance, (2) the effect of power factor, and (3) the difference between the drop in single-phase and polyphase circuits.

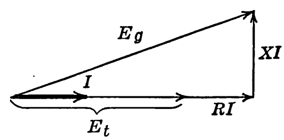

FIG. 31.—Voltage drop due to 100 per cent. P. F.
I is line current, E_t is terminal voltage, E_g is generator voltage, RI is resistance drop, XI is reactance drop.

Reactance in a Single-phase Circuit.—We shall assume, first, that the current is in phase with the terminal voltage—that is, that the load is at 100 per cent. power factor. Fig. 31 is a vector diagram of the current and all the voltages. The current, I, is in phase with the terminal voltage, E_t, and the RI drop is in phase with I, and therefore with E_t. The reactance drop XI leads the current by 90°. The generator voltage, E_g, is the hypotenuse, so that

$$E_g^2 = (E_t + RI)^2 + (XI)^2 \qquad (3)$$

If XI is small compared with E_g, the square is still smaller in its effect; if XI is not over 10 per cent. of E_g, which is usually the case, the error caused by neglecting it does not exceed 0.5 per cent. We have then the simple approximate relationship between E_g and E_t,

$$E_g = E_t + RI, \text{ or } E_g - E_t = RI \qquad (4)$$

which is the same as for a D.C. circuit. That is, *unless the*

[1] See references at the beginning of Chapter X, p. 71.

product XI is excessively large compared with the line voltage, the voltage drop can be calculated just as on D.C. circuits, as RI drop, in case the load current is at unity power factor.

Example.—Compare the results of equations (3) and (4), in case of a 220-volt terminal voltage, where the current output of the line is at unity power factor, the RI drop is 11 volts, and XI is 15 volts, or about 7 per cent. of the line voltage.

According to equation (3)			According to equation (4)
$(E_t + RI)^2 =$	$(220 + 11)^2 =$	53,361	
$(XI)^2 =$	$15^2 =$	225	
$E_g^2 =$		53,586	
$E_g =$		231.51	$E_g = E_t + RI = 220 + 11$ or 231
			Introducing an error of 0.2 per cent.

Power Factor on Single-phase.—The condition is different from the foregoing at any other power factor. Let the current

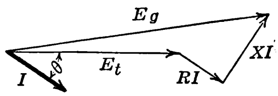

FIG. 32.—Voltage drop due to lagging current.

θ is the angle of lag of the current. Meaning of other symbols is the same as in Fig. 31.

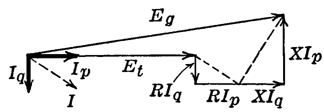

FIG. 33.—The components of voltage drop, with the same conditions as in FIG. 32.

I_p is power component of current (in phase with the voltage), I_q is quadrature component of current (90° from the voltage).

lag by an angle θ as in Fig. 32. The RI drop is in phase with the current, and the XI drop leads the current by 90°; but the reactance has a much greater effect than at 100 per cent. power factor, because it is partly in phase with the voltage. The relation between E_g and E_t can be found by considering the current I in its two components, as in Fig. 33. I_p is the power component ($= I \cos \theta$), and I_q the quadrature component ($= I \sin \theta$). The current is represented as lagging behind the voltage rather than leading, because a lagging current is more often found in practice. The total drop is that due to both of these components. We must take into account, then, the drop due to RI_p, RI_q, XI_p, and XI_q. In each case the RI drop is in phase with its current, as shown in the diagram, and each XI drop leads its current by 90°. The generator voltage, E_g, is the hypotenuse of a triangle whose base is equal to $E_t + RI_p + XI_q$, and whose vertical component is $XI_p - RI_q$. The relation between E_g and E_t is shown by the expression

$$E_g^2 = (E_t + RI_p + XI_q)^2 + (XI_p - RI_q)^2 \qquad (5)$$

In ordinary cases, the hypotenuse is very nearly the same as the base, and

$$E_g = E_t + RI_p + XI_q, \quad \text{or} \quad E_g - E_t = RI_p + XI_q \qquad (6)$$

That is, *unless the quantity* $(XI_p - RI_q)$ *is excessively large, the total drop may be computed as the resistance drop of the power component plus the reactance drop of the quadrature component.*

It should be noted that *both* a low power factor and a considerable reactance are necessary, for the reactance to have much effect on the voltage.

Consider the same case as before, except that the power factor is 86.6 per cent. According to equation (5)

$$\begin{aligned}
(E_t + RI_p + XI_q)^2 &= (220 + 11 \times 0.866 + 15 \times 0.5)^2 = 56{,}188 \\
(XI_p - RI_q)^2 &= (15 \times 0.866 - 11 \times 0.5)^2 = 42 \\
E_g^2 &= 56{,}230 \\
E_g &= 237.11
\end{aligned}$$

According to equation (6)

$$E_g = 220 + 11 \times 0.866 + 15 \times 0.5 = 237.04$$

Introducing an error of 0.03 per cent.

If the current is leading instead of lagging, I_q has a negative value.

Considering the same case as before, according to equation (5),

$$\begin{aligned}
(E_t + RI_p + XI_q) &= (220 + 11 \times 0.866 - 15 \times 0.5)^2 = 49{,}300 \\
(RI_q - XI_p)^2 &= (- 15 \times 0.866 - 11 \times 0.5)^2 = 342 \\
E_g^2 &= 49{,}642 \\
E_g &= 223
\end{aligned}$$

According to equation (6),

$$E_g = 220 + 11 \times 0.866 - 15 \times 0.5 = 222$$

Introducing an error of 0.4 per cent.

Polyphase Circuits.—In a three-phase Y-connected motor or other apparatus, as in Fig. 34(a), if the three windings are alike and the voltages of lines A, B, C are balanced (that is, $AB = BC = CA$), the point O is at neutral voltage, and voltage $OA = OB = OC$. If this apparatus takes current at 100 per cent. power factor, the three currents in a, b, c will be respectively in phase with voltages OA, OB, OC. If these circuits take lagging currents, they lag behind the respective voltages to *neutral,* or if leading currents they lead the same voltages.

In a delta-connected motor, Fig. 35(*a*), if the three elements are all alike, and each takes current at 100 per cent. power factor, the three currents are in phase with the respective voltages *AB*, *BC*, *CA*. The total current entering through lead *A* is the vector sum of currents *ab* and *ac*, and is represented by *aa* in Fig. 35(*b*). *This has the same phase relation as current a* in Fig.

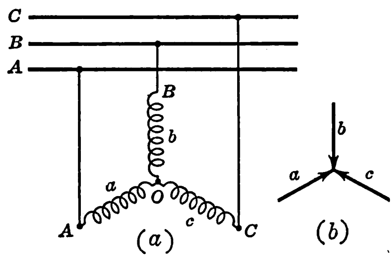

FIG. 34.—Y-connected motor, or other apparatus, on a 3-phase circuit. (*a*) Electrical connections. (*b*) Vector diagram of currents.

34(*b*). Similarly, if the currents *bb* and *cc* were shown, they would be in phase[1] with the corresponding currents, *b* and *c* in Fig. 34(*b*).

We shall now consider the voltage drop in a circuit furnishing current to a *Y*-connected motor or other apparatus; remembering that if it were delta-connected, the phase relations of the line

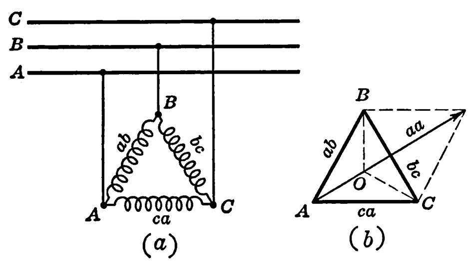

FIG. 35.—Delta-connected motor or other apparatus, on a 3-phase circuit. (*a*) Electrical connections. (*b*) Vector diagram of currents, showing that the total current taken from the line has the same phase relation as if the apparatus were Y-connected.

current, and therefore of the line drop, would be the same as with the *Y*-connection. We shall first find the voltage drop in a single line. In Fig. 36, *I* is the current in line *A*, and E_{Nt}

[1] Of course, if each phase *AB*, *BC* and *CA* takes a *leading* or *lagging current*, the resultant currents, *aa*, *bb*, *cc* are shifted through the same angle as their components.

is the voltage to neutral at the end of the line. The RI drop is in phase with I, and XI is 90° ahead of I, *exactly as in the single-phase diagram,* Figs. 32 and 33. Adding to E_{Nt} the RI and the XI drop, we obtain the voltage to neutral at the generator, E_{Ng}. The voltages of lines B and C to neutral are represented by dotted lines. The *terminal* voltage between lines, E_{Lt}, is shown, between the conductors A and B, and the corresponding *generator* voltage between lines is E_{Lg}. There is the usual ratio of voltage-between-lines to voltage-to-neutral;[1] $E_{Lt} = \sqrt{3}E_{Nt}$ and

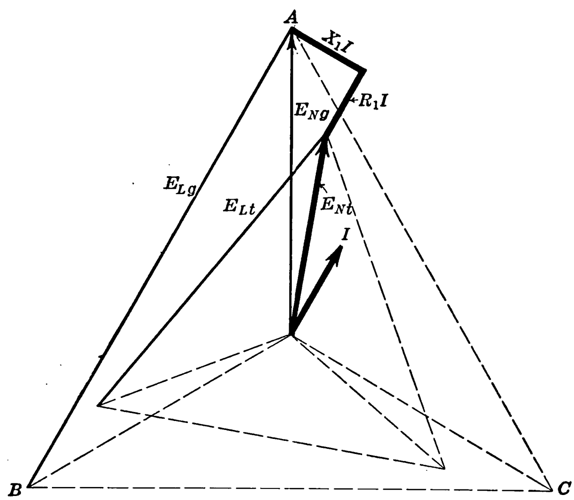

FIG. 36.—Vector diagram of line voltages and voltage drop in a three-phase circuit.

I is current in line A. R_1I is resistance drop in line A. X_1I is reactance drop in line A. E_{Nt} is terminal voltage between A and neutral. E_{Ng} is generator voltage between A and neutral. E_{Lt} is terminal voltage between A and B. E_{Lg} is generator voltage between A and B.

$E_{Lg} = \sqrt{3}E_{Ng}$, so that the decrease in line voltage, $E_{Lg} - E_{Lt}$, is $\sqrt{3}$ times the decrease in voltage to neutral, $E_{Ng} - E_{Nt}$. By comparing with equations (4) and (6), we find that if R_1 is the resistance and X_1 the reactance of a *single* line, the decrease in line voltage on a three-phase circuit at 100 per cent. power factor is,

$$E_{Lg} - E_{Lt} = \sqrt{3}R_1I \qquad (7)$$

and at other power factors,

$$E_{Lg} - E_{Lt} = \sqrt{3}\,(R_1I_p + X_1I_q) \qquad (8)$$

[1] G. 264, Fig. 263.

within the allowable error—assuming that the terms neglected in equations (4) and (6)are not excessively large.

A three-phase 220-volt, 60-cycle motor takes 100 amp. per lead at 80 per cent. power factor, lagging. The motor is 150 ft. from the bus, and the leads are No. 0 stranded conductors, spaced 6 in. apart. What generator voltage is required to provide the rated voltage at the motor?

From Table XII, page 80, $R_1 = 0.1021 \times 150/1{,}000 = 0.01531$.
$X_1 = (0.0464 + 0.0411) \times 150/1{,}000 = 0.01313$.
From Table XIII, $\sin\theta = 0.6$.
From equation (8), $E_{Lg} = 220 + \sqrt{3}(0.01531 \times 100 \times 0.80 + 0.01313 \times 100 \times 0.60) = 223.5$ volts.

TABLE XIII.—CORRESPONDING VALUES FOR POWER FACTOR AND SIN θ.
(For lower power factors, interchange the two rows.)

P.F.($=\cos\theta$)................	1.00	0.950	0.900	0.866	0.800	0.750	0.707
Sin θ........................	0.00	0.312	0.436	0.500	0.600	0.661	0.707

In a two-phase four-wire circuit, the voltage drop in each phase is independent of the other. It is treated exactly as in a single-phase system. On a two-phase three-wire system, the current in the common conductor is the resultant of the other two. In general the phase relation of this current is such that it unbalances a little the voltages of the two phases.

ECONOMY AND SAFETY

Computations for the most economical size of wire, and the requirements for safety are the same as for a D.C. system.

CONCLUSIONS

If the size of wire required for allowable drop, economy or safety is excessively large, the possibilities of improvement are greater than in case of a D.C. system.

Voltage Regulation.—To avoid large decrease of terminal voltage on account of line drop, we may apply apparatus in any one of several ways as follows:

Transformers, making possible a much higher transmission voltage.

Auto-transformers, making possible a little higher transmission voltage. (Auto-transformers cost less than transformers, if the ratio of transformation is small; but they have little or no advantage over transformers if the ratio exceeds 3:1. See Chapter VII, page 47).

Synchronous motors, raising the power factor and thereby eliminating the reactance drop.

Less space between conductors (*e.g.*, by putting them in a cable), thereby somewhat reducing the reactance.

Lower frequency, reducing the reactance.

Automatic voltage regulator, maintaining constant terminal voltage, even with large line drop.

Economy.—If the size of conductors required for economy is prohibitive, transformers or auto-transformers reduce the loss with a given size of conductor, inversely as the square of the transmission voltage, and a synchronous motor or a synchronous converter reduces the loss, inversely as the square of the ratio of the new to the old power factor of the line current.

Safety.—If the size of conductor is excessive for carrying the current safely, an increase in voltage should be considered. The current, and therefore the size of conductor, is thereby reduced. Thus, an increase in voltage is good for all the three requisites: regulation, economy, and safety.

CHAPTER XII

DIRECT-CURRENT GENERATORS[1]

CHARACTERISTICS

Three kinds of data are important to know about the behavior of any D.C. generator: (1) The regulation curve; (2) the efficiency curve; and (3) the load rating.

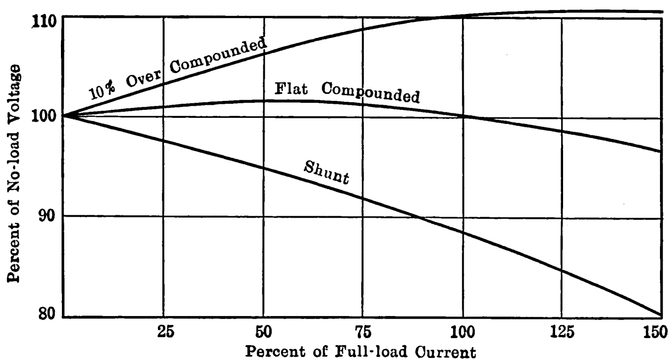

FIG. 37.—Regulation curves of shunt, flat-compounded, and over-compounded generators.

The regulation curve shows the variation of voltage, as the current output is increased from zero to an overload. All ordinary D.C. generators are shunt- or compound-wound. Their regulation is as illustrated in Fig. 37. The regulation curve of a small[2] shunt generator is poor. If the voltage is adjusted to the correct value at light load by the field rheostat, it drops off badly as the load increases; or if the adjustment is made at

[1] G. Chapter XIII, Characteristics; XVI, Efficiency; XXIV, Operation.
S. 8:144–156, Characteristics; 8:177–199, Weight, Cost, Connections; 8:236–256, Operation; 8:275, Acceptance Tests; 10:715–750, Applications.
A. pp. 653–654, Applications; pp. 674–675, Regulation and Efficiency; pp. 685–687, Operation, Cost, Weight.
See references to Chapter VIII, p. 51, for Train-lighting generators.

[2] Shunt generators with capacities of 1000 kw. or more frequently have fairly good regulation.

a heavy load, the voltage rises excessively when the load drops. If it is desirable for any reason to use small shunt generators, the voltage should be kept constant by an attendant who is ever-present, or by an automatic voltage regulator; otherwise, the apparatus that is on the system must be such as can operate on a wide range of voltage.

In the compound generator the voltage at full-load is equal to, or greater or less than at no-load, depending on the number of ampere-turns in the series field. If the voltage is the same at full-load as no-load, the generator is said to be *flat-compounded.* The voltage is then 2 to 6 per cent. higher at points between no-load and full-load. If the voltage is higher at full-load than at no-load, the generator is said to be *overcompounded.* The purpose of overcompounding is to compensate for line drop on long lines, which have relatively high resistances. Another reason for overcompounding is that even on lines of negligible drop the variation of voltage with load *at heavy loads* can be reduced. See Fig. 37. As explained later, it is possible to reduce the compounding of a generator, by putting resistance in parallel with the series field winding. This reduces the voltage by reducing the series field excitation at any given load. It is well to specify fully as much compounding as is ever likely to be required, because it can be reduced as much as necessary, but cannot be increased.

The efficiency of a generator is low at very light loads, because some losses, such as friction, are about as large at no-load as at full-load. The efficiency increases as the load increases; but it drops again at heavy overloads, because some losses, such as copper loss, vary as the square of the load. Generators are usually designed to have their maximum efficiency at 75 to 100 per cent. of the rated full-load, but they may have it at any desired load. Fig. 38 shows the characteristic shape of a generator efficiency curve, and illustrates the fact that the efficiency is nearly the same, through a rather wide range—on this particular machine from 75 per cent. to more than 125 per cent. of full-load. In general the larger the capacity of the machine, the higher is the maximum value of the efficiency. While the maximum value depends on the design and operating conditions, the following general figures are nearly correct for any good D.C. generator:

Kilowatt rating	Maximum efficiency, per cent.
10	85
50	90
1,000	93 to 95

These values also hold nearly true from half-load to 25 per cent. overload.

The load rating of a generator is usually the load that it will carry continuously without a temperature rise of more than 40° or 50°C.,[1] and without excessive sparking at the commutator.

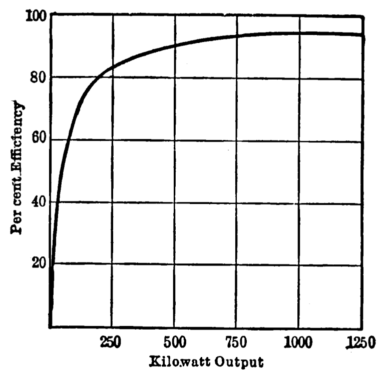

FIG. 38.—Efficiency curves of a 1,000 kw. 600 volt D.C. generator.

PARALLEL OPERATION

Shunt generators operate in parallel very satisfactorily, in that no special provision is required to divide the load between them, and there is very little danger that either machine will be damaged by a partial short-circuit, caused by unequal excitation of the fields. But the poor voltage regulation of small machines makes it impracticable to use them where any approach to constancy of voltage is required; unless there is some provision for voltage regulation, external to the machine.

Compound Generators.—*Adjustment of Compounding.*—Any two compound generators of the same voltage can be operated in parallel, if an equalizer is provided, and a suitable resistance

[1] The A.I.E.E. standardization rules, 1916, permit a temperature rise of 40°C. as measured by the thermometer at the hottest observable point, in machines having cotton, silk and similar insulating materials that are not impregnated. If impregnated, a rise of 50°C. is permitted. The best practice is to have the insulation impregnated.

is permanently connected, if necessary, in *series*[1] with the series field of one generator to adjust the compounding. This resistance should be adjusted so that the total current is divided between the two generators in the right proportion at all loads. It should be used, even if the machines have the same compounding when running separately, unless the *RI* drop in the series field at full-load is the same in the two generators.

If it is desired to reduce the compounding of the *entire plant*, a resistance may be permanently connected in *parallel* with the series field of each machine, as indicated in a previous paragraph; but as the series fields of the several generators are in parallel, *any* shunting resistance is in parallel with *all* the series fields, and does not affect one field much more than another. Thus, where compound generators operate in parallel:

Use shunt resistance in parallel with each series field, to change the compounding of the entire plant.

Use series resistance to change compounding of one machine relative to another. Sometimes a shunt resistance is required in addition, where the generators have dissimilar series field or armature windings.

Connections.—Fig. 1, page 2, shows the principal connections of two compound generators operating in parallel. The equalizer is not necessarily on the switchboard, but to save copper and labor (in cases where the leads are very heavy) it is run under the floor from machine to machine, and connected to switches, mounted on posts or "equalizer pedestals." The saving is considerable in some cases, because the cross-section of the equalizer lead should be at least one-third of that of the main leads.

Switch and Circuit-breaker.—Each generator should have a switch, and either a circuit-breaker or fuse, completely disconnecting at least one pole of the generator. Usually the switches disconnect both poles, even if there is only a single-pole circuit-breaker. If there is an equalizer connection, and only a single-pole circuit-breaker is to be used, the breaker should be connected to the armature terminal that has no equalizer lead.

Meters.—There should be an ammeter in each generator circuit, and a voltmeter that can be connected to a plug switch, across any generator, before that generator is connected to the

[1] And another, if necessary in parallel.

bus. The same voltmeter may be used to measure bus voltage, when another plug switch is used.

Field Rheostat.—A field rheostat is always to be inserted in the shunt field circuit, for voltage regulation. The maximum current of the shunt field winding (when the resistance of the rheostat is cut out) is 1.5 to 3 per cent. of the current output of the generator. The rheostat should therefore have a corresponding maximum current capacity; and for a good control of the voltage the maximum resistance of the rheostat should be about the same as the resistance of the field winding.

COST, WEIGHT AND AVAILABLE SIZES

Cost.—The approximate selling prices of typical 550-volt D.C. generators of usual speeds are given in the list on page 185. At other voltages the same values may be assumed, at least for a first approximation.

Available Sizes.—Usually a machine can be obtained within 25 or 50 per cent. of any desired size. The exact sizes that are available are different in different lines of machines, but the following is a suitable list of sizes in kilowatts, of D.C. generators: 1, 2, 3, 5, 7½, 10, 12½, 15, 20, 25, 35, 50, 60, 75, 100, 125, 150, 200, 300, 400, 500, 600, 750, 1,000, 1,250, 1,500, 2,000, 2,500. Engine-driven generators are usually between 25 and 500 kw.

NUMBER AND SIZE OF GENERATORS

For determining the number of generators, and the size of each, we may proceed as follows:

Kilowatt Capacity of Plant.—First refer to time-load curves of the station, if they are available,[1] and find the maximum power

[1] If time-load curves are not available, take the total connected load (*i.e.*, the sum total of all power that would be furnished if all machines and lamps were in operation at full-load at the same time) and multiply by the *demand factor*, which is the ratio of maximum actual demand to the total connected load. The demand factor for power and lighting, for machine shops and factories, varies through a wide range; but its usual value is about 55 per cent. For power consumers in general, having more than one motor installed, the average of the demand factors in a large number of cases has been found to depend on the total horsepower of motors installed. The following empirical expression indicates what the demand factor is likely to be for any given installation:

$$\text{Demand factor} = 40 \text{ per cent.} \times (\text{HP.} + 30)/(\text{HP.} + 15)$$

where HP. is the total horsepower of the motors installed.

that the plant is regularly required to deliver for any considerable time—say for 2 or 3 hr. (for loads of shorter duration see the note on "*Intermittent Loads,*" page 183). Taking this as the required full-load capacity of the plant, the sum of the rated capacities of the several generators must be *at least* as much as this value. The next paragraph cites conditions such that the total generator capacity must exceed this value.

Allowance for Accidents and Repairs.—When one generator is out of commission for any reason, the other machines must be able to carry the load safely. If there are five or more machines of equal size in the station, the overload when one is shut down is not over 25 per cent., and usually each generator is designed to carry that overload for a time; but if there are less than five generators, the emergency overload is more than 25 per cent., and would be excessive, if it is carried for any considerable time. On this account, the sum of the machine ratings, when any generator is omitted, must equal *at least* 80 per cent. of the station peak load; and it is better that the available generator capacity be 90 or 100 per cent. of the peak load, if it is of long duration (see p. 94 for overload ratings). It is good policy, in general, to overload electrical machines as little as practicable, even though they seem to carry the overload successfully, because there is a gradual deterioration of the insulation with excessive heating.

Number of Generators.—The larger the generator, the less the first cost per kilowatt, and the higher the efficiency of the engine and generator. On the other hand, with a few larger machines the investment in the idle machine is greater. The best number of machines is a compromise between maximum efficiency and minimum investment in the spare engine-generator set. It may be found by trial, by such a method as the following:

The annual cost for fixed charges, and expenses for operating and maintenance are estimated for a suitable combination of, say, two generators, and then repeated for a suitable combination of three generators; and the estimates are if necessary continued, increasing the number of machines until the minimum total annual cost is reached, beyond which an increase in the number of generators results in an increase in the total annual cost.

A numerical example will illustrate the method of computation. Assume the following data:

The plant is required to deliver 2,000 kw., 24 hr. per day, 280 days per year.

Fixed charges for interest, depreciation, insurance and taxes amount to a total of 15 per cent. of the first cost.

The only first cost to be considered is that for engines and generators. No other costs are assumed to be greatly affected by changing the number of generating units.

Cost of engines and generators is as indicated on page 185.

Operating expense per kilowatt-hour of energy delivered to the switchboard, including fuel, attendance, supplies and repairs, but not including fixed charges, is as follows for various numbers and sizes of generating units, under the conditions of operation of this plant:

Number of generating units......	2	3	4	5	6
Output rating of each, kilowatts	2,000	1,000	750	500	400
Cost in cents per kilowatt-hour delivered, for operation and maintenance,[1] including fuel, labor, and supplies....................	0.6	0.65	0.7	0.8	0.9

From the above data we derive the following:

Since the plant is loaded continuously, the total capacity must be 2,000 kw., when one machine is shut down.

Number of units..............	2	3	4	5	6
Size of each generator in kilowatts (see "Sizes Available," page 96)......................	2,000	1,000	750	500	400
First cost of each generator.....	$16,300	$8,300	$6,300	$4,300	$3,500
First cost of each engine........	$40,500	$20,500	$15,500	$10,500	$8,500
Total first cost of each unit.....	$56,800	$28,800	$21,800	$14,800	$12,000
Annual fixed charges for each unit at 15 per cent	$8,520	$4,320	$3,270	$2,220	$1,800
Total energy delivered, by each unit, per year, in millions of kilowatt-hours..............	6.7	4.47	3.78[2]	2.68	2.24
Fixed charges in cents, per kilowatt-hour...................	0.127	0.097	0.087	0.083	0.080
Operating cost in cents, per kilowatt-hour..................	0.6	0.65	0.7	0.8	0.9
Total cost in cents, per kilowatt-hour......................	0.727	0.747	0.787	0.883	0.980

This shows that in spite of the large investment, it pays to install two 2,000-kw. units. A combination of smaller units would be advantageous if the machines were loaded only 8 hr. or less instead of 24 hr. per day.

[1] If the generator is driven by a compound steam engine.

[2] Assume that with this combination of 750-kw. generators all but one is in service at full-load continuously. This is not quite true, because the joint capacity of three machines is 2,250 kw., whereas only 2,000 kw. is the continuous output; but in actual practice usually the full-load requirements of the plant are not so definitely fixed, and there is an advantage in the increased

capacity of the generators. If this is unnecessarily large, the plant may consist of two 600-kw. and two 750-kw. units, which would carry the 2,000-kw. load with hardly an appreciable overload, when any one generator is shut down. Another arrangement would be to have three 750-kw. units and one 500-kw. It is better, however, for the sake of fewer repair parts, to have all the units of the same size rather than to have some a trifle smaller than the others.

CHAPTER XIII

ALTERNATING-CURRENT GENERATORS[1]

CLASSIFICATIONS

Alternators (alternating-current generators) may be variously classified as follows:

Phases.—A single-phase generator is simpler in construction than a polyphase, but it has the objections (1) that the armature conductors cannot be placed so advantageously for economical design;[2] and (2) that single-phase is not so well adapted as polyphase to most of the A.C. motor applications. On account of these objections, nearly all A.C. power is generated as two-phase and three-phase; and of these three-phase is the more common on account of some minor advantages in distribution and use.[3]

Connections between Phases.—Three-phase generators (which nearly always have the phases connected together at the generator) are either *Y*- or delta-connected, the *Y*-connection being preferred (see Fig. 39).

Two-phase generators nearly always have the phases independent, that is, insulated from each other. This is because interconnection is unnecessary for good operation of the system; and it is safer to insulate the phases within the machine, unless there is some reason for interconnection (see Fig. 40(*a*)). If a neutral lead is brought out, for grounding, or for multiple-voltage applications, the neutral points are interconnected, as in Fig. 40(*b*). If the generator is not interconnected as in Fig. 40(*b*), it may be connected to a two-phase three-wire circuit, as in Fig. 40(*c*).

[1] G. Chapter XXXI, Construction and Connections; XXXII, Characteristics.

S. 7:1–15, Types; 7:87–91, Operation; 7:146, Weights; 10:269, 715–750, Costs and Applications.

A. pp. 616–619, Types and Ratings; 638, Efficiency; 645, Phase-connections; 647–652, Operation, weight, cost, speed.

[2] If a single-phase and a polyphase machine have the same size of frame, and run at the same speed, the kilovolt-ampere capacity of the single-phase is from 60 to 70 per cent. of that of the polyphase. See G. 260.

[3] See Chapter III, p. 17, for the advantages of each kind of system.

Frequency should be adapted to the apparatus loaded on the circuits (see Chapter III). In the United States, 60 cycles is the most common frequency. It is used advantageously for arc and incandescent lighting, induction and synchronous motors,

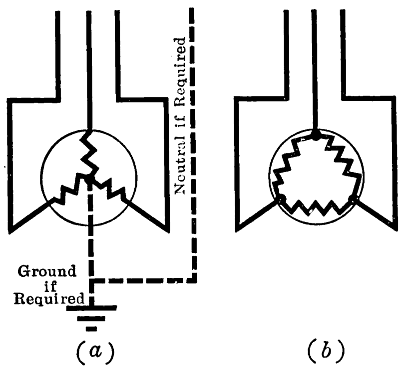

FIG. 39.—Three-phase generators.
(a) Y-connected. (b) Delta-connected.

synchronous converters, and other applications. The only other standard frequency in this country is 25 cycles; an important use for it is in driving single-phase railway motors and slow-speed induction motors.[1] In purchasing a generator it is of

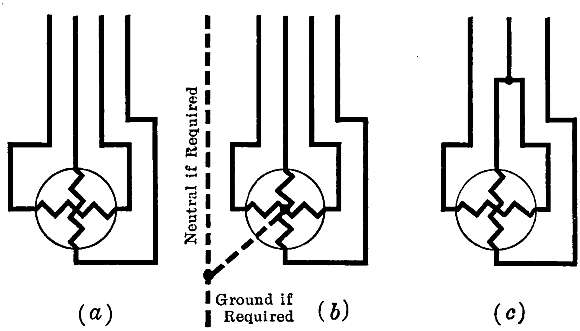

FIG. 40.—Two-phase generators.
(a) Phases independent. (b) Phases interconnected. (c) Two-phase three-wire circuit.

advantage to select one of standard frequency if possible, because by following a standard design, the cost may be less, the delivery more prompt, and operation better.

[1] 25-cycle circuits are also in general use for large transmission, and distribution systems, where power is required for railway and lighting purposes.

Speed and Prime Mover.—The higher the speed of a generator or motor, the more power it can develop, until it reaches the limit of safe or practicable speed. This fact, together with the advantage of high efficiency of the prime mover, is causing turbo-generator sets to be introduced more and more exclusively for all steam-driven A.C. circuits that are of considerable size. The best operating speed of a turbine makes it necessary that the generator have either two or four poles. For 60-cycles, which is the usual frequency, turbo-generators of sizes up to 6,500 kva. usually have two poles, and run at 3,600 r.p.m. Above that capacity, up to 35,000 kva., they have four poles and run at 1,800 r.p.m.

Small alternators are still driven by reciprocating engines, in some cases; these and all large and small generators driven by waterwheels and gas engines run at slower speeds—from 58 r.p.m.[1] for large, slow-speed units, to 900 r.p.m. for high-speed generators suitable for certain applications with waterwheels.

Voltage.[2]—There is no essential difference between high- and low-voltage alternators except the insulation of the armature conductors. But at very high voltages the relative amount of space required for insulation is large, especially in small generators which have only a small total space for armature windings. For this reason, the smaller the kilovolt-ampere capacity, the lower the voltage for which it pays to build the generator. The largest generators are rarely made to operate at more than 13,200 volts. A very common generator voltage is 2,300 or 2,400 volts. It is sufficient for local distribution for several miles, without excessive line drop, and at good efficiency. Sometimes a generator is wound for 2,300 volts with a delta-connection, and insulated well enough to change later to a *Y*-connection, which gives 4,000 volts. Alternators at higher voltages, although not so common, can be furnished as required. Lower voltages, especially 220, 440 and 550 volts, are well suited to many industrial plants.

Revolving Field and Revolving Armature.—The old form of alternator was like a D.C. generator, in that it had a revolving armature. It has now been displaced, except for a few of the very small low-voltage generators, by the revolving field. It is

[1] The Keokuk waterwheel alternators have 124 poles, and run at 58 r.p.m. S. 7:14.

[2] See Chapter III.

easier to bring the high-tension current of the armature through the leads from the stationary winding than through slip-rings, and it is easier to mount and insulate the heavy armature winding on a stationary than on a moving structure.

CHARACTERISTICS

In general the same information is required regarding the operation of alternators as of D.C. generators; and some additional information is also necessary:

Regulation.—The regulation of an alternator is different at different power factors, as illustrated in Fig. 41. With a lagging current, a large decrease in voltage is produced by bringing the

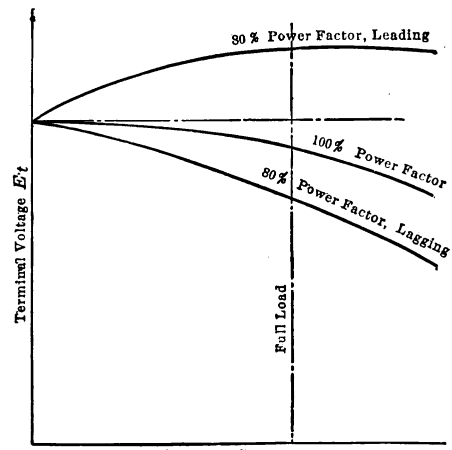

FIG. 41.—Regulation curves of an alternator.

current from no-load up to full-load. With current at 100 per cent. power factor, the decrease is not so great, and with a leading current, the voltage decreases still less or it may actually increase, as is shown in the curve. The difference between these curves is easily explained when we consider the phase relation between induced voltage and the voltage drop in the armature due to impedance.

The efficiency of an alternator with a load at 100 per cent. power factor is practically the same as for a D.C. generator of the same size.[1] For the largest sizes of alternators—from 5,000

[1] See Chapter XII, p. 94, Efficiency curve, and table of maximum efficiencies.

kva. up—the maximum efficiency is as high as 96 or 97 per cent.

The load rating of an alternator is based on temperature rise, as is a D.C. generator rating;[1] but it should be expressed in kilovolt-amperes rather than in kilowatts, because the limiting current output is no greater at low than at high power factor.[2] The output capacities of single-phase and polyphase alternators are as follows:

Single-phase, kva. = kw./P.F. = $EI/1{,}000$

where E is the voltage between terminals, I the rated current of each lead, and P.F. the power factor of the load.

Two-phase, kva. = kw./P.F. = $2 \times EI/1{,}000$.
Three-phase, kva. = kw./P.F. = $\sqrt{3} \times EI/1{,}000$.

In three-phase generators, the current, I, must always be understood as the current per phase in the *external* circuit, and the voltage, E, that between *external* lines.

The engine capacity is based on the *kilowatt,* rather than the kilovolt-ampere output, after allowing for generator efficiency.

REQUISITES FOR PLANT OPERATION

Regulation of Prime Movers and Alternators.[3]—The speed regulation of two engines must be the same in order that two alternators in parallel shall automatically divide the load equally between them when it fluctuates. This is evident, when we consider that, except for a little hunting,[4] alternators operating in parallel and having the same number of poles must have exactly the same speed. If engine A has its governor set for a higher speed than engine B, it will if necessary pull engine B along, by driving generator B as a synchronous motor. In actual operation, if the two engines are governed to have very nearly the same speeds, engine A takes a little the larger part of the load, and that brings its speed down a trifle, according to its speed-regulation curve, until the two speeds are equal.

[1] See Chapter XII, p. 94.

[2] See Chapter, VII, p. 94.

[3] G. 287, 288.

[4] In hunting, one machine speeds up temporarily, so that it leads the other by a small fraction of a cycle; then it slows down until it lags. The machines do not fall out of step, but if the hunting is bad it produces a troublesome pulsation of the current.

If the steam is properly controlled, the two engines may be made to deliver the same amounts of power.

Let us now consider the generators. Just as the engines must have exactly the same speed, the alternators must have exactly the same terminal voltages, neglecting a small drop in the leads to the buses. The power outputs of the two engines are about the same, and the efficiencies of the two alternators are high, so that the *power* outputs of the two alternators must be about equal. The *current* relation of the two generators depends on their load-characteristic curves (see Fig. 41). If one of them has more of a drooping characteristic than the other, it will necessarily deliver a current leading that of the other generator, since the terminal voltages of the two must be equal.

Even if the generators have similar load characteristics, when the rheostats are set differently on the two, the generator having the weaker field will take the leading current.

For perfect parallel operation of alternators at all loads, there are, then, three conditions: (1) that the prime movers have the same variation of speed with load; (2) that the generators have similar load-characteristic curves; and (3) that the field rheostats be so adjusted that the no-load voltages are equal.

Synchronizing.—Three conditions must be satisfied, at least approximately, on all phases, before two alternators can safely be thrown in parallel: (1) The voltages must be equal; (2) the frequencies must be the same; and (3) corresponding circuits of the alternators must be in phase. The voltage is controlled by the generator field rheostat, and measured by means of a voltmeter that can be connected to any generator, by a plug switch.[1] The frequency and phase relation are controlled by the speed of the motor or prime mover, and are indicated by lamps or a synchronism indicator [2] connected by plug switches between the two machines. After the machines have been properly installed, it is necessary only to compare voltages on one phase and to synchronize on one phase, because the ratio of voltages, and the lagging or leading are the same on one phase as on another. If the generator voltage is more than 110 or 220, it is customary to use voltage transformers, having a secondary of about 110 volts, for use with the voltmeter, lamps, and synchronism indicator. Some engineers prefer to synchronize

[1] See Chapter XIX, p. 159.

[2] Sometimes called a synchronoscope. See Chapter XIX, p. 150.

between the buses and the generator that is being started, instead of between one generator and another. The method is essentially the same as that just explained, except that synchronizing connections are always made as if the buses were the running machine.

Connections.—The principal connections of two three-phase alternators operating in parallel are shown in Fig. 2, page 2. In small plants of low voltage, the buses are mounted on or near the switchboard; but in large high-tension plants, only the small secondary circuits of the current and voltage transformers, illustrated in Fig. 3, page 3, and some or all of the D.C. circuits are brought to the switchboard. With such an arrangement all measurements are made and the entire plant is controlled, by means of apparatus on the switchboard; but it would incur unnecessary expense to bring the principal leads, as well as the secondary circuits to the board.

Switch, but No Circuit-breaker.—It is common practice to open all phases of each generator circuit by a two-, three- or four-pole switch. Usually an oil switch is used for this purpose, but for a small generator of 600 volts or less, a knife switch may be used. It is the best practice to omit circuit-breakers on A.C. generator circuits; because the short-circuit current of the generator is not so high as to be dangerous to the machine for a short time, and it is better not to disconnect the machine automatically when a heavy current occurs, thereby putting the total load on the other machines. There are overload circuit-breakers in the outgoing feeders, and these offer sufficient protection to the generators.

Meters.—(1) There must be means for measuring the current in each phase. This usually consists of one ammeter for each generator, and a switching device for inserting the meter in any phase, as desired (see Chapter XIX, pages 160, 161). Usually the ammeter is connected to the secondaries of current transformers. (2) There must be a voltmeter and synchronizing outfit as mentioned above, under *synchronizing*. Usually only one voltmeter and one synchronism indicator are necessary for the entire station. (3) It is important to know the power factor of the load on each generator, in order to bring it as near unity as possible. For this a power-factor meter is valuable, although the power factor can be calculated if watts, amperes and volts are known. (4) Sometimes a wattmeter is preferable to a power-factor meter, especially if the kilowatt output of each generator is to be observed closely. Sometimes, but rarely, both a power-factor meter and a wattmeter are used. (5) In addition, if permanent records are to be kept, graphic and integrating meters may be included as mentioned in Chapter XIX, page 164.

Means for Voltage Regulation.—The voltage variation of an alternator with variation of current and power factor is so great that some means must be provided, outside the generator, to obtain even approximately constant terminal voltage. This regulation is most successfully accomplished by the automatic or hand control of the generator field current, either directly, or more often indirectly through the control of the exciter field.[1]

Excitation.—*Arrangement of Exciters.*—If each generator does not have its own exciter, it is good practice to provide two or more exciters in the station, of sufficient capacity to carry the total excitation load with one exciter shut down. The exciters are usually compound-wound, and arranged so that if desired they may be operated in parallel. They may be either motor- or steam-driven. Motor-driven exciters are efficient and simple in their operation, and should be used wherever practicable; but there must be at least one exciter that has some way of running, before there is any voltage on the A.C. buses. Exciter connections and equipment are in general the same as in case of other D.C. generators, except that circuit-breakers are usually omitted, special switches are used for connecting to the alternator fields, and the voltage regulator is usually connected to the exciter-field rheostats.

Switches.—Ordinary knife switches can be used for connecting the exciters to the exciter buses, provided a special field switch is inserted between the exciter buses and each alternator field. This field switch must be so constructed that even when it is partly opened the current in the generator field winding can continue to flow until it has gradually died away. The inductance of the field winding of a large alternator is so great that, if such a provision were not made, the extremely high voltage caused by opening the circuit suddenly would strain, and perhaps puncture the insulation of the field winding. One arrangement of such a field switch is shown in Fig. 42. Besides the main switch-contacts there is an extra contact that is closed at just the instant before the main contacts are opened. The field current can

[1] See Chapters XIV and XVI, for means for automatic voltage regulation.

circulate through this contact and a resistance box in series with it, until the energy stored in the field is dissipated.

Voltage and Power-factor Adjustments by Rheostats.—Where alternators are operating in parallel, it may be necessary to change the voltage of a single generator, in order to change the power factor on that machine. But in order to raise or lower the voltage at the buses, the voltages of all the generators should be changed together. Each of these changes can be made readily by a suitable manipulation of the exciter and alternator rheostats. The appropriate current capacities and maximum resistances of alternator- and exciter-field rheostats can be obtained from the following:

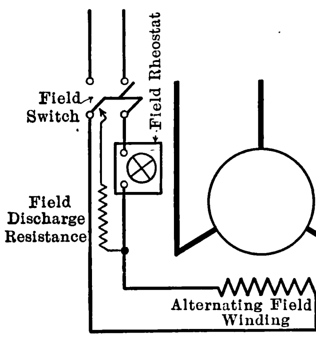

FIG. 42.—Alternator field connections through a field switch, with field-discharge resistance.

Size of Alternator-field Rheostats.—It is found in practice that this rheostat should have about twice as much resistance as the alternator-field winding. Of course, it should also have the same maximum current capacity as the field winding. The alternator-field current, and the resistance of the field winding can be found approximately for a given voltage of excitation from the fact that the maximum power in kilowatts expended in exciting a turbo-generator is 0.75 to 1.5 per cent. of the kilovolt-ampere capacity of the alternator; the power required for exciting slower speed generators, driven by engines and waterwheels, is 1.5 to 3 per cent.

Exciter-field Rheostats.—For exciters, it is found in practice that generally the resistance of the field rheostat should be about the same as that of the exciter-field winding. The exciter shunt-field current and resistance can be determined from the fact that the maximum field current is 1 to 3 per cent. of the output current rating of the exciter.

Cost.—The approximate selling price can be obtained from page 185.

CHAPTER XIV

REGULATING TRANSFORMERS

Transformers with variable ratios are used to regulate current and voltage. For the best operation, this regulation should be automatic, but there are cases where hand regulation is allowable. There are two distinct kinds of regulating transformers in common use: the constant-current regulating transformer, and the induction voltage regulator.

The constant-current regulating transformer[1] (or constant-current transformer—which must not be confused with the current or ammeter transformer) has a stationary primary winding and a movable secondary.[2] The repulsive force between the two windings is counterbalanced by a weight; when the current becomes too great, it predominates over the weight, and moves one away from the other. When the secondary is so moved, only a part of the primary flux links with the secondary, and only a part of the secondary flux links with the primary, so that the terminal voltage of the secondary automatically decreases enough to bring the current to the steady value for which it is counterbalanced. This transformer is used for obtaining constant current for series arc- and tungsten-lighting circuits, when the primary is connected to a suitable constant-potential A.C. circuit. By changing the counterweight, the value of the secondary current is correspondingly changed. Customary line currents range from 3½ to 10 amp. The connections of constant-current regulating transformers are illustrated in Fig. 43. The primaries are in each case connected to three-phase constant-potential buses through oil switches. Each transformer circuit is essentially single-phase, on both primary and secondary, even though connections are made to a three-phase bus. The complete secondary circuit of one of the transformers is shown. The others have similar circuits which are omitted from the diagram.

Directly across the secondary is either a plug, or an oil switch, P_1, by which it can be short-circuited. Such a short-circuit does

[1] G. 295, S.6: 9, 162–172. Compare 6: 249–252; A. p. 1606.

[2] Or stationary secondary and movable primary.

no harm, as noted above, but causes the secondary to move away from the primary, so that it is taking practically no power from the primary. This plug should be inserted before the oil switch in the primary is opened.

Two other plug or oil switches, P_2, P_2, are in series with the secondary line, connecting the transformer to the outside circuit. If there are several transformers and several outside circuits, sometimes the switches are arranged so that any transformer can be connected to any circuit. An ammeter is in series with the secondary, to indicate whether the current remains at the right value. If it is too high or too low, it is brought to

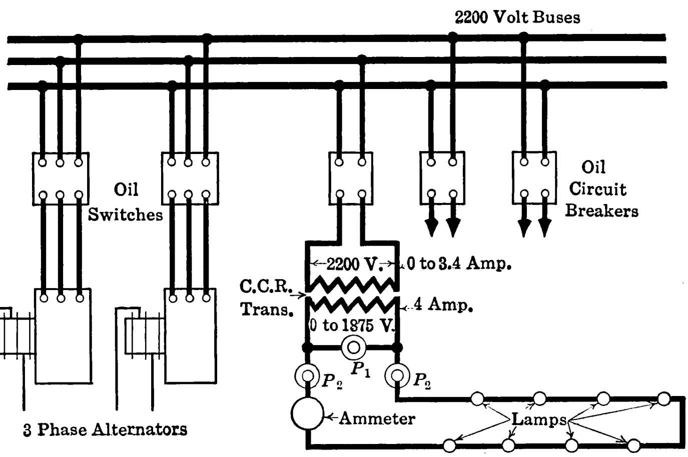

FIG. 43.—Constant-current regulating transformer with primary connected to constant voltage buses and secondary connected to a series-lighting circuit.

the right value by adjusting the counterweight. In the outside circuit, all the lamps are connected in series. These may be either arc or tungsten lamps; the present tendency is toward tungsten lamps.

If one of these transformers is to operate from 2,200-volt buses, to light a maximum of seventy-five 100-watt, 4-amp. lamps, assuming that line drop is negligible,

Transformer secondary ampere capacity	= 4	= 4
Transformer secondary kilovolt-ampere capacity	= 75/1,000 × 100	= 7.5
Transformer secondary voltage capacity	= 7.5 × 1,000/4	= 1,875
Transformer primary voltage capacity	= 2,200	= 2,200
Transformer primary kilovolt-ampere capacity	=	approximately 7.5
Transformer primary ampere capacity	=	approximately 7.5 × 1,000/2,200 = 3.4

As the number of lamps decreases, the secondary voltage approaches zero.

Constant-current A.C. circuits are best suited for use where small amounts of single-phase power are required at low voltage, at points along an extended line, or over a large area. These restrictions practically limit constant-current A.C. circuits to series-lighting systems in streets, parks, railroad and factory yards, and large buildings. They are admirably adapted to such systems—especially for tungsten lighting, because the best efficiency of tungsten lamps is on such a very low voltage per lamp as can be applied only where the lamps are put in series. Furthermore, the candlepower of a tungsten lamp does not decrease as much with aging on a constant-current as on a constant potential circuit.

The induction voltage regulator[1] is essentially a transformer in which the primary is connected across the buses, and

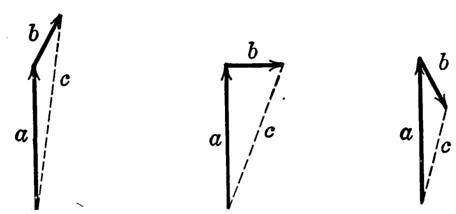

FIG. 44.—Vector diagram of voltages of polyphase induction voltage regulator.

a is bus voltage. *b* is regulator secondary voltage. *c*, the dotted line, is the resulting feeder voltage. In position 1, the regulator is turned nearly to the position of maximum feeder voltage. In position 2, the feeder voltage is very little more than the bus voltage. In position 3, the feeder voltage is much less than the bus voltage.

the secondary in series with the line. The primary is made rotatable, and the heavy secondary winding is stationary. The voltage induced in the secondary either increases or decreases the line voltage, by an amount depending on the relative positions of primary and secondary. These regulators are made both as single-phase and as polyphase. In the polyphase regulator there is a primary and a secondary winding for each phase, so that the voltages are increased or decreased on all phases at the same time. The vector diagram, Fig. 44, shows how voltage regulation is accomplished on a polyphase regulator. In position 1, the bus or primary voltage, *a*, and secondary, *b*, are nearly in phase; and the resultant line voltage, *c*, is nearly at its maximum. In position 2, the secondary is 90° out of phase with the primary, and the line voltage, *c*, is almost the same as the bus voltage.

[1] G. 308, 369; S.6: 238–248; 24: 210–214; A. p. 1607.

In position 3 the primary and secondary are nearly in opposition, and the voltage of the line is smaller than that of the bus.

The connections of a polyphase regulator are illustrated in Fig. 45. The diagram represents the regulator as located at the beginning of the feeder, with its primary connected through an oil circuit-breaker to the power-station buses. This is according to standard practice. The three primary windings of the regulator, *a, a, a,* are delta-connected, and the three secondaries are in series with the three conductors of the outgoing feeder. The voltages indicated on the diagram are typical of regulator operation: the primary voltage is 2,300; the regulator raises it to 2,500, and line drop brings it down to 2,200 at the end of the line.

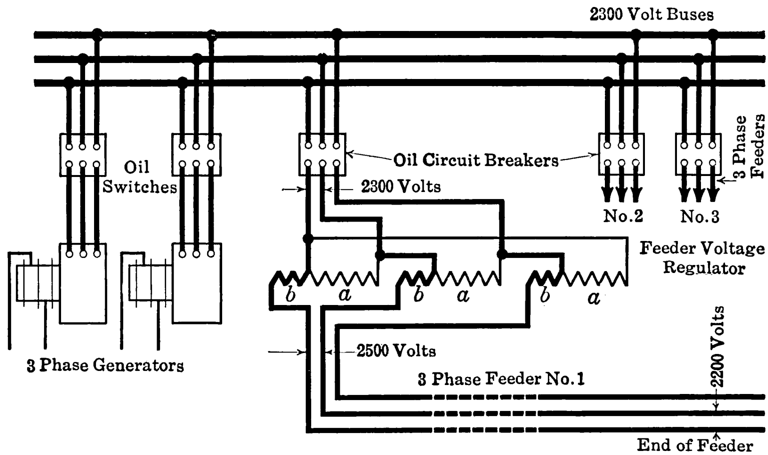

FIG. 45.—Three-phase induction feeder voltage regulator and connected equipment.
a = Primary circuits, between lines. *b* = Secondary circuits, in series with lines.

When the line current is so small that the line drop is negligible, the feeder terminal voltage would rise to 2,300, except for the regulator; but the regulator is turned to such a position that it decreases instead of increases the voltage, thereby holding it constant at 2,200. The connections for a single-phase regulator are the same as for one phase of a three-phase regulator. The number of turns in the secondary is usually 5, 10, or 20 per cent. of the number in the primary, so that the maximum possible boosting or bucking is 5, 10, or 20 per cent. of the primary voltage.

The regulators can be operated by hand; but in many cases it is important to maintain a constant voltage without keeping an operator continually watching the voltmeter. A relay (sometimes called a contact-making voltmeter) is then used, which controls the regulator and automatically raises the voltage, when it is too low at the end of the line. The method of accomplishing this is described in Chapter XVI.

Voltage regulators fill important places where there are several feeders of different lengths, each having a different line drop. It is not possible to regulate the generator voltage for all these feeders, because when the line drop is large on one feeder it may be small on another. Thus in Fig. 45, if regulators are put on feeders Nos. 2 and 3, the terminal voltages of those feeders, as well as of No. 1, are maintained constant.

CHAPTER XV

INSTRUMENT TRANSFORMERS[1]

These transformers differ from all the foregoing, in that their secondaries connect only to meters, relays, and similar apparatus, so that in some sense they furnish no useful power. There are two kinds of instrument transformers—voltage and current transformers.

1. Voltage transformers (otherwise known as shunt, potential or voltmeter transformers) are the same in form, winding and theory of operation as the power transformers that carry the main currents. They have the same connections in their primaries as power transformers sometimes have.[2] But they are very much smaller—having a capacity of 200 volt-amp. or less—and are used only to furnish power to voltmeters, and the voltage windings of wattmeters, over- and undervoltage relays, voltage-regulating relays and the like. Besides reducing the voltage to a value that is convenient for use with the various instruments, they insulate the instruments from the high-tension circuit, so that they may be handled safely.

The primaries of these transformers are made for all the voltages that are used in practice. The secondaries are commonly wound for about 110 volts, thereby adapting the transformers for use with ordinary instruments.

There is a slight variation of the secondary voltage, dependent on the phase and amount of current flowing from the transformer to the meters, but a good transformer holds a true ratio between primary and secondary voltages, within a fraction of 1 per cent.,

[1] "Characteristics and Grouping of Current Transformers," by Harold W. Brown. *The Electric Journal*, vol. VIII, 1911, pp. 642, 1023, 1109. See also references on Chapter XVI, p. 121.

S. 6:10, 182–192; 3:79, 103–105; 24:741, Theory, Errors, Applications. S. 10:826, 827, Costs. A. pp. 1638–1652, Theory, Errors, Applications, Costs.

[2] See Chapter VII, p. 49.

if the voltage is reasonably high but not above the rated voltage, and the current is not in excess of the rating.

Based on this accuracy of transformation, it is rather interesting to see how fully all the conditions of the primary are reproduced in miniature in the secondary. Instead of winding instruments at great expense for 2,200 to 110,000 volts, or whatever the line voltage may be, they are nearly all wound for the standard 110 volts, and the task of the voltage transformers is to show on 100 volts all the fluctuations and the phase relations that exist on the high-voltage line.

The connection of voltage transformers almost invariably used on three-phase circuits is that shown in Fig. 46, which is the *V*-connection. It was stated in Chapter VII that this connection is not good for ordinary power purposes; but for instrument use, the power handled is so small, and the secondary voltage so constant even with an unsymmetrical arrangement of transformers, that it is in practically universal use. The advantage over a delta-connection is in the saving in cost and space, and in simplicity of connections. The three secondary voltages, *ab*, *bc*, *ca*, correspond in phase and amount to the primary voltages, *AB*, *BC*, *CA*. On two-phase four-wire circuits there are four, instead of three primary leads—two from phase *A* to one transformer, and two from phase *B* to the other. For simplicity of wiring, the secondary connections are the same as for three-phase—requiring only three, instead of four wires. This is illustrated in Fig. 47.

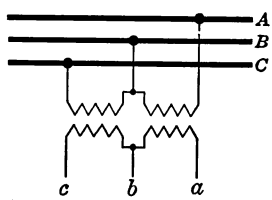

FIG. 46.—Grouping of voltage transformers on a three-phase circuit.

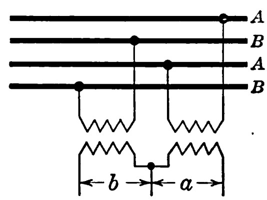

FIG. 47.—Grouping of voltage transformers on a two-phase circuit.

There are various other ways of grouping voltage transformers, but they are rarely used. They correspond to the groups of power transformers, shown in Fig. 23, page 49.

The following are customary primary voltage ratings of voltage transformers:

200	4,000	20,000
400	5,000	25,000
500	6,000	30,000
600	10,000	40,000
1,000	12,000	50,000
2,000	15,000	60,000
3,000		

Current Transformers (otherwise called Series or Ammeter Transformers).—The construction of one form of current transformer is illustrated in Fig. 48. The laminated punchings are represented as circular; they may be of any convenient shape. With this form of transformer, the primary is simply a straight conductor passing through the opening in the punchings. The alternating current in the primary induces a flux in the iron

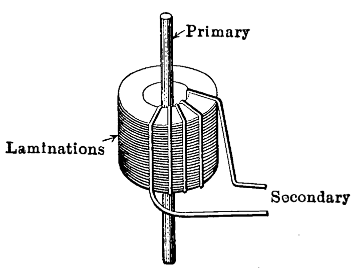

FIG. 48.—One kind of current transformer.

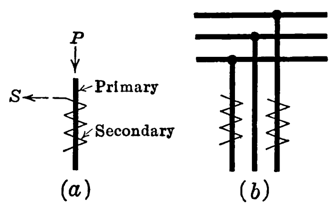

FIG. 49.—Conventional representation of current transformers.

(a) Representation of a single transformer. The straight line represents the primary, and the zigzag line the secondary. To distinguish between positive and negative terminals the secondary lead marked *S* is the one from which current flows, when the primary current is entering at *P*.
(b) Two current transformers on two of the conductors of a three-phase circuit.

around it; the secondary is wound around the iron, so that the flux in the iron induces an e.m.f. in the secondary. Only a few turns are shown; a much larger number are actually required. More primary turns are obtained if necessary by passing the primary conductor several times through the opening. The number of turns required is determined by the design of the transformer.

A current transformer may be represented diagrammatically as in Fig. 49, where the straight line represents the primary and the zigzag line the secondary. The significance of this representation of transformers becomes at once apparent from the description of the transformer in the preceding paragraph.

Current transformers are sometimes represented in diagrams in several other ways, but they are no simpler or clearer than this.

The same relationships hold in these as in other transformers—the voltage ratio is as the number of turns, and the current ratio inversely as the turns—but in these transformers the primary is put in *series* with the line, and the primary voltage is merely a small *line drop*, whereas on power transformers, voltage transformers and all others that we have considered, the primary is connected across the line. If the secondary of an *ordinary* transformer is short-circuited, an excessive current flows in the primary and in the secondary; but if a *current* transformer is short-circuited, the primary current cannot be more than is flowing in the main line. The effect of the short-circuit is merely to reduce the voltage across the secondary, and so across the primary. This makes the transformer work all the better; because a high voltage across the primary calls for a large exciting current, and therefore introduces errors in ratio and phase relation. A short-circuit eliminates these errors. On account of these possible errors, if the charge for electrical energy is based on watt-hour meter indications, the watt-hour meter should not be connected to the current transformers that actuate relays, or circuit-breaker trip-coils, unless it has been found that no excessive error is produced by the extra apparatus. The added apparatus sometimes has sufficient impedance to introduce an error, decreasing the meter readings by 2 or 3 per cent.[1] Consider what this means, in case a customer is purchasing 5,000 kw., 10 hr. per day, 25 days per month, at 1 ct. per kw.-hr., The error in the meter indication reduces the bill by 2 per cent., which amounts to $3,000 per year, and would be enough to pay for the extra pair of transformers for the polyphase circuit about once in 3 or 4 days!

If the current transformers are already installed, it is of more than passing interest to make a test on this point as follows: see that an indicating wattmeter is in the circuit, and connect a knife switch around the trip-coil, or any other apparatus that may be under suspicion. If it is a polyphase circuit, and there are two or more trip-coils or relays, a two- or three-pole switch should be used, one pole being connected to short-circuit each trip-coil or relay. When the load is steady, at about normal load and power factor, open and close the switch, taking several

[1] See Figs. 89 to 93, pp. 156 to 158.

good readings with the switch alternately open and closed. It is easy to estimate from these figures whether it would pay to install an extra pair of transformers, in order to obtain a true reading of the watt-hour meter. Of course, such an error may not be excessive for an ammeter or even a wattmeter, as for a watt-hour meter, because so great accuracy is not usually required. For a relay, it is well within the allowable limit of error.

If the secondary of an ordinary transformer is open-circuited, there is only a small exciting current in the primary. But in a current transformer the primary is the main-line current, and if the secondary is open-circuited, all the main-line current acts as an exciting current, and the voltage (primary and secondary) goes up to many times its value under normal operation. For this reason *an open circuit in the secondary of a current transformer is dangerous.* There have been conditions such that death has resulted from touching the two terminals of the secondary of an open-circuited current transformer, whereas in normal operation the voltage across the secondary is usually from 1 to 10 volts. Even if the transformers are so placed that there is no danger to life, the voltage may still be high enough to destroy the insulation, or the iron loss at high voltage may be enough to burn out the transformer. The current transformer secondary should always be short-circuited when not in regular service, if the primary is carrying any current. Switches for this purpose are described in Chapter XIX.

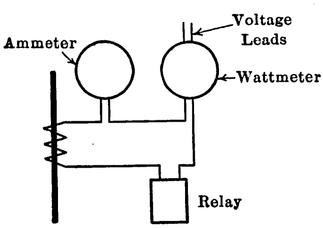

FIG. 50.—The right way to connect instruments to a current transformer.

Another point of difference between these and the ordinary transformers is in the secondary connections. Lamps, motors, or any other pieces of apparatus are usually put in parallel on the ordinary transformer; but all instruments on the secondary of a current transformer must be in series. This is obvious because otherwise the current would be divided between the several instruments; no one of them would have all the current of the transformer. The right connections are illustrated in Fig. 50, where an ammeter, the current element of a wattmeter, and the coil of a relay are connected in series to a current transformer. In Fig. 51, are illustrated three of the many wrong ways of connecting.

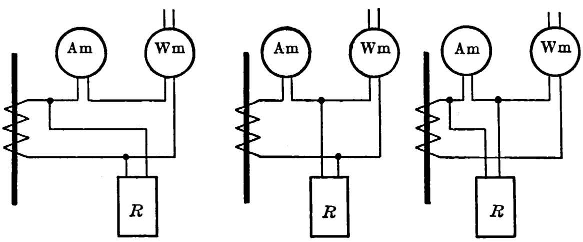

FIG. 51.—Three wrong ways of connecting the same instruments as in Fig. 50 to a current transformer.

Transformers are grouped, on polyphase circuits, so as to obtain indications on all phases. One arrangement of current transformers is shown in Fig. 52, which represents a three-phase circuit, in which a current transformer is put on each of the lines, *A*, *B*, *C;* and meters, *a*, *b*, *c* are in the secondaries of the respective lines. The three secondary circuits are combined in the common return wire, *r*, instead of coming back independently to their respective transformers.

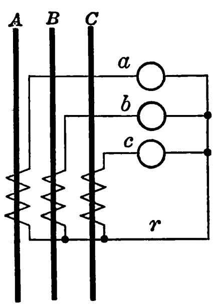

FIG. 52.—Three current transformers and connections, on a three-phase circuit.

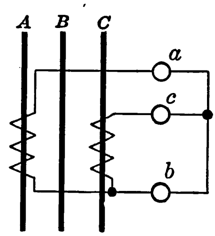

FIG. 53.—Two current transformers and connections on a three-phase circuit.

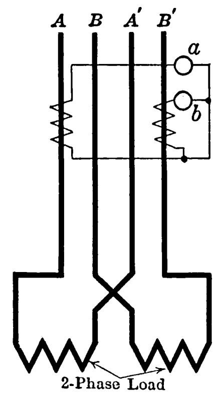

FIG. 54.—Two current transformers and connections on a two-phase circuit.

There is another grouping for a three-wire ungrounded circuit, as illustrated in Fig. 53, which saves one transformer. The two transformers have the same ratio. The secondary currents, *a* and *c*, are in phase with the primary, *A* and *C;* and *b*, which is the resultant of a and c, is proportional to and in phase with B, which is the resultant of A and C. This grouping does not give correct indications for instruments in line b, if the primary circuit has such connections that there is any primary current returning through ground or any other conductor. It is standard practice to use this grouping, where there is not likely to be any ground return current, and there is no neutral wire.

On a two-phase system such as is shown in Fig. 54 there are four wires, and the two phases are entirely insulated from each other. Wires A and A' carry the current for phase A, and B and B' for phase B. The current must be the same in A' as in A, and the same in B' as in B; so that only two current transformers are required to indicate the currents in the four wires.

The following are customary primary current ratings of current transformers:

5	50	250
10	60	300
15	80	450
20	100	500
25	120	600
30	160	800
40	200	1,000 amp.

Advantages of Using Instrument Transformers.—Several things are accomplished by this use of current and voltage transformers: (1) Both the current and the voltage instruments are insulated from the high-tension line, so they are safe to handle; (2) the voltage elements do not require the high-voltage winding, nor the current elements the large current winding, which would be expensive in some cases; and (3) all current instruments can be made for a standard current of 5 amp., and all voltage instruments for a standard voltage of 110 volts, thereby standardizing the manufacture of instruments and reducing their cost. Set over against these advantages is the cost of the transformers, but in the majority of cases it is better to use the transformers.

CHAPTER XVI

CONTROLLING AND REGULATING EQUIPMENT[1]

This chapter treats of the automatic and manually operated apparatus that is used to adapt the several circuits to their varied requirements. It does not include automatic circuit-breaking apparatus, which is discussed in Chapter XVII, nor measuring and indicating apparatus covered in Chapter XIX. The present discussion is taken up under the following headings: (1) Circuit-opening and closing equipment, (2) rheostats for controlling motors and generators; and (3) automatic regulating equipment.

CIRCUIT-OPENING AND CLOSING EQUIPMENT

Knife Switches.—On D.C. circuits, knife switches can be used for all ordinary voltages. A knife switch may be omitted if a two-pole circuit-breaker is arranged so that one pole can be closed at a time. Otherwise it is not safe to use a two-pole breaker as a switch, because there may be a short-circuit on the line, while the breaker is being held in by hand. A single-pole switch is used on a single-polarity system (in which the opposite side of all equipment is grounded); usually a two-pole switch is used on a double-polarity system (in which neither side is grounded); and on a three-wire system either a two- or three-pole switch is used, depending on the application.

Knife switches are used on low-voltage single-phase and polyphase circuits, as well as on D.C. But on voltages above 550, and even on lower voltages, oil switches are often used instead of knife switches on A.C. circuits.

[1] G. Chapter VI, Rheostats; Chapters XIX, XX, XXI, Switches, Starters, Controllers; Par. 276, Regulators. S. 10: 761–836, Switching Equipment; 15: 429–467, Motor Control; 10: 751–760, Regulators.

A. pp. 220–227, 1483–1503, Circuit-breakers and Switches; 1363–1370, 276–278, Motor Starters and Controllers; 1231–1240, Rheostats; 1212–1215, Regulators.

"Meter and Relay Connections," by HAROLD W. BROWN. *The Electric Journal*, vol. V, 1908, pp. 260, 406, 460, 530, 597, 660, 725; vol. VI, 1909, pp. 47, 113, 173, 298, 430.

A knife switch, of whatever capacity, should be rugged in its construction; and should conform to the requirements of the National Electric Code, for its rated current and voltage. In prescribing switches, several features are to be specified:

1. *Number of Poles.*—Usually the number of poles is made sufficient so that a single switch opens the entire circuit, *e.g.*, a four-pole switch rather than one or two two-pole switches, on a two-phase four-wire circuit.

2. *Single-throw or Double-throw.*—Single-throw switches are used, in all ordinary cases. A double-thrown switch is required, for reversing the polarity, for connecting a circuit to either one of two machines, and for similar applications (see Fig. 55).

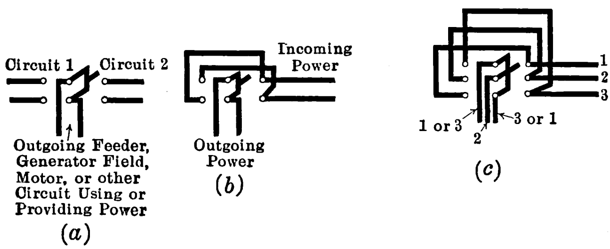

FIG. 55.—Applications of double-throw switches.

In (*a*) a two-wire circuit may be connected to either circuit 1 or circuit 2. Three- and four-wire circuits may be similarly connected. If one side of the circuit is permanently closed, a single-pole double-throw switch may be used.

In (*b*) a two-pole double-throw switch is connected as a reversing switch. The leads for incoming and outgoing power may be interchanged without affecting the operation of the switch. See Figs. 59 and 61 for application of the reversing principle to a control switch and an auxiliary relay, for reversing a motor.

In (*c*) the connections are the same as in (*b*), with the addition of wire No. 2. It is suitable for reversing the direction of rotation of induction motors, by reversing the sequence of the phases. The same connection may be used to reverse the polarity of a D.C. three-wire system.

3. *Front- or Rear-connected.*—Rear-connected switches are used on switchboards; their use in other places has the advantage of keeping the leads out of the way, but sometimes the wiring is made more expensive thereby.

4. *Rated Current.*—The current rating should be such that the switch will carry that current continuously without excessive heating, for as much as an hour or so, or until the temperature becomes constant.

5. *Voltage.*—The voltage to be specified is the voltage between poles, and unless otherwise stated it is the same as the voltage across the gap after the circuit is opened.

Special Applications.—If any special features are required, they should be stated; *e.g.*, if it is used as a quick-break switch, or a field switch (see Fig. 42, page 108, for one form of a field switch).

Oil switches are required if the A.C. voltage or current is so high that with a knife switch there would be excessive arcing on opening the switch. The contact terminals are submerged in oil, so that when the switch is opened, the oil flows into the gap between the terminals, insulating them from each other and stopping the current at the zero point. One form of oil switch is illustrated in Fig. 56, which shows a single-pole switch, or one pole of a two-, three-, or four-pole switch[1] or circuit-breaker. Fig. 57 shows diagrammatically the arrangement of the three poles in a three-pole switch. They are all controlled by a single handle.

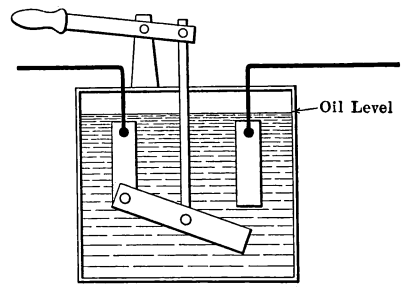

FIG. 56.—Arrangement of one type of oil switch.

Disconnecting switches, which are similar to knife switches, are sometimes used on high voltages, to open the circuit when there is no current flowing in the line. It is often important to insert them on one or both sides of transformers, circuit-breakers, and other apparatus, so that the apparatus can be insulated, and handled safely for repairs and changes. Fig. 58 illustrates a few important applications of disconnecting switches.

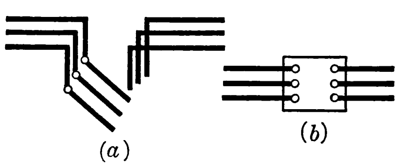

FIG. 57.—Diagrammatic representation of a three-pole oil switch.
(*a*) Showing switch contacts. (*b*) As usually represented.

Control switches are small switches, ordinarily of the drum type. They are used to open and close electrically-operated switches and circuit-breakers that are too heavy or too far away to be controlled by hand, and for various other purposes. Fig. 59 shows two such applications. A control switch sometimes has a safety device, preventing the accidental opening and closing

[1] The essential difference between an oil switch and an oil circuit-breaker is that the breaker is made to open on any required overload, whereas the switch many not be able to stand such severe conditions. Some manufacturers call oil switches *non-automatic oil circuit-breakers.*

of circuits; it may also have connections for indicating lamps, which show whether the switch or circuit-breaker that it controls is open or closed. The short-time current capacity of the control switch must be sufficient to operate the tripping and closing

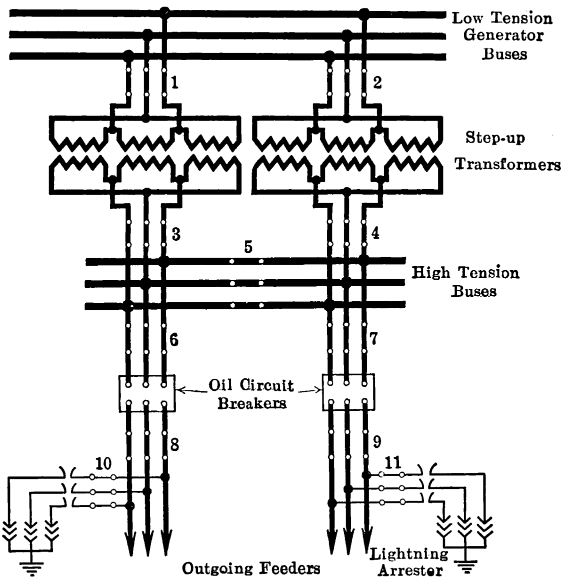

FIG. 58.—Applications of disconnecting switches.

1 and 3, or 2 and 4 for disconnecting transformers; 5 for sectionalizing buses; 6 and 8, or 7 and 9 for disconnecting a circuit-breaker; 10 or 11 for disconnecting a lightning arrester.

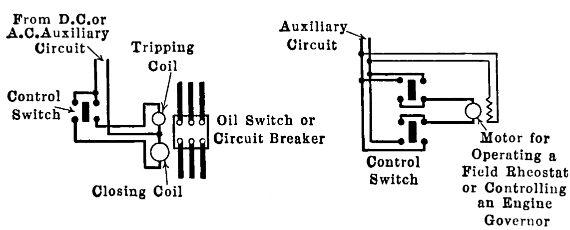

FIG. 59.—Applications of control switches.

Each black rectangle represents a moving connector, mounted on the drum; each black circle represents a stationary contact finger. When the drum is turned to the right, the rectangular connector makes connections between one pair of contact fingers; and when to the left, between another pair.

coils, or the small motor used to open and close the circuit-breaker. The voltage rating should be the voltage of the auxiliary circuit to which the control switch is connected.

Rheostats Controlling Motors and Generators.—There are several different applications of rheostats:

(*a*) D.C. generator field rheostats for adjustment of D.C. generator and line voltage.

(*b*) A.C. generator field rheostats for adjustment of A.C. generator power factor and line voltage.

(*c*) Exciter field rheostats, which are also for adjustment of A.C. generator and line voltage.

(*d*) Shunt-motor field rheostats for adjustment of motor speeds.

(*e*) Shunt-motor armature rheostats for adjustment of motor speeds.

(*f*) Shunt-motor starting rheostats.

(*g*) Series-motor controllers.

(*h*) Synchronous-motor field rheostats for power-factor adjustment.

(*i*) Induction-motor rheostats for use in series with the motor in starting.

(*j*) Induction-motor rheostats similar to the foregoing, for speed regulation.

(*k*) Induction-motor rheostats for use in series with the line and motor primary, for starting (an application that is little used).

In prescribing rheostats for the foregoing, and in general for other purposes, it is necessary to specify:

1. The maximum current that it is to carry.
2. Whether this current is to be for only a fraction of a minute, or for continuous service (*i.e.*, long enough to reach practically constant temperature).
3. The total resistance.
4. The number of steps in the resistance.
5. The voltage for which it is to be insulated (the voltage of the circuit).
6. Any other information of value, such as the current when all resistance is in the circuit, and other details of operation.

The number of steps should be sufficient for the smallest necessary adjustment.

The current capacity in the several parts of the rheostat may be graded, if desirable, especially if the current is much less when the entire rheostat is in circuit than when it is cut out.

The resistance may be embedded in enamel, wound in helical springs, wound on porcelain, or mounted otherwise. That embedded in enamel is very compact, and is satisfactory if the current is not in danger of exceeding the rating of the rheostat; but an excessive current for a short time may be enough to destroy the entire rheostat, whereas in some other forms the damaged parts can be replaced. Not only the current-carrying capacity of the wire of the rheostat, but also the ventilation or other means of cooling must have careful attention, especially in a rheostat absorbing a large amount of power for a long period of time.

In case a rheostat is at a distance from the switchboard, it can be operated by means of a small motor, controlled by a control switch, as illustrated in Fig. 59.

AUTOMATIC REGULATING EQUIPMENT

This equipment is employed for maintaining constant current and constant voltage, and occasionally for some other purposes. Constant-current and constant-voltage regulating transformers are explained in Chapter XIV. We shall consider some further voltage-regulating equipment.

The importance of voltage regulation can hardly be overestimated, where power is used for lighting, or for testing purposes. At best it is not commercially practicable to have the voltage strictly constant, but voltage-regulating equipment can be provided that holds the voltage within a fraction of 1 per cent. of a constant value.

Generator Voltage Regulator.—The elements of this rather complicated device are illustrated in Fig. 60. R_a, R_a are alternator field rheostats, and R_e the exciter field rheostat. When the bus voltage is too high, the plunger in the voltage regulator is drawn up, and the contact is opened. This puts the resistance of the exciter rheostat in series with the exciter field, the exciter voltage then drops, decreasing the alternator field current, and so the voltage of the alternator. As soon as the voltage is too low, the plunger in the voltage regulator drops, the contact closes, and the voltage is raised. This regulation takes place very rapidly, and is a most satisfactory method of maintaining a constant bus voltage. On account of the rapid operation of the regulator, the per cent. variation of voltage is very slight.

This type of regulator renders its greatest service when applied to A.C. generators, because their voltage regulation is so much poorer than that of compound D.C. generators. But the regulation of even D.C. generators is improved by such a voltage regulator. If the D.C. generator is not too large, the regulator may be connected to act directly on the generator field current;

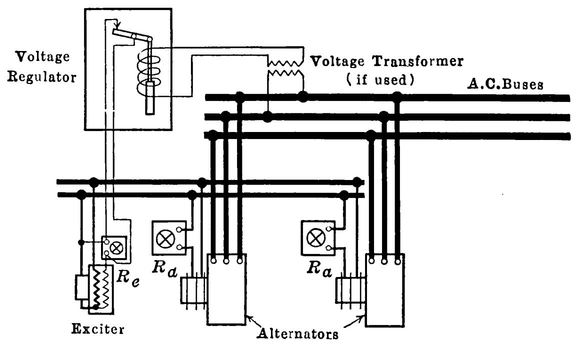

FIG. 60.—Generator voltage regulator and connections.
In many cases the bus voltage is too high to connect directly to the voltage regulator. A voltage transformer is then employed to step the voltage down to a suitable value.

but for very large generators, it is well to employ exciters very much as they are employed for alternators.

A voltage-regulating relay, or contact-making voltmeter, is an instrument somewhat like the voltage regulator just described, but its operation is altogether different; it regulates the voltage

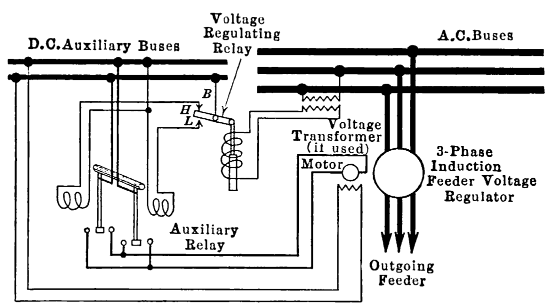

FIG. 61.—Voltage regulating relay and auxiliary relay, regulating the feeder voltage by means of an induction regulator. (The internal connections of the induction regulator are illustrated in Fig. 45, p. 112.)

of a feeder, instead of that of a generator. The connections of the voltage-regulating relay are shown in Fig. 61. The actual raising of the voltage is done by the three-phase induction regulator, as explained in Chapter XIV. A small motor is connected by gear and wormwheel to rotate the induction regulator, and it is the province of the relay to run the motor as required, to maintain constant voltage. The winding of the relay is connected to the secondary of a voltage transformer whose primary is across one phase of the feeder. When the feeder voltage is too high, the plunger of the relay rises, operates a contact lever, and closes the contact L; and when the voltage is too low, it closes contact H. The leads from the relay contacts, H and L, are connected so as to operate the motor. On account of the delicate construction of the relay, its contacts are not heavy enough to carry the motor current, and an additional relay, called a relay switch or auxiliary relay, is so arranged that when the contact of the regulating relay is closed a small current passes through the coil of the auxiliary relay, which has contacts of heavier construction, capable of carrying the full motor current.[1] When these contacts are closed, the motor is rotated in the required direction until the voltage becomes normal. The diagram shows connections from D.C. auxiliary buses, operating a D.C. motor. Sometimes A.C. auxiliary buses, and an induction motor, are employed.

It is a matter of great industrial importance, that by means of this equipment several feeders of different lengths can be taken from a single set of buses, and even though the load fluctuations on each feeder are independent of those on any other, the voltage may be held practically constant at the beginning or end, or at any other point on each feeder. If it is to be kept constant at any point except the beginning, it is possible to compensate for line drop, as explained in the next paragraph.

Line-drop Compensator.—Thus far we have considered only such voltage-regulating equipment as would maintain constant voltage at the buses. The results would be like those with a D.C. flat-compound generator, in that no provision has been made for line drop. The voltage at the end of the line is less than at the buses, on account of both resistance and reactance of the line. The essentials of a simple and effective means of compensating for voltage drop are shown in Fig. 62. The primary of a voltage transformer is connected between buses C and A. This gives a secondary voltage corresponding to the

[1] This use of an auxiliary relay, to utilize a small current in performing a heavy operation is not uncommon, especially in connection with relays that are delicately constructed for very sensitive operation.

bus voltage; the compensator is used where it is desirable to find how the line drop affects the voltage. A resistance, R, and reactance, X, are adjusted so that when they are connected in the current transformer secondary circuit, their effects are equivalent to line resistance and reactance. That is, if a current in one of the *main* conductors is such as to produce a drop that is 10 per cent. of the *bus* voltage, the *secondary* current produces a drop that is 10 per cent. of the *secondary* of the voltage transformer. Two current transformers are shown in the diagram—one on line C and one on line A—because in correcting the CA

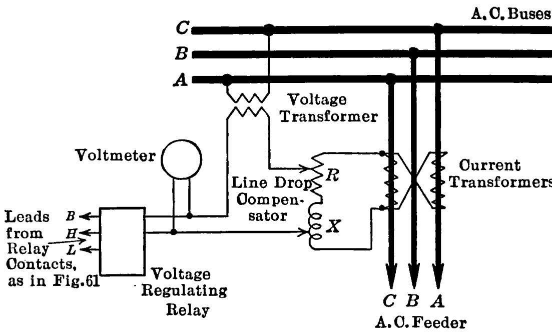

FIG. 62.—Line-drop compensator and connections.

voltage we must take account of the drop produced in the two lines, by their respective currents. In actual construction the compensator is modified slightly from that here shown, but the principle of operation is as indicated. Some line-drop compensators are made to compensate for any resistance drop not exceeding 6 per cent. (at full load current), and any reactance drop not exceeding 6 per cent. Others compensate for larger resistance and reactance drops—sometimes as much as 36 per cent. each.

A voltmeter connected to the voltage transformer and line-drop compensator, as in Fig. 62, indicates the voltage at the end of the line, even though the equipment is at the power station. A voltage-regulating relay with these connections maintains a constant voltage at the terminus, just as it would maintain a constant voltage at the power station if the line-drop compensator were omitted.

CHAPTER XVII

CIRCUIT-BREAKING EQUIPMENT[1]

Protection of electric apparatus and circuits is equivalent to insurance. The greater the possibility of trouble, and the greater the loss in case of trouble, the more important it is to guard against it. Automatic protection falls into two classes: Protection by circuit-breaking equipment against overload, short-circuit and other dangerous conditions of the circuit; and protection by lightning-arrester equipment against sudden and excessively high voltages, due to lightning and other line disturbances. Circuit-breaking equipment is treated in this chapter, and lightning-arrester in Chapter XVIII.

Fuses, carbon circuit-breakers, oil circuit-breakers, and relays comprise the essentials of circuit-breaking equipment.

FUSES[2]

Fuses are more commonly used on low than on high voltage, and for small than for large currents; although they are used in some cases on all voltages up to 110,000, and for currents (at low voltages) as high as 1200 amp. They are not applicable to circuits where the total kilowatt capacity of the generators back of the fuses is very large, in which case circuit-breakers should be used; nor are they applicable to circuits requiring selective opening.[3] Fuses are particularly applicable to low-voltage lighting circuits and the primaries of transformers, and to similar cases, where a relatively small, inexpensive piece of apparatus is required, which does not operate often, but which offers positive protection against a short-circuit. Obviously fuses are not applicable to cases where they would be blown out frequently, for the cost of fuses would be unnecessarily large.

The fusing material is sometimes German silver or aluminum,

[1] See references at the beginning of Chapter XVI, p. 121.

[2] See S. 13: 103, 104, General Principles, Comparison with Circuit-breakers.

[3] That is, opening only in certain cases of overload; this is explained in the discussion of Relays, p. 140.

but more often an alloy with a low melting temperature. Usually fuses are enclosed, to prevent the melted metal from flying and doing damage, and also in some cases to quench the arc. There are three forms of enclosed fuses: the Edison plug-type fuses, which fit the thread of an ordinary Edison lamp socket, and are suitable for small currents and low voltages; cartridge fuses with ferule contacts, which are suitable only for small currents but can be used on higher voltages; and cartridge fuses with knife-blade contacts, for large currents and higher voltages.[1]

For a large current at a high voltage, sometimes an "expulsion fuse" is employed—that is, a fuse mounted in a holder shaped like a gun, that blows out the vaporized fuse by the force of its own expansion.

CIRCUIT-BREAKERS

A circuit-breaker must be provided of such size and construction that there is no excessive heating at the contacts or in the conductors, when it is carrying the required current. The space between all parts that are alive when the breaker is open must be sufficient to prevent arcing from one terminal to another; such arcing is liable to occur at the time of opening the breaker, especially under conditions of a bad short-circuit. Based on these two requirements, a circuit-breaker must have a sufficient "rated ampere capacity" and a sufficient "ultimate breaking capacity," as follows:

The rated ampere capacity should be based on the maximum current that the line is expected to carry. For example, if there is one motor on the line, whose normal current is 100 amp., but which may be expected to carry a 25 per cent. overload, a 125-amp. breaker is required. If the overload is for less than an hour, the additional heating of the circuit-breaker is small enough so that in some cases it may be disregarded.

The following carbon breakers are obtainable: 1, 2, 3, and 4 pole; 250, 300, 600, 750 volts; 5, 10, 25, 50, 75, 100, 150, 200, 300, 400, 600, and 800 amp.

The ultimate breaking capacity, expressed in amperes, is the largest current that the breaker is expected to open. This may be many times the rated full-load current of the circuit. Before deciding what this must be, several facts should be noted:

[1] See National Electrical Code for allowable ratings.

1. The best engineering practice is to put circuit-breakers in *D.C. generator and feeder* circuits, and in A.C. *feeder* circuits, but not in A.C. generator circuits.

2. A D.C. generator may deliver, on short-circuit, for an instant, about 30 times full-load current, but the heavy current rapidly demagnetizes the field, reducing the voltage and the short-circuit current, so that after 2 sec., the breaker need only be one that will open 10 times full-load current at rated voltage.

3. An A.C. generator will deliver on short-circuit, for an instant, usually, 12 times full-load current, but the heavy current demagnetizes the field, so that after 2 sec. the breaker need only be one that will open 2 to 3 times full-load current at rated voltage.

4. If several A.C. generators are connected in parallel to the same buses, the short-circuit current in a feeder is the sum of the short-circuit currents of all the generators, because the A.C. generators themselves have individually no overload protection.

5. If the circuit-breaker is in the secondary circuit of a transformer, or at a distance out on a line, the short-circuit current is reduced by transformer or line impedance. If the transformer capacity is small compared with that of the generator, the short-circuit current depends chiefly on the transformer, rather than on the generator. Ordinary transformers with high-tension windings of 16,500 volts or less have an impedance drop of 2.5 to 4 per cent. at full-load, so that the short-circuit current (*i.e.*, at 100 per cent. drop) is from 40 to 25 times full-load current.

Based on these facts, the size of the breaker is different under different conditions of service. The following figures are typical, applying approximately in ordinary cases:

D.C. Generator Circuit.—If the breaker is set for instantaneous operation, it should have an ultimate capacity of 30 times full-load. If the operation of the breaker is delayed for 2 sec.[1] the ultimate capacity need be only 10 times full-load.

D.C. Feeder Circuit.—Breaker ultimate capacity should be 10 to 30 times the sum of the full-load currents of all the generators.

For example, if four D.C. generators are in operation at one time, and each generator capacity is 100 amp., the ultimate breaking capacity of each feeder breaker should be 4,000 to 12,000 amp., even though it may carry normally, say, 100 amp.

A.C. Feeder Circuit.—If a feeder circuit-breaker is in the secondary circuit of a transformer, the ultimate breaking capacity

[1] By a method explained later in the chapter.

need not exceed 25 to 40 times the transformer rated capacity. (Information can be obtained from the manufacturer, as to the short-circuit current on any transformer.)

If the breaker is at a distance from the generator, the ultimate breaking capacity need not exceed the short-circuit current on the line, which is the rated line voltage divided by the line impedance.

For example, on a 2,200-volt, 60-cycle circuit, 400 ft. long, consisting of No. 1 stranded conductors, spaced 15 in. apart (see Table XII, page 81):

Line resistance for two wires $= 0.1288 \times 2 \times 400/1{,}000 = 0.103$ ohm.

Line reactance for two wires $= (0.0491 + 0.0621) \times 2 \times 400/1{,}000 =$ 0.0890 ohm.

Line impedance for two wires $= \sqrt{0.103^2 + 0.0890^2} = 0.136$ ohm.

Short-circuit current $= 2{,}200/0.136 = 16{,}200$ amp.,

which is the required ultimate capacity of the breaker.

If the breaker is near the generator, is not in the secondary circuit of a transformer, and opens instantaneously, its ultimate breaking capacity should be about 12 times the rating of the generator. If there are two or more generators, it should be 12 times the sum of the rated capacities. If the breaker does not open for 2 sec., its ultimate capacity need be only 2 or 3 times the sum of the generator capacities, and if more than 2 sec. the capacity is still more reduced.

Thus if there are three 1,000-kva., 2,200-volt, three-phase alternators in a station, and the circuit-breakers are set for a 2-sec. time limit, the ultimate breaking capacity of the circuit-breakers should be $3 \times 3 \times 1{,}000 \times 1{,}000/(2{,}200 \times 1.73)$ or 2,370 amp.

From these computations it is possible to find the approximate size of circuit-breaker; but as the manufacturer knows the limitations of each breaker, he will prefer to specify the size of breaker to use, basing his choice on the following:

1. The maximum continuous load.
2. The maximum possible instantaneous overload.
3. The maximum overload that all the generators can sustain (for a fraction of a minute) on short-circuit.
4. The maximum time element in the operation of the breaker, that can be allowed with safety to the system.
5. Length, size and spacing of conductors from the generator to the circuit-breaker, and frequency of the system.
6. The size of transformer, if the breaker is in a transformer secondary.

Oil circuit-breakers are required where the current or voltage is so high that a carbon breaker is not sure to open the circuit on overload or short-circuit. They are nearly always used on over 750 volts, and in many cases, especially on A.C. circuits, they are used on lower voltages.

The contacts are submerged in oil, and in general the construction of an oil circuit-breaker is similar to that of an oil switch, such as is described and illustrated in Chapter XVI, page 123.

When the breaker opens under the worst conditions, an arc forms across the gap. This arc is vaporized metal and oil, which therefore expands and puts the oil under considerable pressure. The design of the breaker must be adequate to stand the pressure, and to prevent the oil from rushing out under the heavy pressure through the opening in the top of the tank; the size of the contacts must be sufficient to prevent being burned up after a few operations; and the insulating distance through oil to other parts of the breaker must be enough so that an arc will not be established during the commotion of opening on short-circuit. The higher the voltage, and the larger the current, the larger the tanks must be.

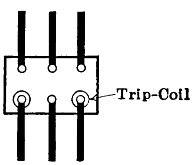

Fig. 63.—Oil circuit-breaker, operated by two trip-coils.

For three-phase circuits, the three lines are opened by a single breaker. Sometimes the three poles of the breaker are in separate oil tanks, but the operating mechanism is all in one system, so that there is essentially only one operation in opening all the poles. Two-phase four-wire and three-wire circuits require respectively four-pole and three-pole breakers.

An oil circuit-breaker is tripped either by a trip-coil in series with the line, or by a coil connected to some other circuit. Fig. 63 is a diagram representing a three-pole oil breaker that is tripped by coils in series with two of the conductors of the three-phase line. As an overload or short-circuit cannot occur under ordinary conditions in the third conductor, without flowing also in one or both of the other two, it is frequently considered adequate to provide only the two-pole protection. But there is a possibility of circumstances in which *both* the generator and the third conductor become grounded, as in Fig. 64. The current then flows from the generator through the ground to the grounded wire and back, without flowing through either trip-coil. For this reason, as an added precaution, sometimes the third pole of the breaker also has overload protection.

Trip-coils in series with the main conductors are satisfactory, if there are no restrictions as to the time and circumstances of operation of the breaker; but the difficulties already mentioned, and others make it important in many cases that the breaker exercise a high degree of discretion in its operation. The breaker may then be tripped from an auxiliary circuit, as in Fig. 65, by a trip-coil that operates when a contact, *R*, is closed by a relay.[1] If the breaker is at a distance from the switchboard where it is controlled, or if it is too heavy to be controlled by hand, a coil is provided for closing, as well as for opening the breaker. Such a closing coil is shown in Fig. 65, which is operated by closing contact *C* by hand. For tripping (opening) the breaker by hand, contact *T* is employed.

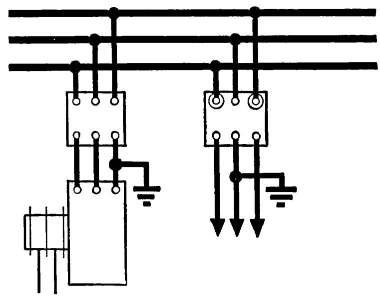

FIG. 64.—A possible, but improbable condition of grounding, in which two trip-coils are inadequate for protecting the circuit.

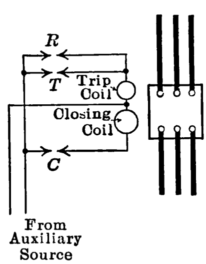

FIG. 65.—Electrically-operated circuit-breaker.

R = Contact closed automatically on overload, to trip the breaker.
T = Contact closed manually to trip the breaker.
C = Contact closed manually to open the breaker.

Carbon circuit-breakers are ordinarily limited to A.C. and D.C. circuits of 750 volts or less. The operation of the breaker in its simplest form is as follows: when an overload occurs, an electromagnetic device releases the arm of the breaker, which flies open. As it starts to open, it separates the main copper contacts, and the current is deflected to flow through a carbon contact. As the breaker opens still further, the carbon contacts open; by this time the copper contacts have moved away, so that there is no arcing of the copper, but it is restricted to the carbon. The non-arcing tendency of the carbon allows the breaker to open without excessive arcing. In some breakers there is an intermediate contact of phosphor-bronze, that breaks after the copper, but before the carbon contacts. This serves to

[1] See Relays, pp. 136-141.

protect the copper in case the carbon contacts are burned away, or for any reason fail to operate.

Some two-pole carbon breakers are arranged so that one pole may be closed at a time, but both poles are opened automatically by an overload. The advantage of this arrangement is that it is not necessary to provide a knife switch to use along with the breaker.

The electromagnetic device that trips the breaker is usually energized by the main current of the breaker, but instead of this or in addition to it the breaker may be actuated by a device operating on underload (when the current becomes less than a prescribed amount), or undervoltage. An example of underload operation is in case of charging a storage battery. When the battery becomes charged, the current drops off and the breaker is opened.[1] An example of undervoltage operation is the disconnecting of a motor, if for any reason the line is temporarily dead. When the power comes on the line again, if the motor were not disconnected, it might be damaged by the excessive current that would flow.

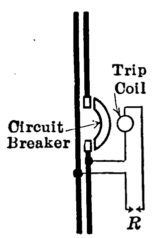

FIG. 66.—Carbon circuit-breaker, tripped by a coil that is energized by closing a contact.

Sometimes the breaker is provided with a trip-coil that is operated by some outside apparatus, as in Fig. 66. The coil has no current in it, until the contact, *R*, is closed. The contact, *R*, may be closed by hand, or in case of any abnormal condition of the circuit it may be closed automatically.[2]

Carbon breakers can be obtained with one, two, three or four poles as required. As they are used more often on D.C. than on A.C. circuits, the breakers are in most cases single-pole or two-pole. The size of breaker must be sufficient to carry the rated current and to open any possible overload or short-circuit, as already explained.

PROTECTIVE RELAYS

Relays are either protective or regulating. Examples of regulating relays were explained in Chapter XVI. In this chapter only protective relays are considered.

[1] However, this is not the best criterion on which to limit the battery charge.

[2] See Relays, p. 139, Fig. 70.

A protective relay is used to operate a circuit-breaker, where it is necessary to exercise much discretion in opening the circuit. If instantaneous operation is permissible on overload, the breaker can be set to operate satisfactorily without a relay; and it is even possible to make the breaker delay its operation, thereby introducing a time element. But the most accurate control of the time element, and various other desirable features are obtained only by means of relays.

A protective relay is an electromagnetic device that opens or closes a contact and thereby operates a circuit-breaker, when certain abnormal conditions exist on the line that is being protected. Thus relays are employed to open the breaker in case of overload, underload, overvoltage, undervoltage, overspeed, reversal of flow of power, and various other abnormal conditions. Of these, overload relays are in more general use than any of the others. Relays are somewhat like meters in their operation, except that they are more rugged; and whatever can be measured by any electric meter can be used to operate a relay, and thereby a cicuit-breaker.

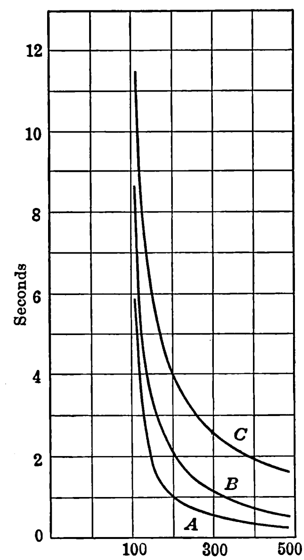

FIG. 67.—Time-load curves of an inverse time-limit relay.

Time Limit.—Just as the motion of a meter can be damped, so the operation of a relay may be made slow. In some relays the time of operation is the same under all conditions of overload, and in others it is less in case of a heavy overload than when the overload is slight. The first is known as a definite time-limit, and the second as an inverse time-limit relay. The name does not mean that the time is strictly in inverse proportion to the load, but that in general at larger overloads the time is less. This inverse time-limit is of great importance, because the circuit is not opened without giving an opportunity for the overload to stop; and the less the overload the longer is it safe to leave the circuit closed.

In Fig. 67 are curves showing the operation of an *inverse* time-limit relay. The lower curve, representing the operating characteristics with setting A, shows that if the current is 125 per cent. of the maximum continuous load (25 per cent. overload), the relay operates in about 3 sec.; but at 400 per cent., it operates in 0.3 sec. With settings B and C the time is longer in each case; but with any setting the time is relatively long at small overloads, and very short on heavy overloads. If the load is heavy enough, the time with any setting is less than 2 sec. It will be remembered, however, that the circuit-breakers have less work to perform if there is a time element of at least 2 sec.

The operation of a *definite* time-limit relay is very different from Fig. 67. The relay can be set to operate in the required number of seconds, and it will take that length of time, whatever the overload. This type of relay obviously has the advantage of not tripping the circuit-breaker too quickly on heavy overloads.

Fig. 68 shows the operation of a relay that *combines* the definite and inverse time limits. The time is long on a slight overload,

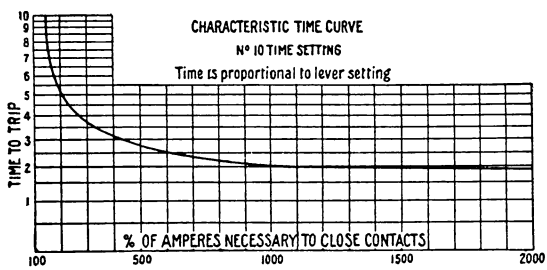

FIG. 68.—Time-load curve of an inverse time-limit relay having a definite minimum time.

and shorter on a heavy overload, but it is never appreciably less than a certain minimum which can be made large or small, as desired. With No. 10 setting, for example, at 200 per cent. of maximum continuous load (100 per cent. overload), the relay operates in 5 sec.; at 1,000 per cent. it operates in only 2 sec.; but at heavier overloads there is hardly any appreciable decrease in time. This operation is not so severe on the circuit-breaker as the ordinary inverse time limit; and the system is not as likely to be tied up unnecessarily by a slight overload, as if the relays had a definite time limit. There is another important use of this relay, in case two breakers are in series. Let us consider breaker A, Fig. 69, which is on a feeder circuit, and is located at the power station; and breaker *B*, which is on a motor circuit branching from the feeder. If the relay at the motor has a 1-sec. setting, and the one at the power station a 2-sec. setting, as in Fig. 68, there is no possibility that motor trouble will tie up the entire feeder, because the motor breaker will open ahead of the feeder breaker, and restrict the trouble to the motor circuit. But if the relay of Fig. 67 is used on both breakers, the difference in time between settings *A* and *B* is so little that both breakers may be opened, and the entire feeder will be temporarily tied up.

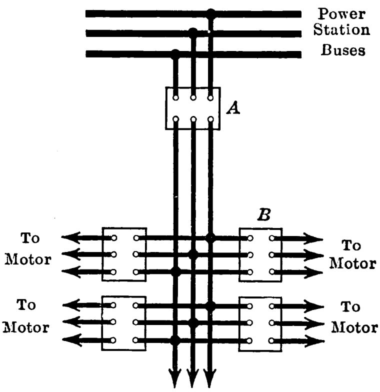

FIG. 69.—Circuit-breakers which should preferably be operated by relays having inverse time limit with definite minimum.

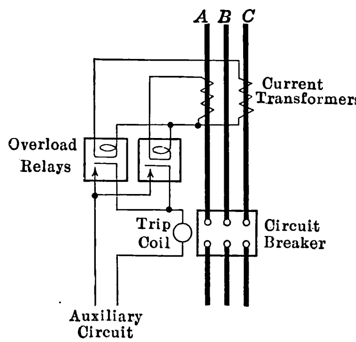

FIG. 70.—Two overload relays and two current transformers protecting a three-phase circuit.

Applications.—Relays used on A.C. circuits are not connected in series with the line, but are used with current transformers.[1] The connection of *two relays to two current transformers* on a three-phase circuit is illustrated in Fig. 70. If there is an overload on either outside conductor, at least one of the relays closes its contact, and the breaker is opened by a current flowing from the auxiliary circuit, through the contact of that relay, and through the trip-coil. The circuit is fully protected by this arrangement except in a special case of grounding, such as is illustrated in Fig. 64, page 135.

Fig. 71 is the same as Fig. 70, except that there are *three* instead of two current transformers, offering the full protection on three conductors which is not afforded by Fig. 70. There are only two relays, but each takes the resultant of the secondary

[1] See Chapter XV.

currents from two of the current transformers. If it is remembered that no current can flow in the transformer secondary, without a corresponding primary current, it can be shown that any possible overload, short-circuit or ground will operate one or both of the relays, and so the circuit-breaker. *Three relays* are sometimes used in this case instead of two, but the added relay is superfluous. This combination of three current transformers and two relays is known as the *Z-connection.*

By an ingenious arrangement of connections, it is possible to utilize the current from the transformers, to trip the breaker

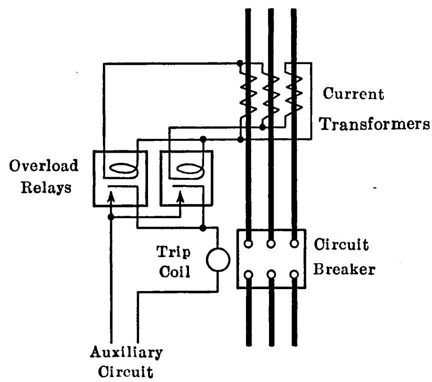

FIG. 71.—Two overload relays and three "Z-connected" current transformers protecting a three-phase circuit.

without the necessity of an auxiliary circuit, but the standard connections of Figs. 70 and 71 are sufficient to illustrate the applications.

Another application of relays is on *parallel feeders.* In Fig. 72, there are two three-phase lines feeding from the generating station to the substation. This is done, so that if there is a break or short-circuit in one line the other will carry the power. But if a short-circuit occurs at *S*, the current on short-circuit may feed into it *from both directions,* and breakers will be opened on *both* lines. In this case, reverse-load relays that are instantaneous in their action may be installed in the substation. These relays open as soon as the power begins to feed back, and it is then impossible for that fault to open the other feeder. This serves as an outline of an application of reverse-load relays; some difficulties have to be met, which need not be considered in this discussion.

A different application of relays is utilized in the Mertz-Price system. Two current transformers, *a* and *b*, Fig. 73, are at opposite ends of a transmission line, and their secondaries are connected together by two small wires running the entire length of the line, with a relay, *R*, in their circuit. The connections are such that in normal operation the two transformers

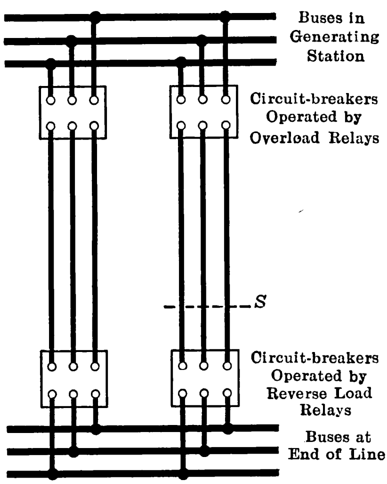

FIG. 72.—Parallel feeders protected by overload and reverse-load relays.

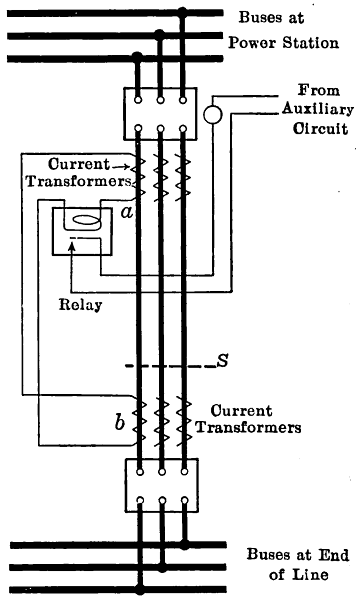

FIG. 73.—Mertz-Price system for protecting against short-circuits and grounds.

oppose each other. If the current at *a* is the same as that at *b*, the effects of the two transformers are equal, and neutralize each other. But if there is a ground or short-circuit at *S*, disturbing the balance, or reversing the current at one end, a current flows through the relay, which closes a contact and trips the circuit-breaker.

CHAPTER XVIII

LIGHTNING-ARRESTER EQUIPMENT[1]

When lightning strikes a line, it passes on to ground by the easiest path. If there is no easier one, it punctures the insulation of a machine or transformer, or passes through the thin flanges of a line insulator. The excessive voltage comes with such extreme suddenness as to make it impracticable to operate a mechanism, connecting the line by an easy path to ground. The lightning discharge is equivalent to a high-frequency current, and on this account a choke coil located where the line enters a power station, and connected in series with the line, prevents most of the lightning discharge from entering the building. But this alone is not sufficient; an easy path to ground must be established. This path cannot exist under normal operating conditions, because the line would then be grounded; but it must be established instantly when the lightning strikes. Two satisfactory media have been found for this purpose: the air gap and the aluminum cell. Either of these, when connected between line and ground and properly adjusted, breaks down the instant there is an excessive voltage stress. We shall consider several arrangements of air gaps, and some further facts about aluminum cells.

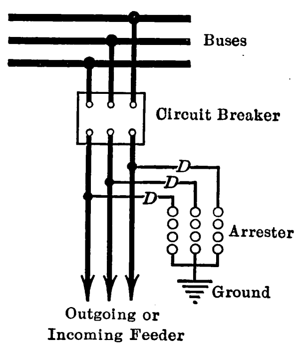

FIG. 74.—Multigap lightning arrester.

Disconnecting switches, if used to disconnect the lightning arrester, are inserted at *D, D, D*. For simplicity, circuit-breakers and disconnecting switches are omitted from succeeding diagrams of lightning arresters. They are connected as shown here.

A multigap arrester, Fig. 74, consists of a series of metal cylinders, placed close together but not touching. These little cylinders are arranged so that each line of the three-phase or

[1] G. 372, 374.
S. 10:850–868; 11:69–80, 220; 12:146–154; 24:733–735.
A. pp. 869–872; 360–361.

other circuit is connected to ground through a series of small air gaps. The advantage of several small gaps in series, instead of one large gap, is that after the lightning has passed, the spark across the little gaps does not develop into an arc, which might continue grounding and short-circuiting the line; whereas with a single long gap the vapor of the metal might produce a serious persistent short-circuit. The cylinders of the arrester are made of a "non-arcing" alloy—that is, one that does not tend to continue the arc. This also tends to quench the spark as soon as the lightning has passed. Every arrester must have some such means of stopping the current from flowing to ground after the lightning

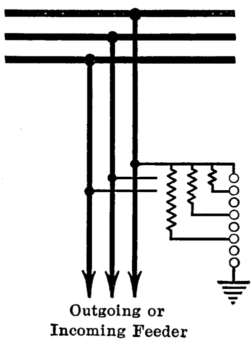

FIG. 75.—Multigap arrester with resistance elements in parallel. Connections to the other phases are the same as the one shown.

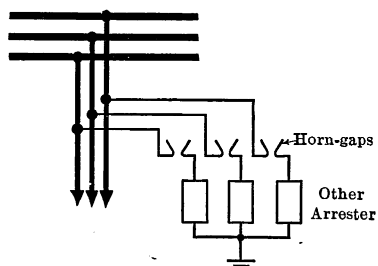

FIG. 76.—Horn-gaps used in conjunction with some other lightning arrester.

discharge. This type of arrester is suitable for A.C., but not D.C., and is made for use in conjunction with various arrangements of resistances—for example, such as that in Fig. 75—for voltages ranging as high as 50,000.

A horn-gap arrester, Fig. 76, consists of a gap such as would be formed between the two sides of a V if the bottom of the V were removed. A three-phase arrester consists essentially of three such horn-gaps, each connecting from one line to ground; a resistance rod, an aluminum arrester, or some other additional element is put in series with each horn-gap, preventing a bad short-circuit which would otherwise occur. When the lightning discharge has passed, the heat of the arc and the magnetic effect of the current tend to carry it upward until it is stretched out so long that it breaks.

A magnetic blowout arrester, Fig. 77, is similar to a horn-gap, in that there is a gap in series with another element, and there is a means of blowing out the arc. In this case the series element is a resistance rod made of carborundum, and the blowout is an electromagnet connected in parallel with a part of the resistance. This arrester is made for all D.C. circuits up to 1,500 volts.

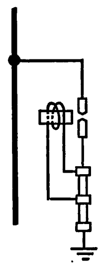

Fig. 77.—Magnetic blowout lightning arrester.

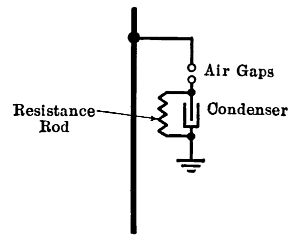

Fig. 78.—Condenser lightning arrester.

A condenser arrester, Fig. 78, consists of a condenser in parallel with a resistance rod, and these two in series with a very small spark gap. The high-frequency A.C. charges and discharges the condenser, with a very low voltage to ground. If there is also a continuous charge (not alternating), it flows to ground through the resistance. This is intended for line and car use on D.C. circuits up to 1,500 volts.

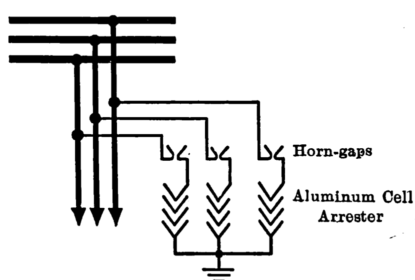

Fig. 79.—Aluminum cell lightning arrester, with horn-gaps in series.

A multipath arrester is one in which a special composition acts as a partial conductor, filled with minute spark gaps. The relatively large mass of the substance absorbs the heat of the minute sparks; and as soon as the lightning discharge stops, the path to ground ceases to conduct the current. This arrester is intended for use on 400- to 750-volt D.C. and A.C. circuits.

An aluminum arrester, Fig. 79, is made up of a series of aluminum pans, each inside of the one below, and each filled with an electrolytic solution, and immersed in oil. The surfaces of the aluminum pans are covered with a film of aluminum hydroxide, which acts almost as an insulator until the voltage reaches a certain value. But when the voltage becomes excessive, the film breaks down, and the whole arrester becomes a good conductor. And as soon as the voltage drops again, the insulating film is again restored. This type of arrester is commonly used in conjunction with a horn-gap, which has the effect of insulating the arrester from the line, except during the lightning discharge. This arrester is adapted for all voltages from 2,000 up, and for lower voltages on D.C.

Relative Merits of Arresters.—In selecting a lightning arrester, the line voltage of the system is to be considered first, then the severity of the lightning and the total current capacity of the generators in the vicinity; because large generators may be capable of pouring a large current through the arrester to ground, after the lightning strikes, before normal conditions are again established. The ideal arrester acts on an electric circuit as a good safety valve does on a steam boiler. When there is a slight excess in voltage, the current flows freely to ground, through the equivalent of a low resistance; but as soon as the voltage becomes normal, the current to ground is cut off by an increase in the equivalent resistance.

The aluminum arrester performs its function *much* better than any other does on very high voltages; and it is recommended as the preferable arrester to apply on voltages even as low as 2,000. For D.C. circuits of even lower voltage it is of advantage, where the lightning is very severe. The reason for the success of the aluminum arrester is that the resistance is extremely low to the high voltage of the lightning, but it is extremely high as soon as the lightning has passed. The disadvantage of the aluminum arrester is that it requires a little attention. It should be "charged" every day—that is, connected across the line without an air gap in series—to keep the insulating film in good condition. The cost is higher for aluminum arresters than for suitable types of spark-gap arresters, especially for low-voltage circuits.

Choke coils are put in series with the line, as it enters or leaves a building, to keep the lightning out. They are coils, wound without iron, and having a quite low inductance. Being in series with the line, they introduce a reactance, $2\pi fL$, where f is the line frequency and L the inductance of the coil. The inductance is so low that the drop is almost negligible in normal operation; but the lightning is equivalent to an extremely high-frequency current, and the opposition offered to the lightning is correspondingly great.

Choke coils differ, first, as to current-carrying capacity, second, as to the voltage for which they are insulated from ground, and third, as to their inductance. An increase in any of these increases the cost of the choke coil. The current and voltage capacities must be those of the line. The larger the inductance, the more effective is the choking in keeping the lightning out of the building. On short lines of low voltage, the importance of choke coils is relatively small—in fact, sometimes both choke coils and arresters may be omitted—but on voltages from 2,200 up on long lines, subject to severe lightning disturbances, choke coils and arresters are important. A choke coil may be considered as equivalent to a multiplier, increasing the effectiveness of the arrester. It can be omitted where the arrester is adequate without it.

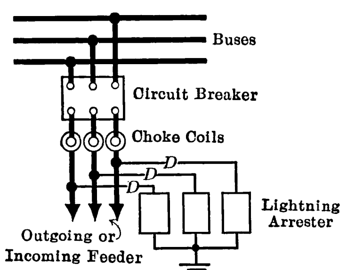

FIG. 80.—Relative connections of lighting arrester, choke coils and circuit-breaker.
Disconnecting switches at D, D, D, if used.

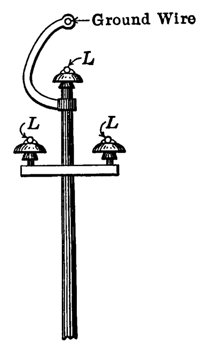

FIG. 81.—Ground wire, above the line wires L, L, L.

The larger the inductance of a choke coil, the more must one end of the coil be insulated from the other; for when the lightning strikes, the pressure exerted may be about proportional to the inductance. Sometimes choke coils of heavy inductance, intended for use on high-tension lines, are immersed in oil for better insulation.

Fig. 80 shows a suitable arrangement of choke coils and arresters, connected to a line entering a power station.

Ground Connections.—The path to ground must be good, to insure proper operation of the arrester. It should have as few turns, and as little horizontal length, as possible. It should go down to moist earth, and should have exposed there several square feet of surface, consisting of sheet copper, iron pipes or rods, or other adequate grounding surface.

If the ground wire is continued along the transmission line, *over* the other wires, as in Fig. 81, it helps to shield the other wires and the arrester from lightning disturbances. This would be an unnecessary expense in some cases, but in others it is of material value.

CHAPTER XIX

MEASURING AND INDICATING APPARATUS

This chapter is treated under four heads:

1. Meters and the quantities measured.
2. Characteristics of meters.
3. Meter switching devices.
4. Meter applications.

METERS AND THE QUANTITIES MEASURED

The instruments that we consider are those in common use in commercial and industrial plants, for indicating current, voltage, frequency, grounds, and single-phase and polyphase power, energy and power factor. Some of them are so well known as to require little or no description.

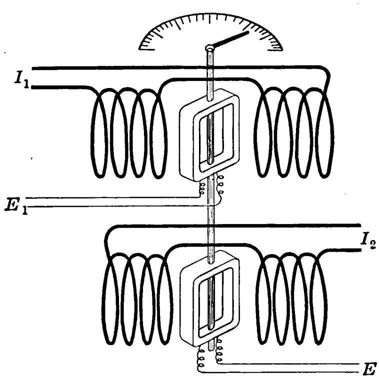

FIG. 82.—Diagram of polyphase wattmeter.

Current circuit I_1 and voltage circuit E_1 comprise one meter element; circuits I_2 and E_2 comprise the other element. In induction types of meters both the current and the voltage circuits are stationary. The currents in these stationary circuits induce eddy currents in rotable disks or drums, and these eddy currents react with the magnetic field, rotating the moving element.

A polyphase wattmeter consists of two single-phase meter elements that are electrically complete and distinct; they act on a single pointer, tending to deflect it, and the deflection is opposed by a spring. The connections are illustrated in Fig. 82. The scale indication is equivalent to that of two single-phase wattmeters. It is at once evident that two-phase power can be measured with this meter, by connecting one phase to one wattmeter element and the other phase to the other element. It has been shown in a variety of ways that three-phase power can be similarly measured.[1]

A watt-hour meter (formerly called an integrating wattmeter or a recording wattmeter) makes a continuous record, summing up the total energy that has flowed since any given time, so that by reading dial indications every day, month, or other period, the energy used in each period is obtained directly. Watt-hour meters are either single-phase or polyphase. The polyphase

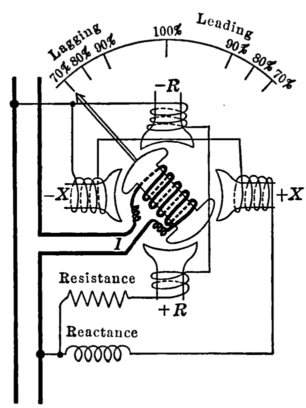

FIG. 83.—Diagram showing the principle of operation of a single-phase power-factor meter.

Winding I is a current winding; it is connected either in series with the line or to the secondary of a current transformer whose primary is in series with the line.

Windings $+R$ and $-R$ are voltage windings with resistance in series.

Windings $+X$ and $-X$ are voltage windings with reactance in series. These windings are connected either across the main circuit or to the secondary of a voltage transformer whose primary is across the circuit.

In polyphase meters, sometimes winding I is a voltage winding, connected across the circuit, and windings $+R$, $-R$, $+X$, $-X$, or similar windings are current windings, connected in series with the several phases. The resistance and reactance are then omitted.

In one important type of power factor meter, winding I is stationary, but the form of the coil and the iron core are such that the core can rotate as required to indicate the power factor.

watt-hour meter consists of two single-phase elements, arranged as in wattmeters.

Power-factor meters, or power-factor indicators, usually have two fields, one produced by the line current and the other by the line voltage. Either the current or the voltage field is made rotating, the other being simply an alternating field. The moving element of the meter is made so that it is deflected to a posi-

[1] Compare G. 267, Fig. 271, which applies to one polyphase meter, as well as to two single-phase.

S. 3: 171–177.

A. p. 1825.

tion that is determined by the relation of the current and voltage fields. These meters can be obtained for single-phase, two-phase and three-phase circuits.

The principle of operation (but not the form of the instrument) of a single-phase power-factor meter is illustrated in Fig. 83. The four stationary poles, $+R$, $+X$, $-R$, $-X$, are excited by windings connected across the voltage, with reactance and resistance respectively in circuit, as indicated. The combined effect of these four windings is to produce a rotating field. The central rotating electromagnet is excited by a winding, I, which is connected in series with the line, and carries the line current. It is attracted to the position in which the rotating field of $+R$, $+X$, $-R$, $-X$ is in phase with the current in I. The angular position of the moving element is shown by the pointer, and with suitable calibration it indicates the power factor.

With some variation, this discussion applies to all types of power-factor meters, for single-phase and polyphase circuits.

Synchronism indicators, or synchronoscopes, are made on the same principle as power-factor meters, except that windings $+R$, $+X$, $-R$, $-X$ are voltage windings connected across the "running" machine, and winding I is a voltage winding connected across the "starting" machine.[1] The pointer takes a position depending on the relation of these two fields. If one is gaining on the other, or losing, the fact is indicated by a rotation of the pointer, to the right or left. This rotation is very slow when the starting machine has about the right speed. When the pointer is stationary, or nearly so, pointing vertically upward, the machines are exactly or approximately in synchronism, and the switch of the incoming machine may be closed.

Lamps for Synchronizing.—Lamps may be connected in series between the two machines, so as to show by their brilliancy when the machines are in phase. With the customary arrangement of connections, when the lamps go out the machines are in synchronism. The most approved method of synchronizing is by using *both* the lamps and the synchroscope.[2]

[1] The terms "running" machine and "starting" machine refer to the machine already connected to the buses and the one to be synchronized. Sometimes the starting machine is referred to as "incoming."

[2] Harold W. Brown, "Apparatus for Synchronizing," *The Electric Journal*, vol. v, p. 530, September, 1908.

Harold W. Brown and S. S. Neu, "Phasing out for Synchronizing Polyphase Circuits," *The Electric Journal*, vol. ix, p. 427, May, 1912.

Frequency meters are of two distinct kinds. One is similar to a differential voltmeter, in that it has two voltmeter elements opposed to each other, tending to deflect the pointer in opposite directions. As in Fig. 84, both of the voltage windings are connected across the same circuit, so that if each had the same impedance in series with it the meter would always indicate zero. One winding has a large resistance and no reactance in series with it, so that its current at a given voltage is the same at all frequencies; the other winding has a large reactance and small resistance, and of course the reactance varies directly with the frequency. Thus the element having the large reactance is weak at high frequencies, but strong at low frequencies; so

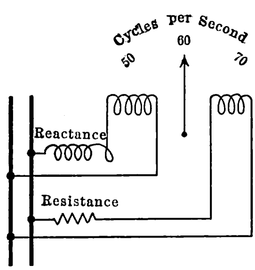

FIG. 84.—Connections of resistance-and-reactance frequency meter.

The resistance element exerts a torque that is independent of frequency; the reactance element exerts a torque that decreases as the frequency is increased.

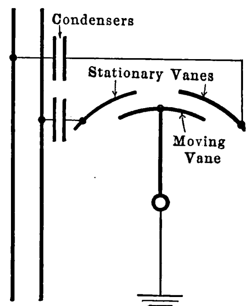

FIG. 85.—Electrostatic ground detector.

that with the right calibration the pointer indicates the different frequencies.

The other kind of frequency meter has a series of vibrating reeds each tuned for a different frequency. A coil is placed in such a position that it tends to make all the reeds vibrate, and the frequency is indicated by the one having the greatest vibration.

A ground detector is sometimes made in the form of a differential electrostatic voltmeter—that is, an electrostatic voltmeter which shows by its deflection if the voltage from one line to ground is greater than from another to ground. One form is illustrated in Fig. 85.

A ground detecting lamp may be connected from each line to ground. If one lamp goes out or burns dim, it indicates that the corresponding line is grounded. This is illustrated in Fig. 86 (see also Fig. 99, p. 161).

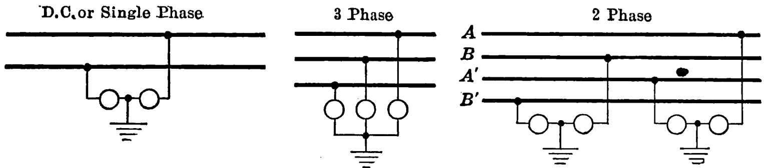

Fig. 86.—Arrangement of ground detecting lamps on D.C., single-phase and polyphase circuits.

CHARACTERISTICS OF METERS

There is a great variation in the characteristics of the various kinds of meters; the accuracy depends on the calibration and construction of the meter, and in part on whether the meter is used under exactly the conditions for which it was made. Some meters can be used indiscriminately under widely varying conditions; others are subject to considerable errors[1] due to excessively high or low temperature, mechanical balance, friction, aging, distorted wave form of current or voltage, thermo-electromotive forces, and perhaps a few other causes, which are more or less beyond the control of the user, but should be specified in purchasing meters. In addition to these are several features and conditions causing errors, as mentioned below, which should be considered in both purchasing and using meters:

The scale of a meter may have equally spaced divisions, such as are in most of the permanent magnet types of voltmeters and ammeters, or the spaces may be wide near the middle of the scale and narrow at each end, or they may increase gradually, so that they are widest at the end of the scale. These are illustrated in Fig. 87. Where it is possible, the best meter for all-round use has a uniform scale, but if readings are nearly always taken in a certain part of the scale, there is a possible advantage in having the divisions wider in that part. Also, in general, the longer the scale the smaller will be the reading error.

[1] Cyril Jansky, "Electric Meters," p. 345 (New York: McGraw-Hill Book Co., Inc.), First Edition, 1913.

A meter should be selected, preferably, of such a full-scale indication that in ordinary use the indications are beyond the mid-

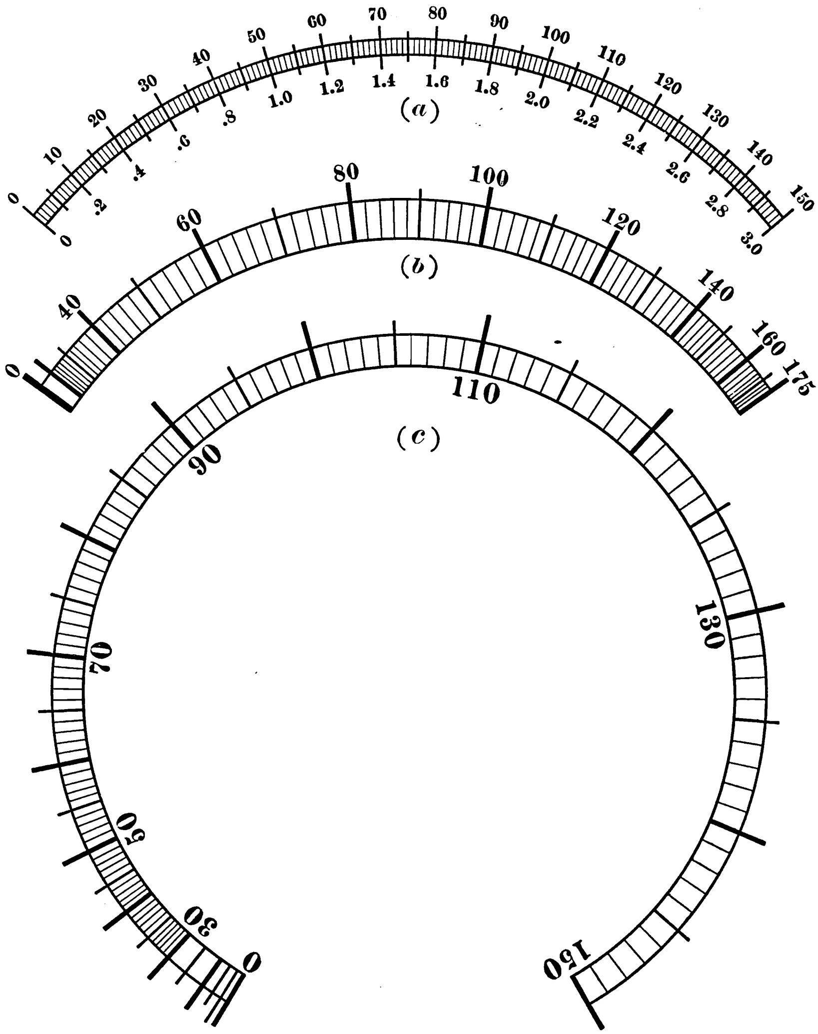

FIG. 87.—Typical voltmeter or ammeter scales.
(a) Uniform scale divisions. (b) Wide divisions near middle of scale. (c) Wide divisions near end of scale.

dle of the scale. Accuracy is sacrificed in taking readings at much less than one-half of full scale. For example, a current of 50 amp. cannot be measured on a 200-amp. ammeter with the same per cent. accuracy with which 150 amp. can be measured.

Any meter may have more than one set of terminals or connections, by which the meter can be made to indicate either large or small quantities, as illustrated in Fig. 87*a*. It is then convenient to have the numbers on the two scales in different colors, to agree with markings on the corresponding meter terminals. If two sets of numbers are shown on the scale, such a meter is called a "double-scale" meter.

In some cases meters are required to read both positive and negative quantities—*e.g.*, incoming and outgoing kilowatts. They are then provided with a scale extending both to the right

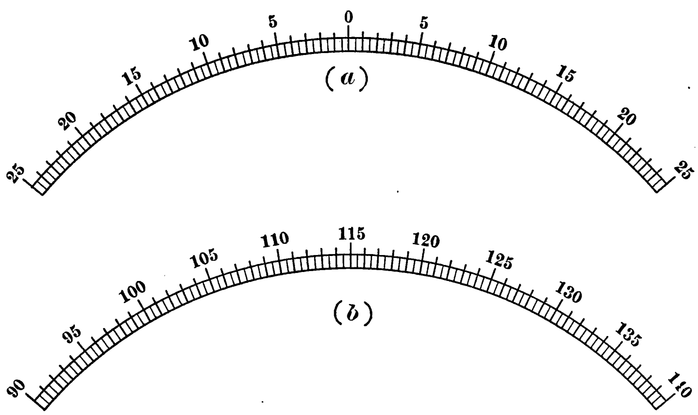

Fig. 88.—Scales with Shifted zero.
(*a*) Zero-center scale. (*b*) Suppressed-zero scale.

and to the left of zero, as in Fig. 88*a*. Such a meter is called a "double-reading" meter, or the scale a "zero-center" scale. In certain meters a zero reading is never required, and relatively wide scale divisions are desirable. The zero may then be "suppressed," as in Fig. 88*b*. This has the disadvantage, however, that it is less convenient to adjust the pointer if an error on zero is introduced by a bent pointer or in any other way.

Frequency affects some kinds of meters, and not others. In general, it has little effect on meters of the dynamometer and Kelvin balance type. The effect of frequency on some induction-type meters is greater than on others. The fact that meters are nearly always used on either 25- or 60-cycle circuits, and that the variation from the normal frequency is very slight, makes the disturbance due to frequency rather insignificant in most cases.

Voltage.—A change of the magnetic condition of the iron with voltage may effect the accuracy of a wattmeter, or a watt-hour meter. It may also effect an ammeter whose field is produced by an electromagnet. Voltage variation may effect the resistance-and-reactance type of frequency meter, because both of the opposing elements are weaker at low voltage. Usually all these effects are negligible when the meter is used within 10 per cent. of the rated voltage.

Low power factor has no effect on the accuracy of any meters except wattmeters and watt-hour meters. If even these meters are properly adjusted for power factor it should have no effect on them.

Unbalancing of phases of a polyphase wattmeter or watt-hour meter should have no effect if the two elements of the meter are independently correct at high and low power factors and there is no stray-field effect of one element of the meter on the other.

A stray-field may affect the accuracy of a meter if it has the same frequency as the quantity that the meter indicates, or both the field and the quantity measured are from a D.C. source. A D.C. ammeter or voltmeter should not be too near a D.C. conductor carrying a heavy current. Strong A.C. fields are not so likely to be near the A.C. meters, but they also should be avoided unless they are known to have a negligible effect. Some switchboard and other meters have iron cases, which shield them very largely against such magnetic disturbances.

Instrument transformers, including both current and voltage transformers, have negligible errors if they are not furnishing power to too many instruments; but if the number of instruments is too great, considerable errors are introduced, both in ratio and in "phase displacement" (*i.e.*, phase error). Ammeters, voltmeters and other apparatus operating on current or voltage are affected by ratio errors; wattmeters and watt-hour meters are affected by both ratio and phase displacement.[1] The effect of current transformers on the accuracy of watt-hour meter indications is illustrated in Figs. 89 to 91, in which typical instruments are connected to current transformers that are compensated for a secondary load (*i.e.*, load due to the meter winding)

[1] See Chapter XV, "Current Transformers."

of 25 volt-amp.[1] In each of these figures, six curves are drawn. Three of them show the error in the watt-hour meter itself, when

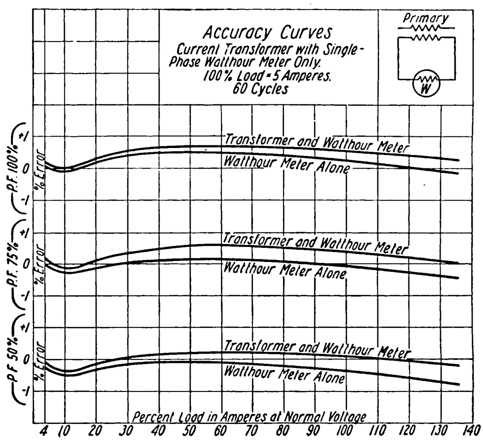

FIG. 89.—Typical accuracy curves, showing the errors at various loads and power factors, when a single phase watt-hour meter is connected directly and through a current transformer to a single-phase 60-cycle circuit.

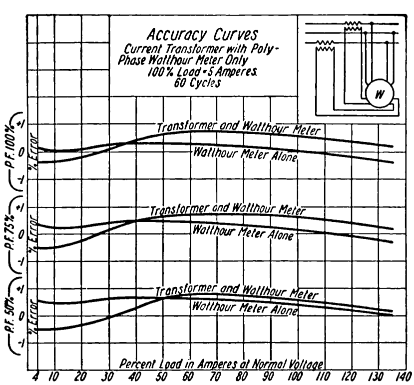

FIG. 90.—Same as Fig. 89, except that a *polyphase* watt-hour meter is connected to a *three*-phase circuit.

the load is respectively at 50, 75, and 100 per cent. power factor.

[1] The meaning of "a secondary load of 25 volt-amp." is somewhat arbitrary, referring to the secondary volt-ampere output of the current transformer at rated full-load current.

A watt-hour meter is a load of about 2 volt-amp.

An ammeter is a load of about 5 volt-amp.

A trip-coil is a load of about 50 volt-amp.

The other three curves in each figure show the combined error of the wattmeter and the current transformer. The difference between the two curves shows the transformer error.[1] Fig. 89 shows that on a single-phase system, if nothing but the watt-hour meter is connected to the transformer, the transformer error is practically zero at light load, rising to about 0.5 per cent.

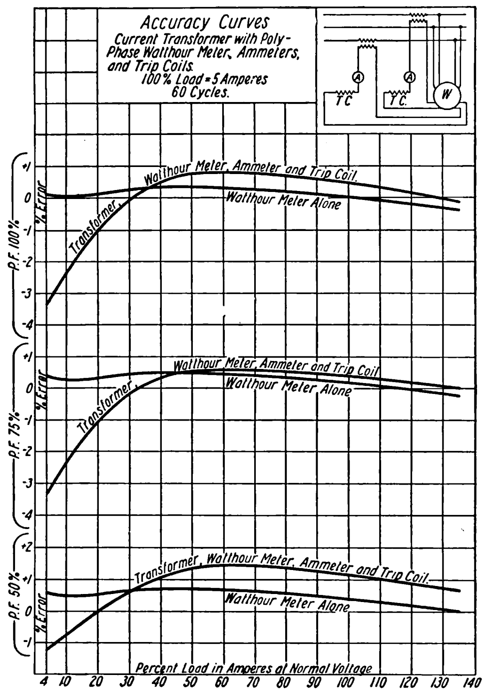

FIG. 91.—Same as Fig. 90, except that ammeters and circuit-breaker trip-coils are connected in series with the current transformers.

When the trip-coils are inserted, note the relatively large errors with light load at all power factors, and with full load at 50 per cent. power factor. This is in spite of the very high quality of design and construction of this type of transformer.

at 30 per cent. overload, depending a trifle on the power factor. Fig. 90 shows that on a three-phase system, with a polyphase watt-hour meter, the errors are of about the same order, except that there is a negative error of about 1 per cent. at light loads. Fig. 91 shows that if trip-coils and ammeters are connected in series with the watt-hour meter, this negative error at light load is considerably increased, but there is a larger positive error,

[1] The curves were furnished by courtesy of the Westinghouse Electric and Manufacturing Co. and represent tests on Westinghouse equipment.

at large loads and low power factor. (This error is chiefly due to the trip-coils—not to the ammeters.) The conclusion to be reached from these curves is that where considerable accuracy is required[1] at light load or low power factor, the watt-hour meter should not be put on current transformers that operate trip-coils.

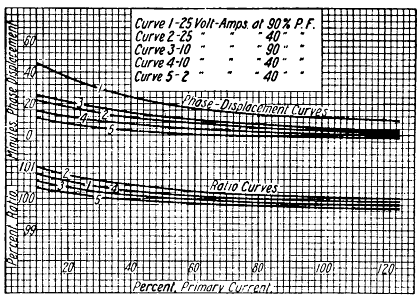

FIG. 92.

(Curves are for 60-cycles.)

The advantage of this transformer is in its small errors.

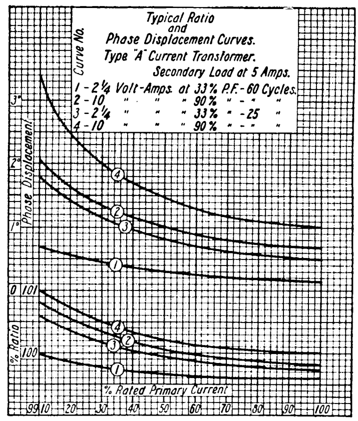

FIG. 93.

(Curves are for 25 and 60 cycles.)

The advantage of this transformer is that its cost is only two-thirds the cost of the transformer of Fig. 92.

FIG. 92.—Transformer of 50 volt-amperes capacity, compensated for 25 volt-amperes.

Fig. 93.—Transformer of 10 volt-amperes capacity, compensated for 10 volt-amperes.

FIGS. 92 and 93.—Ratio and phase displacement curves of current transformers.

The meaning of 101 per cent. ratio is that primary current/secondary current is 101 per cent. of the correct (rated) ratio.

The meaning of 60 minutes phase displacement is that the secondary current is 1 degree (1/360 of a cycle) ahead of the primary. If the primary has a lagging current, this displacement tends to make a wattmeter or watt-hour meter reading too high, whereas the ratio error tends to make it too low; so that the two errors tend to neutralize each other.

The effect of phase displacement on wattmeter and watt-hour meter indications is as follows:

With a lagging current having a power factor of	The error per cent. introduced per degree of phase displacement is
1.00	0.02 of 1
0.90	0.85 of 1
0.80	1.3
0.70	1.7

Fig. 92 shows ratio and phase displacement curves of a transformer such as was used in Figs. 89 to 91, under various conditions of loading, with various instruments connected to the transformer secondary. Fig. 93 is similar to Fig. 92, but refers to a transformer of 10 volt-amp. secondary capacity.

[1] For example, where charges for electric energy are made from the meter readings.

METER SWITCHING DEVICES

The number of meters required in a plant is very much reduced, if suitable plugging or other switching devices are employed for shifting some of the meters from circuit to circuit, or from phase to phase of a circuit. Following are a few of these devices:

Four-point Voltmeter Plugs and Receptacles.—The receptacle is merely four terminals, to each of which a permanent and a plug connection can be made. Fig. 94 shows a suitable arrangement of connections. Of the three receptacles, one connects to the buses and two to generators. All the receptacles connect to the one voltmeter. The plug, when inserted in any receptacle, puts the voltage of the buses or of one of the generators on the voltmeter. It is essential that only one plug be

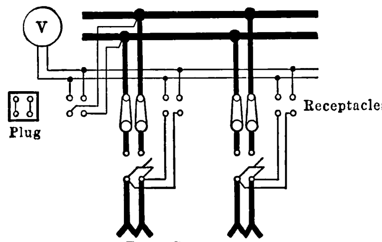

FIG. 94.—Four-point receptacles for measuring generator and bus voltage on a two-wire system.

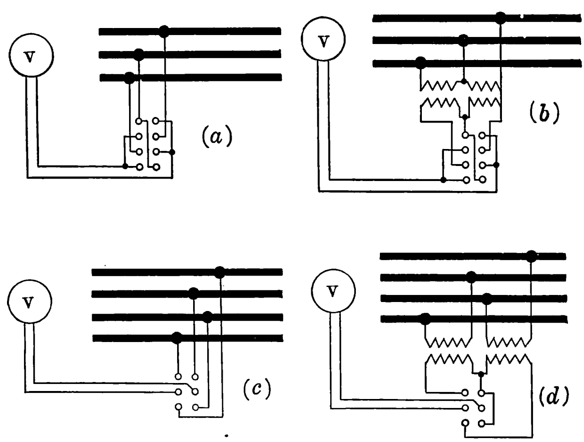

FIG. 95.—Eight-point and six-point receptacles.

(*a*) Eight-point receptacle for measuring voltage on three-phase circuits; may also be used on D.C. or single-phase, three-wire circuits. (*b*) Same as (*a*) where voltage transformers are used. (*c*) Six-point receptacle for measuring voltage on two-phase circuit. (*d*) Same as (*c*) where voltage transformers are used.

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.

Eight-point Receptacles.—Fig. 95, *a* and *b*, shows how an eight-point receptacle may be used on a three-phase circuit just as the four-point is used in Fig. 94, on D.C. or single-phase. A four-point *plug* is used as before; there are three possible positions for the plug in each receptacle, for measuring the voltage of the three phases. In Fig. 95 *c* and *d*, a six-point receptacle is used on a two-phase circuit.

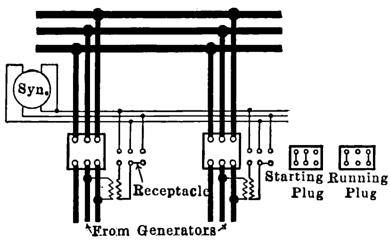

FIG. 96.—Synchronizing plugs and receptacles for synchronizing "between machines."

Synchronizing Plugs and Receptacles.—Various plugs and receptacles, such as those just described, are used for connecting the machines to the synchronism indicator. One arrangement is shown in Fig. 96, in which there are two kinds of plugs—one for the starting and one for the running machine. The difference between the plugs is such that the starting machine connects to the top of the synchronism indicator, and the running machine to the bottom. The diagram shows one of several synchronism indicators that are on the market. The order of leads is different in different types, but the method of synchronizing is essentially the same. Some engineers prefer to connect the lower, or running leads of the synchronism indicator to the buses in all cases, instead of connecting to one particular machine. The arrangement of wiring is then somewhat different, but the results are essentially the same. This is illustrated in Fig. 103. In the one case they synchronize "between machines" and in the other to the buses.

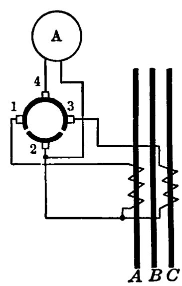

FIG. 97.—Rotating ammeter-switch.

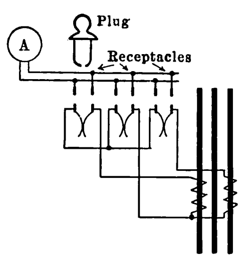

FIG. 98.—Ammeter plug and receptacles.

Rotating Ammeter Switch.—Switching devices for use with current transformers and ammeters should be constructed so that the ammeter can be inserted in any phase, without opening the circuit of any current transformer. Such devices are made on two different plans, illustrated in Figs. 97 and 98. A drum switch is made in several forms similar to Fig. 97. With the switch in the position shown, the currents from current transformers *A* and *C*, entering the switch at terminals 1 and 3, must flow through the ammeter before they can return. Since the resultant of the *A* and *C* currents is the *B* current (see Chapter XV, p. 119), the ammeter must now be indicating that current; but if the switch is rotated so that the small segment of the drum bridges from 1 to 2, only the *C* current flows through the ammeter; and by rotating the switch in the other direction the *A* current is indicated.

Ammeter Plugs and Receptacles.—The other device, which is represented in Fig. 98, consists of one plug and as many receptacles as there are lines in which the current is to be measured.

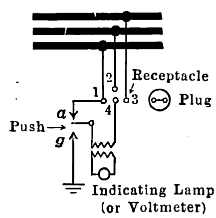

FIG. 99.—Ground detecting switches.

The plug is inserted across 1-4, 2-4, or 3-4, connecting one end of the voltage transformer primary to any one of the three line wires. If the ground detecting push is pressed, it makes contact at *g* and connects the other end of the primary to ground. The indicating lamp in the transformer secondary will be dark, or at most only dimly lighted, if connection is made to a line wire that is grounded.

When the push is not depressed, a spring presses the movable contact against *a*, connecting to line 1. If the plug is in position 2-4, or 3-4, the lamp then indicates full-line voltage by its brilliancy.

In case a little better indication is required in measuring ground voltages, the indicating lamp is replaced by a voltmeter.

The construction of plugs and receptacles is not exactly according to the diagram, which is intended to show the principle, rather than the form of the apparatus. As the plug is inserted, it first connects its two contact surfaces to the ammeter, and then to the transformer; and after that the lower path of the current is opened, forcing the current to flow up through the ammeter.

This device is sometimes preferred to the rotating switch, as by use of a special plug it permits connecting portable meters in the circuit to check the switchboard instruments.

Ground detector switches are made in a variety of forms. One arrangement of switches and a transformer is illustrated in Fig. 99, by which the voltage from any phase to ground is indicated roughly by a lamp or a little better by a voltmeter. Only a 110-volt lamp or voltmeter is required, if it is connected to the line through a voltage transformer, as shown.

METER APPLICATIONS

Meter Equipment for D.C. Switchboards.—Only one voltmeter is necessary for the entire board. One four-point plug should be furnished and there should be a receptacle for each generator. One receptacle in addition may be provided to measure bus voltage, if desired. This is illustrated in Fig. 94.

One ammeter is necessary for each D.C. generator. It is not customary to switch D.C. ammeters from one ammeter shunt to another, first, on account of the possible error due to contact

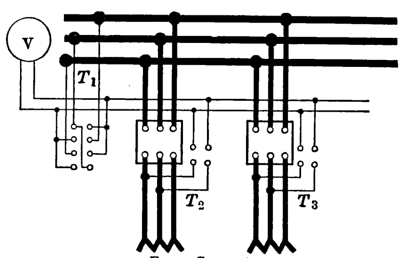

FIG. 100.—Voltmeter receptacles for measuring voltages on all phases of the buses and on one phase of each generator.

On high voltage circuits two voltage transformers are inserted at T_1, and one each at T_2 and T_3.

resistance, and second, because each generator needs its own ammeter continuously on the circuit. Ammeters are used on the more important outgoing feeders, but may be omitted from small feeders whose current is not likely to be excessively high.

Wattmeters are not ordinarily used on D.C. circuits, but watt-hour meters may be used on any generator or feeder circuit whose total energy is being observed closely.

Meter Equipment for Three-phase Switchboards.—There is usually only one voltmeter for the entire board, with the necessary plug and receptacles. An arrangement very frequently used is illustrated in Fig. 100, in which an eight-point receptacle is used to measure voltages on all phases of the buses, and in addition one four-point receptacle connects to each generator circuit, to measure the generator voltage before synchronizing. Sometimes an eight-point receptacle is connected to each generator, to measure voltage on all phases as in Fig. 101. The bus receptacles are then omitted. In still other cases two voltmeters are used as in Fig. 102; one for making measurements on all phases of the buses, and the other for one phase of each generator.

A synchronism indicator with all necessary plugs and receptacles, should preferably be installed in every large plant. Fig.

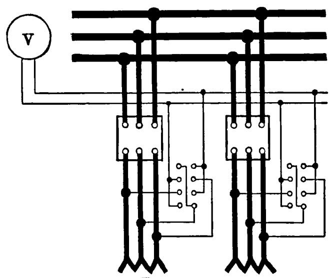

Fig. 101.—Voltmeter receptacles for measuring voltages on all phases of the generators.

Voltage transformers are added on high voltage circuits.

96 shows an arrangement for synchronizing between two generators, and Fig. 103 for synchronizing between a generator and the buses. Both arrangements are in common use.

One ammeter is provided for each generator, usually with a switching device for measuring the current in any particular

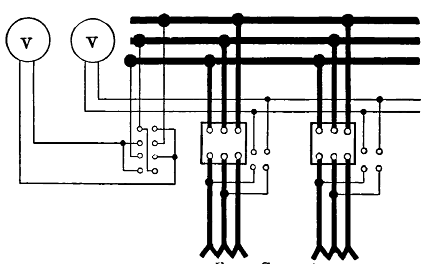

Fig. 102.—Voltmeter receptacles used with two voltmeters—one indicating bus voltages and one, generator voltages.

Voltage transformers are added on high-voltage circuits.

conductor. Ammeters may be installed also on the more important feeder circuits. The connections may be as in Fig. 97 or 98.

Wattmeters, watt-hour meters and power-factor meters are important in many cases; they may be used in any combination, on generator and feeder circuits, if there is special need of them. Fig. 104 shows a suitable arrangement where all these instruments are on a three-phase generator circuit.

A constant-current lighting circuit requires no meters except an ammeter in the constant-current side of the transformer. It may be connected as in Fig. 105, or the ammeter transformer

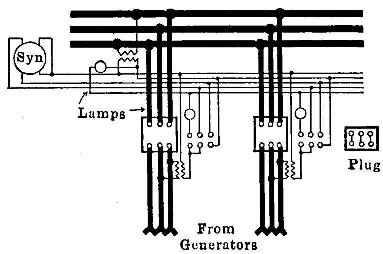

FIG. 103.—An arrangement of synchronism indicator and lamps for synchronizing a generator or motor "to the buses."

(shown dotted) may be omitted, in which case the ammeter is put directly in the lighting circuit.

Recording Meters.—There are three kinds of records made by meters: (1) a graphic record made by a pen, showing the fluctuation of current, voltage, power, power factor, frequency, or any other quantity to be measured; this is made by a "graphic" or

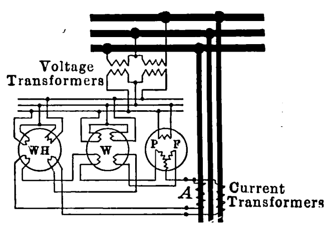

FIG. 104.—Watt-hour meter, wattmeter and power-factor meter on a three-phase circuit. If ammeters are also used, they may be inserted at the three dots at *A*.

"curve-drawing" meter. (2) An integrated record, showing the total energy in watt-hours or the total ampere-hours that have been delivered in a prescribed time; this record is made by a watt-hour or ampere-hour meter. (3) A record of the maximum power taken during any one minute, or other interval of time; it is made by a "maximum-demand" meter. The graphic meters may be an unnecessary luxury on ordinary circuits, on account of the first cost and paper, but in some cases the commercial and industrial advantages gained would warrant even a greater outlay. Meters of the integrating type are less expensive, and are in common use on all kinds of circuits. Comparing

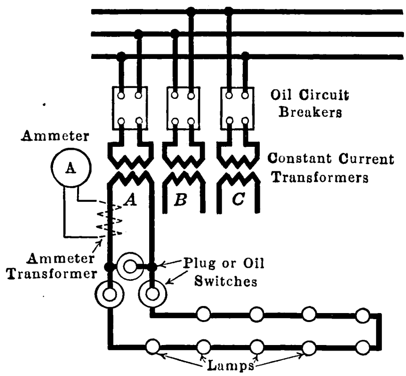

FIG. 105.—Connections for a series-lighting circuit.
The connections for circuits *B* and *C* are the same as for *A*. The ammeter transformer is sometimes omitted, and the ammeter is connected directly in the lamp circuit.

them with the graphic meters, the graphic record has the advantage of furnishing information not only at fixed times, but continuously. A maximum demand meter is used where a large user obtains a low rate for power, but is penalized for peak loads.

CHAPTER XX

MOTOR APPLICATIONS[1]

In selecting a motor for any particular service, the following are to be considered:

1. *The kind of motor* that is best suited to that service: whether D.C.—shunt, series or compound; or A.C.—squirrel-cage induction, phase-wound induction, or synchronous; also whether any special features (such as a flywheel, or series resistance) are desirable on account of special conditions of loading, or speed requirements (see Table XIII, p. 167, also Chapter IV, "D.C. Motors," p. 22, and Chapter V, "A.C. Motors," p. 28).

2. *The kind of system* best suited to that service: whether 110, 220, 440, 550 volts, or a higher voltage; and if A.C. whether 25 or 60 cycles; one- two- or three-phase (see Chapter III, p. 16).

3. *The size of motor* required for continuous duty (see Table XIV, p. 170, and the notes following the table).

4. *The best available speed of motor.* See Table II, p. 24, for D.C. motors, and Table III, p. 30, for induction motors. The best speed for a synchronous motor is usually the same as the no-load speed of an induction motor of the same size.

5. *Changes in motor rating,* on account of (*a*) inclosing the motor, (*b*) intermittent or variable loading of the motor, or (*c*) effect of change of speed on motor rating (see p. 183).

6. *Available sizes of motors.* Usually a motor can be obtained within 25 or 50 per cent. of any desired size. The exact sizes that are available are different in different lines of machines; the following sizes (horsepower) of D.C. and A.C. motors are usually available: 1, 2, 3, 5, 7½, 10, 12½, 15, 20, 25, 35, 50, 60, 75, 100, 125, 150, 200, 250, 300, 400, 500, 600, 750, 1,000, 1,250, 1,500, 2,000, 2,500. If the power required for any motor application exceeds a standard size by 5 per cent. or less, it is usually safe to use that standard size.

7. *The total load in case of group drive* is less than the sum of the loads on the several machines, unless all the machines in the group are operating at full-load at the same time. Usually the horsepower of the motor driving a group of machines should be 40 to 80 per cent. of the sum total of the full-load horsepower required by the several machines in the group.

[1] See foot note, p. 167.

TABLE XIII.—KINDS OF MOTORS FOR VARIOUS INDUSTRIAL MOTOR APPLICATIONS [1]

Motor application	Motors usually preferred (See list of abbreviations, p.168.)	Motors sometimes satisfactory
Machine shops:		
Bending and forming machines	Com.	SC. or WR., Slp.
Bolt and rivet headers	Shu., VS.	SC. or WR.
Boring mills	Com.	SC. or WR., Slp.
Drill presses	Shu., VS.	SC. or WR.
Drills, radial	Shu., VS.	SC. or WR.
Emery wheels	GD.	SC.
Grinders	GD.	SC.
Grind stones	GD.	SC.
Hammers	Com.	SC. or WR., Slp.
Lathes, axle	Shu., VS.	SC. or WR.
Lathes, engine	Shu., VS.	SC. or WR.
Lathes, wheel	Shu., VS.	SC. or WR.
Milling machines	Shu., VS.	SC. or WR.
Pipe threading and cutting-off machines	Shu., VS.	SC. or WR.
Planers	Com. or Rev.	SC.
Polishing and buffing	Shu. or SC.	
Presses, hydrostatic	Shu. or SC.	
Punch presses	Com., FW.	SC. or WR., Slp., FW.
Rolls, bending	Com.	WR.
Saws	Shu., VS.	SC. or WR.
Screw machines, automatic:		
Large	Shu., VS.	SC. or WR.
Small	GD.	
Shapers (if not GD.)	Shu.	SC. or WR.
Shears	Com., FW.	SC. or WR., Slp., FW.
Slotters and key-seaters (if not GD.)	Shu., VS.	SC. or WR.
Wood shops:		
Wood-working machinery:		
Small starting torque	SC.	Shu. enclosed.
Large starting torque	WR.	Shu. enclosed.
Various industrial applications:		
Air compressors:		
Reciprocating	Syn.,FW, or Com.	SC. or others.
Centrifugal	WR. or Shu.	SC.
Blowers	Shu., SC. or WR.	
Cement mills:		
Applications requiring large starting torque	WR.	
Applications requiring variable speed	WR.	
All others	SC.	
Coal and ore handling	Ser.	WR.
Coal crushers	Com. enclosed or WR.	SC.
Cranes	Ser.	WR.
Elevators	Spe., Com. or WR.	RI. or SC.

[1] See also the following, regarding industrial motor applications:
G. Chapter XVII, XVIII, XXXVII, XL, paragraph 364.
S. Section 15.
A. pp. 892, 972.

TABLE XIII.—KINDS OF MOTORS FOR VARIOUS INDUSTRIAL MOTOR APPLICATIONS.—*Concluded*

Motor application	Motors usually preferred (See list of abbreviations below.)	Motors sometimes satisfactory
Fans:		
Centrifugal	Shu., SC. or WR.	
Propeller	Ser., SC. or WR.	Shu.
Hoists	WR.	Ser. or Com. or Ilg.
Locomotives	Ser.	WR. if polyphase.
Paper and pulp mills:		
Small units	SC.	
Large units	WR.	
Low starting torque	Syn.	
Powder mills	SC.	
Pumps:		
Centrifugal	Shu., SC., WR.	Syn.
Reciprocating	(Motor depends on conditions) Com., Shu., SC., WR., or Syn.	
Refrigerating:		
Ammonia compressors	WR., MS.	Shu.
Steel rolling mills	WR., SS., FW.	Com., FW.
Telpherage	Ser.	WR.
Textile mills	SC. or Syn.	Shu. or Dif.
Turn tables and transfer tables	Ser.	WR.

Abbreviations (arranged alphabetically)

Com. = D.C. compound motor.

Dif. = D.C. differential compound motor.

FW. indicates that a flywheel should preferably be mounted on the motor shaft or geared to the motor, to relieve the motor of short-time overloads.

GD. = Group drive by any approximately constant-speed motor.

Ilg. = Ilgner system, consisting of an induction-motor-generator set with flywheel, driving a shunt motor. See p. 40.

MS. = Multi-speed induction motor, which has two or three synchronous speeds. See A. p. 977, S. 7 : 276; 15 : 304.

Rev. = D.C. motor specially adapted to reversing.

RI. = Combination single-phase repulsion-induction motor.

SC. = Squirrel-cage induction motor.

Ser. = D.C. series motor.

Shu. = D.C. shunt motor.

Slp. indicates that squirrel-cage and phase-wound induction motors are to have sufficient resistance in the rotor circuit to introduce about 10 per cent. slip at full-load.

Spe. indicates that the motor is to be of special construction.

SS. indicates that a 25-cycle motor is desirable, for slow speed.

Syn. = Synchronous motor with self-starting winding.

VS. indicates that the motor specified is especially preferable only where variable speed by hand regulation is required.

WR. = Induction motor with wound rotor and slip-rings connecting to an external rheostat.

SIZES OF MOTORS

In the following table some of the formulas for motor horsepower have a purely theoretical basis and others are empirical, being based on experimental data.[1] The power required depends so much on the nature of the work to be done that in some cases the formulas cannot be more than a first approximation.

Where the power can be expressed in terms of a single variable, that variable is written as A in the formula in the second column; the third column states what is meant by A, or by the several variables; and the fourth column gives the range through which the data indicate that the formula is correct. In most cases the range may be continued both upward and downward, without excessive errors. Where this column is left blank, the formula holds for all ordinary ranges.

[1] Most of the formulas are revised from data appearing in Section 15 of the "Standard Handbook for Electrical Engineers," Fourth Edition, 1915 (New York, McGraw-Hill Book Co., Inc.); and from *Leaflets* 3,516A and 3,554A on "Machine Tool Applications," issued by the Westinghouse Electric and Manufacturing Co.

TABLE XIV.—SIZES OF MOTORS

Motor application	Motor horsepower	Where A and other letters indicate (in inches unless stated otherwise)	Range of data on which the formula is based (in inches unless stated otherwise)
Metal-working Machinery.			
Bending and forming machines	$0.006A^2$	Width.	29 to 63 (head movement, 14 to 20 in.)
Bolt cutters, single	$1\frac{1}{3}A$	Diameter of bolt.	1 to 6
Bolt-heading, upsetting and forging machines	$8A$	Diameter of bolt.	¾ to 6
Boring machines	$A/3$	Maximum boring diameter.	20 to 40
Boring and turning mills, for light work	$A/12$		
Boring and turning mills, for average work	$A/8$	Size of mill (diameter).	37 to 300
Boring and turning mills, for heavy work	$A/4$		
Drilling, boring and milling machines, single or multiple-spindle, per spindle	$3(A-2)$	Diameter of spindle.	3½ to 6½
Drilling machines	KD^2F	D = diameter of drill in inches. F = feed in inches per minute. For cast iron, $K=0.5$ to 0.8; wrought iron and machinery steel, $K=0.9$; hard steel (0.5 per cent. carbon and harder) $K=1.6$ to 2; brass and similar alloys, $K=0.3$ to 0.4.	
Drilling machines, multiple-spindle, per spindle	$1A$	Diameter of drill.	¼ to 2
Drilling machines, radial, for light work	$A/3$		
Drilling machines, radial, for average work	$2A/3$	Arm in feet.	3 to 10 ft.
Drilling machines, radial, for heavy work	A		
Drilling machines, upright	$(A-15)/6$	Diameter of table.	20 to 60
Gear cutters	From $1.1A-8$ to $1.3A-8$	Face of gear.	9 to 14

TABLE XIV.—SIZES OF MOTORS.—*Continued*

Motor application	Motor horsepower	Where A and other letters indicate (in inches unless stated otherwise)	Range of data on which the formula is based (in inches unless stated otherwise)
Grinders, emery wheels, etc., per pair of wheels	From $(A-4)/3$ to $(A-4)/2$	Diameter of wheels.	6 to 26
Grinding machines, for grinding shafts, etc., average work	$0.5A$	Diameter of wheel.	10 to 18
Grinding machines, for grinding shafts, etc., heavy work	$0.8A$		
Hammers	From $A/25$ to $A/15$	Weight of hammer head in *pounds*.	15 to 200 lb.
Hammers, Bliss drop hammers	$A/100$	Weight of hammer head in *pounds*.	15 to 200 lb.
Lathes and similar machine tools	$KSFC$	S = speed of rotation in feet per minute. C = cut (difference between radius before and after cut is made) in inches. F = feed (distance along axis) in inches per revolution. K depends on the material being machined, and on shape of tool. With a round nosed tool, for cast iron, K = 3.5 to 6; for wrought iron or machinery steel, K = 7; for hard steel (0.5 per cent. carbon and harder) K = 12 to 15; for brass and similar alloys, K = 2.5 to 3.	
Lathes, engine, average	$0.4A-5$	Swing	14 to 84
Lathes, engine, heavy	$0.6A-5$	Swing	12 to 84
Lathes, axle, single	5 to 10		
Lathes, axle, double	10 to 20		
Lathes, wheel, main drive, average	$A/4$	Wheel diameter.	48 to 100
Lathes, wheel, main drive, heavy	$0.6A-8$	Wheel diameter.	48 to 100
Lathes, wheel, tail stock	5 to 7½		
Milling machine, vertical slabbing	$A/3$	Width of work.	24 to 42
Milling machine, vertical	$1\frac{1}{4}A-10$	Height under work.	12 to 24
Milling machine, plain	$\frac{1}{2}A-10$	Table feed.	34 to 50
Milling machine, universal	From $A-$ to $2\frac{1}{2}A$	No. of machine (not inches).	Nos. 1 to 5

TABLE XIV.—SIZES OF MOTORS.—*Continued*

Motor application	Motor horsepower	Where A and other letters indicate (in inches unless stated otherwise)	Range of data on which the formula is based (in inches unless stated otherwise)
Milling machine, horizontal slab miller, average	$0.35A$	Width between housings.	24 to 72
Milling machine, horizontal slab miller, heavy	$1\frac{1}{3}(A-16)$		
Nut tappers, 4 to 10 spindles	3 to 5		Up to 2
Pipe-threading and cutting-off machines	$(A+5)/3$	Maximum size pipe.	2 to 24
Planers, ordinary sizes, average duty	$(A-1)^2B/4$	A = width between housings in *feet.*	
Planers, ordinary sizes, heavy duty	$(A-1)^2B/3$	B = length of platen in *feet.*	
Planers, large sizes, average duty	$20+(A-1)^2B/40$		
Planers, large sizes, heavy duty	$30+(A-1)^2B/30$		
Planers, rotary	$0.45\ (B-15)$	Diameter of cutter.	24 to 100
Polishing and buffing, per pair of wheels	From $(A-5)/5$ to $(A-5)/2$	Diameter of wheels.	6 to 14
Presses, hydrostatic wheel	$3+A/50$	Size in *tons.*	100 to 600 tons
Punching machines	From $3.5A(B+\frac{1}{4})$ to $7A(B+\frac{1}{4})$	A = diameter. B = thickness.	From ⅜ diameter × ¼ thick to 2½ diameter × 1½ thick.
Rolls, bending and straightening	$3\frac{1}{3}AB$	A = width in *feet.* B = thickness in *inches.*	From 4 ft. × ⅜ in. to 10 ft. × 1½ in.
Saws, cold and cutoff, medium	$0.4\ (A-12)$	Size of saw.	20 to 32
Saws, cold and cutoff, large	$0.8\ (A-16)$	Size of saw.	32 to 48
Shapers	$A/6$	Stroke.	12 to 30
Shears, sheet metal	$0.4A$	Cross-section of cut in square inches.	From ⅛ × 30 to ¼ × 96.
Shears, lever	$1.5A\ (B+2)$	A and B are the dimensions of cross-sections of material; A is the larger and B the smaller dimension.	From 1 × 1 to 1½ × 8 or 3½ × 3½
Slotters and key-seating machines	$A/2$	Stroke.	6 to 14

TABLE XIV.—SIZES OF MOTORS.—*Continued*

Motor application	Motor horsepower	Where A and other letters indicate (in inches unless stated otherwise)	Range of data on which the formula is based (in inches unless stated otherwise)
Wood-working Machinery.			
Saw Mills.			
Band saws	150 to 250		
Circular saws, per pair	250 to 300		Diameter 60
Band resaws	$10A$	Width of saw.	5 to 10
Circular resaws, single	100		Diameter 72
Edgers	$8NT$	N = number of saws. T = thickness of stock.	From 2 to 8 saws, each from 6 to 32 in., with a feed of 200 ft. per min.
Slashers, per saw	3.5 to 7		From 4 to 14 saws, each 36 to 46 in.
Trimmers, per saw	2.5		From 2 to 20 saws, each 18 to 30 in.
Planing Mills.			
Ripping and resawing by band saws	$0.6A$ to $1.2A$	Number of square feet of cut per minute.	From 6-in. to 24-in. stock (*i.e.*, 0.5 to 2 ft.); feed from 22 to 70 ft. per min.
Ripping and resawing by circular saws	$0.4A$ to A	Number of square feet of cut per minute.	From 6-in. to 24-in. stock (*i.e.*, 0.5 to 2 ft.); feed from 22 to 70 ft. per min.
Surfacing two sides	0.3 to $0.6A$	Number of square feet of each surface per minute.	Stock 12 in. to 30 in. (1 to 2.5 ft.) wide; feed from 18 to 80 ft. per min.
Band saws—resaw, rip, scroll or combination	$5A$	Width of saw.	½ to 8
Circular saws, cutoff	$0.45\ (A - 5)$	Diameter.	10 to 36
Circular saws, rip, self-feed, 50 to 160 ft. per min.	$A - 5$	Diameter.	14 to 36

TABLE XIV.—SIZES OF MOTORS.—*Continued*

Motor application	Motor horsepower	Where A and other letters indicate (in inches unless stated otherwise)	Range of data on which the formula is based (in inches unless stated otherwise)
Circular saws, rip, hand-feed	$0.65 (A - 5)$	Diameter.	12 to 36
Circular saws, resaw, feed 30 to 80 ft. per min.	$0.65 (A - 5)$	Diameter.	24 to 48
Planers, matchers and flooring machines (feed 40 to 80 ft. per min.)	$22 + \frac{2}{3}A$	Capacity (width).	9 to 30
Timber sizers, 4 heads, 25 to 85 ft. per min., average	50		Capacity from 20 × 12 to 30 × 20.
Timber sizers, 4 heads, 25 to 85 ft. per min., heavy	75		
Tenoning machines	3 to 15		
Outside moulders or stickers, 4 heads, feed ranging from 10 to 80 ft. per min.	$A + B$	A = maximum width of stock. B = maximum thickness of stock.	From 4 × 4 to 14 × 5 or 10 × 8.
Mortising machines	$3A$	Maximum size of chisel or bit.	1 to 2½
Sanding machines, drum sanders, 3 drums	$0.4 (A - 12)$	Face of drum.	30 to 84
Sanding machines, drum sanders, 2 drums	$0.33 (A - 12)$	Face of drum.	30 to 48
Sanding machines, drum sanders, 1 drum	$0.25 (A - 12)$	Face of drum.	30 to 42
Sanding machines, belt sanders, 1 belt	$0.25A$	Width of belt.	6 to 18
Shapers, single-spindle	3		
Shapers, double-spindle	5		
Lathes, speed	0.5 to 1		
Lathes, pattern	$A/6$	Swing.	16 to 32
Cranes, Hoists and Telphers.			
Hoisting, continuous duty	$\frac{VW}{33,000E}$	V = Velocity in feet per minute. If velocity is variable, V in the formula is the maximum velocity.	

TABLE XIV.—SIZES OF MOTORS.—*Continued*

Motor application	Motor horsepower	Where A and other letters indicate (in inches unless stated otherwise)	Range of data on which the formula is based (in inches unless stated otherwise)
Trolley, steady travel (power for friction).	$\frac{VWF}{33{,}000}$	W = Weight in pounds. For hoisting it includes weight of load, and of bucket or hook if appreciable. For trolley it includes in addition, weight of trolley and trolley motor. For bridge it includes all the foregoing, and in addition weight of bridge. E = Efficiency of hoist and gearing. It is usually about 80 per cent. F = Tractive force in pounds per pound weight. For trolley motion it is about 0.015 and for bridge motion about 0.02. A = acceleration in feet per second per second. g = acceleration of gravity = 32.2. E = time of acceleration in seconds. W_m = weight of armature and gear of trolley motor, in pounds. r_g = gear ratio: $\frac{\text{motor r.p.m.}}{\text{track wheel r.p.m.}}$	
Trolley, average power for acceleration from rest at a given average rate.[1]	$\frac{VWA}{33{,}000 \times 2g}$		
Trolley, average power for acceleration from rest in a given time.[1]	$\frac{V^2W}{33{,}000 \times 2gt}$		
Trolley, average power for *both* friction and uniform acceleration from rest.[1]	$\frac{VW}{66{,}000}\left(F + \frac{A}{g}\right)$		
Bridge, steady travel (power for friction and wind pressure).	$\frac{V(WF + wa)}{33{,}000}$		
Bridge, average power for friction, wind pressure and acceleration from rest.	$\frac{V}{66{,}000}\left(WF + W\frac{A}{g} + wa\right)$		
Hoisting, trolley or bridge, intermittent duty[2].	$P_w\sqrt{\frac{t_w}{t_t}}$		
Hoisting, trolley or bridge, variable duty[2]	$\sqrt{P_1{}^2\frac{t_1}{t_t} + P_2{}^2\frac{t_2}{t_t} + \cdots}$		

[1] These formulas do not include the power required to accelerate the rotation of the armature and gears. This omission is likely to introduce an error of several per cent. in size of trolley motor. It is negligible with reference to hoisting and bridge motors. To make the correction, $\frac{VW_mA}{66{,}000\,g}\left(r_g\frac{R_m}{R_t}\right)^2$, or its equivalent, $\frac{V^2W_m}{66{,}000gt}\left(r_g\frac{R_m}{R_t}\right)^2$, should be added to the expression.

[2] The power given in the expressions for intermittent and variable duty is the root-mean-square value of power for the entire cycle. This value is used, because the *average* heating of the motor armature is nearly proportional to the mean square of the current, which is proportional to the mean square of the power. Another condition must be satisfied in applying a motor to intermittent or variable duty: *The short-time load (during a part of a cycle of operations) must not exceed the short-time capacity of the motor.* Usually a motor should be installed that would carry any ordinary load for 10 to 30 min., even though it will probably never be required to carry the load for that length of time, continuously.

TABLE XIV.—SIZES OF MOTORS.—*Continued*

Motor application	Motor horsepower	Where A and other letters indicate (in inches unless stated otherwise)	Range of data on which the formula is based (in inches unless stated otherwise)
		R_m = radius of gyration of armature and gear (about 0.7 of armature radius), in inches. R_t = radius of track wheel in inches. w = Wind pressure opposing motion of bridge, in pounds per square foot. It is negligible on in-door cranes. Its value is approximately $0.004v^2$ where v is wind velocity in miles per hour. If the bridge is travelling against the wind, v is the sum of wind and bridge velocities in miles per hour. a = area in square feet of surface directly facing the wind. P_w = horsepower delivered during the working part of a cycle of operations. P_1, P_2 . . . = horsepower delivered during certain parts, t_1, t_2 . . . of a cycle of operations. $\frac{t_w}{t_t}$ = ratio of time of working to total time in a cycle of operations. $\frac{t_1}{t_t}, \frac{t_2}{t_t}$ . . . = ratio of the times of certain operations to the total time of a cycle of operations.	
Conveyors and Belt Elevators.		H = height of elevation in feet.	For belt elevators, H = 40 to 60 ft., T = 35 to 200 tons per hr.
Horizontal screw conveyors	$CTL/1{,}000$	T = tons conveyed or elevated per hour. L = length of conveyor.	
Belt conveyors	$CTL/1{,}000 + TH/1{,}000$	In screw conveyors, C depends on material conveyed: For coal or cement, $C = 1.6$. For sand, gravel or ashes, $C = 2.4$.	For belt conveyors, W = 12 to 36 in.
Belt elevators	$H/5 + TH/800$	For grain, $C = 0.8$. In belt conveyors, C depends on width of belt, $= \frac{1}{3} - 4W/1{,}000$, where W is width in inches.	

TABLE XIV.—SIZES OF MOTORS.—*Concluded*

Motor application	Motor horsepower	Where A and other letters indicate (in inches unless stated otherwise)	Range of data on which the formula is based (in inches unless stated otherwise)
Cement Plants.			
Crushers	$AB/25 + T/C$	A and B = the dimensions of the opening of the crusher in inches.	A and B range from 10 × 7 to 84 × 60.
Crushers	From $T/2 + T/C$ to $T/4 + T/C$	C = size of crushed material in inches. T = tons crushed per hour.	C = 1 to 11. T = 2½ to 450.
Ball mills and tube mills	$NX(W + w)/6{,}000$	N = revolutions per minute. X = ft. distance from center of rotation to center of gravity of cement[1] and balls or pebbles in ft. $W + w$ = bbs. weight of cement and balls or pebbles in lbs.	
Maxecon (Kent) mills	25 to 50		
Kilns	A/8 to A/5	Length in feet.	60 to 170 ft.
Pumps and Compressors.			
Pumps (water)	$\frac{GH}{3{,}950E}$	G = gallons per minute. H = static head + friction head in feet of water. E = pump efficiency = 0.6 to 0.8.	G = 100 to 2,000 gal. per min. H = 25 ft. or more.
Air compressors	$0.214V$	V = volume in cubic feet per minute of free air compressed to 100 lb. per sq. in.	V = 500 or more cu. ft. per min.
Steel Plants.			
Rolling mills	KNT	N = number of times original length to which finished material is elongated. T = number of tons rolled per hour. For rolling high carbon billets to rods K = 8 billets to light rails 6 billets to flats and squares 5 ingots to billets 3 slabs to plates 2.5	N = 4 to 15. T = 5 to 100.
Refrigerating Plants.			
Ammonia compressors	$0.5 + 1.5A$	T = Capacity in tons of ice produced in 24 hr.	1 ton or more.

[1] See p. 181 for explanation.

Notes on Table XIV

The following examples will illustrate the use of the formulas:

Bending and Forming Machines.—A machine taking work 34 in. wide requires 0.4 (34 − 15) or 7.6 hp. From the list of available sizes on page 166, a 7½-hp. motor would be selected.

Drilling Machines.—There are seven different formulas for the horsepower required for a drilling machine. For a machine that is required to perform well-defined operations the first formula may be used. If it has two spindles, and is to drill holes ½ in. in diameter in brass, with a feed of 1 in. per min., the power required is 2×0.3 (or 0.5) $\times 0.5^2 \times 1 = 0.167$ hp. Probably a 1-hp. motor would be used unless this is one of a group of machines driven by a single motor (see page 166, paragraph 7).

If the same drilling machine is for general use, the power required per spindle may be obtained from the formula $A/8$, where A is the diameter of the largest drill that will be used. The total power, then, is $2 \times ½/8$ or 0.125 hp.

If the diameter of the spindle, or the diameter of the table is given, or if the length of arm of a radial drilling machine is given, ordinary values of power required for such machines are similarly obtained. Where data are obtainable for applying more than one formula, the values of horsepower may be computed by the several formulas, and averaged.

Edgers (for Wood-working).—If an edger has four saws, and is used on 6-in. stock, the motor should be of $8 \times 4 \times 6$ or 192 hp. A 200-hp. motor would be selected.

Ripping and resawing by band saws. The power required for this and other wood-working depends on the dryness and kind of wood. For ripping 12-in. (1-ft.) wet oak with a feed of 30 ft. per min., the power required is $1.2 \times 1 \times 30 = 36$ hp. A 35-hp. motor would be used for this purpose.

Cranes Assume the Following Full-load Data:

Capacity of crane (load)	60 tons
(Weight of hook is negligible)	
Weight of trolley, including motor	25 tons
Weight of bridge	50 tons
Hoisting and lowering speed	20 ft. per min.
Maximum trolley-travel speed	100 ft. per min.
Maximum bridge-travel speed	250 ft. per min.
Average trolley acceleration and retardation	3 ft. per sec. per sec.
Average bridge acceleration	0.5 ft. per sec. per sec.
Bridge retardation must be at least as much as its average acceleration.	
Wind velocity	20 miles per hr.
Area facing the wind	280 sq. ft.
Diameter of trolley-motor armature	18 in.
(radius of gyration = 0.7×18 in.)	

Diameter of trolley track wheel............	12 in.
Trolley gear ratio, $\frac{\text{motor r.p.m.}}{\text{track wheel r.p.m.}}$, ...	2 : 1
Weight of motor armature and gear........	1,000 lb.
Motor efficiency for each motor	0.90
Maximum hoisting distance...............	20 ft.
Maximum distance of trolley travel in each direction..............................	40 ft.
Maximum distance of bridge travel in each direction	400 ft.
One-half of the hoisting and lowering may be performed during bridge and trolley travel.	
Other data are found in the table.	

Dynamic Braking.—As is customary, the motors are provided with "dynamic braking"—that is, in place of a friction brake, each motor is connected to operate as a generator sending power back into the line.

Let P_m = mechanical power developed, which is delivered either from the motor to the crane, or from the crane to the motor;

P_i = electric power input when the machine is running as a motor;

P_o = electric power output when the machine is running as a generator;

e = efficiency of conversion in either direction. It takes account of all or nearly all losses in the motor; it also takes account of losses in gears and bearings of the crane, if they have not been included elsewhere.

The relations between mechanical and electrical power are:

$$P_i = P_m/e; \qquad P_o = P_m e$$

so that if the same mechanical power is developed in the two directions,

$$P_o = P_i e^2.$$

That is, the electric power *output* in lowering a hoist or retarding a trolley or bridge is e^2 times the electric power *input* to produce the same mechanical power in the reverse direction. Heating of the armature depends on the electric, not the mechanical power developed, so that the ability to receive is greater than that to deliver mechanical power. For example, if a motor has an efficiency of 0.90, and is receiving 123 mechanical hp., the heating is the same[1] as if it were delivering 123×0.90^2 or 100 hp. Stated differently—if a machine is operating as a generator, receiving a certain amount of mechanical power, the *equivalent mechanical power output* (in its effect in heating the motor) is the mechanical power received multiplied by the square of the efficiency;

$$P_{eq} = P_m e^2.$$

This is an important point that is not always understood clearly.

[1] Subject to slight variations on account of different field excitation during braking.

COMPUTATIONS.—

Hoisting motor:

Power for hoisting $= \dfrac{20 \times 60 \times 2{,}000}{33{,}000 \times 0.80} = 91$ hp. where 0.80 is the efficiency of gears and crane bearings.

Mechanical power developed in lowering is the same as in hoisting.

Overall efficiency is 0.80×0.90 or 0.72. The *equivalent* power, in its effect on the motor during dynamic braking $= 91 \times 0.72^2 = 47$ hp.

Trolley motor:

Power for steady travel $= \dfrac{100 \times (60 + 25) \times 2{,}000 \times 0.015}{33{,}000} = 7.7$ hp.

Average power during acceleration[1] =

$$\frac{100 \times (60 + 25) \times 2{,}000}{66{,}000}\left(0.015 + \frac{3}{32.2}\right) = 28 \text{ hp.}$$

Average mechanical power during retardation is due to the difference, instead of the sum of the effects of acceleration and friction:

$$\frac{100 \times (60 + 25) \times 2{,}000}{66{,}000}\left(\frac{3}{32.2} - 0.015\right) = 20.2 \text{ hp.}$$

The *equivalent* power, in its effect on the motor during dynamic breaking, is $20.2/e^2$. The efficiency, e, takes account of only motor losses, since other losses are included in the allowance for friction. The equivalent power $= 20.2 \times 90^2 = 16.3$ hp.

Bridge motor:

In computing wind pressure, the velocity of the bridge in miles per hour is required: $\dfrac{250 \times 60}{5{,}280} = 3$ miles per hr.

Wind pressure per square foot, $w = 0.004\ (3 + 20)^2 = 2.1$ lb.

Total power for steady travel against the wind is

$$\frac{250\ (60 + 25 + 50) \times 2{,}000 \times 0.02 + 2.1 \times 280}{33{,}000} = 45.5 \text{ hp.}$$

Average power for acceleration and retardation is computed the same as for the trolley motor. During retardation, friction exerts a retarding force of WF lb. on a mass W, thereby producing a retardation of WFg/W, or Fg. The retardation due to friction is, therefore, $Fg = 0.02 \times 32.2 = 0.644$ ft. per sec. per sec. Since this is greater than the required retardation (0.5), dynamic braking is unnecessary except for emergencies.

Time computations:

Time for hoisting = 20/20 .... 1 min.

Time for lowering .... 1 min.

Time for accelerating trolley $= V/A = \dfrac{100}{60 \times 3}$ .... 0.56 sec.

[1] The effect of acceleration of rotation of the motor armature is neglected in this computation. If it is taken into account, the following must be added to the mechanical horsepower during acceleration and retardation:

$$\frac{100 \times 1{,}000 \times 3}{66{,}000 \times 32.2}\left(2 \times 0.7 \times \frac{18}{12}\right)^2 = 0.6 \text{ hp.}$$

Distance covered during acceleration	$= \frac{100}{2 \times 60} \times 0.56$	$= 0.46$ ft.
Distance covered during retardation		$= 0.46$ ft.
Remaining distance of trolley travel	$= 40 - 2 \times 0.46$	$= 39$ ft.
Time for steady travel	$= 39/100$	$= 0.39$ min.
Time for accelerating bridge	$= \frac{250}{60 \times 0.5}$	$= 8.3$ sec.
Space for accelerating	$= \frac{250 \times 8.3}{2 \times 60}$	$= 17$ ft.
Time for retarding	$= \frac{250}{60 \times 0.644}$	$= 6.5$ sec.
Space for retarding	$= \frac{250 \times 6.5}{2 \times 60}$	$= 13.5$ ft.
Space for steady travel	$= 400 - 30$	$= 370$ ft.
Time for steady travel	$= \frac{370}{250}$	$= 1.48$ min.
Total time for crane travel	$= 1.48 + \frac{8.3 + 6.5}{60}$	$= 1\frac{3}{4}$ min.

Since one-half of the lowering and hoisting can be during bridge travel, and trolley travel is during bridge travel, the total time of one trip

$$= \frac{1+1}{2} + 1\tfrac{3}{4} = 2\tfrac{3}{4} \text{ min., approx.}$$

If the crane carries no load on the return trip, the time for raising and lowering the hook may usually be neglected; and we may assume that the bridge and trolley speed is the same at light-load as at full-load. The time for the round trip then $= 1\frac{3}{4} + 2\frac{3}{4} = 4\frac{1}{2}$ min.

Root-mean-square computations:

Root-mean-square of power in hoisting[1] =

$$\sqrt{P_1^2 \frac{t_1}{t_t} + P_2^2 \frac{t_2}{t_t}} = \sqrt{91^2 \times \frac{1}{4\frac{1}{2}} + 47^2 \times \frac{1}{4\frac{1}{2}}} = 48 \text{ hp.}$$

That is, the motor should be able to carry 48 hp. continuously, and 91 hp. for a short time.

The root-mean-square horsepower of the other motors is found in the same way. Motor speeds and gear ratios must be determined after referring to speed characteristics of available motors.

Cement Plants—Ball and Tube Mills.—These mills are cylindrical in form, as in Fig. 106. They are filled about one-half full of cast-iron balls, pebbles, or other means for pulverizing the cement, and they are filled to the same depth with the material to be pulverized. A motor is connected to each mill, rotating it and causing the balls or pebbles to fall on the material, pulverizing it. The center of gravity of the contents is at a distance *OG* from the center of rotation; this distance can be obtained from Table XV, after finding the area of cross-section of the material. The slope of the surface at which the balls or pebbles begin to fall is about 45° from the

[1] Theoretically, the values of P_1 and P_2 should themselves be the root-mean-square values, for times t_1 and t_2 respectively. Practically, the average value is easier to find, and in all ordinary cases the error is negligible in assuming that the average values are the same as root-mean-square values for the respective times.

horizontal. The power in foot-pounds per minute, required to rotate the mass is $2\pi \times$ torque in foot-pounds $\times$ r.p.m. From these data, having given the weight of material and r.p.m., the power expended in the tube can be computed. The formula for horsepower given in Table XIV is based on the assumption that the angle is 45°, and that about 25 per cent. is added to the power expended in the tube for gear and bearing friction. These are usually good assumptions to make.

ASSUME THE FOLLOWING DATA:

The mill contains 60,000 lb. of cast-iron balls, and the interstices between the balls are filled with material to be pulverized. Cast iron (solid) weighs 450 lb. per cu. ft. Cement material—if balls were omitted—would weigh 85 lb. per cu. ft. Of the total space filled with the mixture, 60 per cent. is occupied by iron and 40 per cent. by cement material.

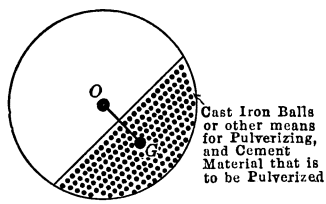

FIG. 106.—Position of load in a tube mill during rotation. The surface is inclined about 45 degrees from the horizontal.
O = Center of rotation. G = Center of gravity of load.

The inside diameter of the tube is 69 in. ($5\frac{3}{4}$ ft.), and the length 21 ft. The mill makes 22 r.p.m.

COMPUTATIONS:

$$\text{Cubic feet of mixture} = \frac{60,000}{0.60 \times 450} = 222 \text{ cu. ft.}$$

TABLE XV.—CENTER OF GRAVITY OF SEGMENT OF A CIRCLE

(Used in Computing Horsepower of Tube-mill and Ball-mill Motors)

Columns headed "Area" give the area of the segment in terms of the square of the diameter, D^2. Columns headed "Distance" give the distance from the center of gravity to the center of rotation in terms of the diameter, D.

Area	Distance	Area	Distance	Area	Distance
$0.05D^2$	$0.431D$	$0.3927D^2$	$0.212D$	$0.6D^2$	$0.103D$
$0.1D^2$	$0.391D$	(½ of com	plete circle)	$0.65D^2$	$0.076D$
$0.15D^2$	$0.355D$			$0.7D^2$	$0.049D$
$0.2D^2$	$0.322D$	$0.4D^2$	$0.208D$	$0.75D^2$	$0.021D$
$0.25D^2$	$0.292D$	$0.45D^2$	$0.181D$	$0.7854D^2$	0
$0.3D^2$	$0.263D$	$0.5D^2$	$0.155D$	(complete	circle)
$0.35D^2$	$0.235D$	$0.55D^2$	$0.129D$		

$$\text{Sectional area} = \frac{222}{21} = 10.6 \text{ sq. ft.}$$

$$\text{In terms of square of diameter, area} = \frac{10.6D^2}{5.75^2} = 0.32D^2$$

From Table XV, distance to center of gravity = $0.252D$ = 1.44 ft.

$$\text{Weight of cement material} = \frac{0.40 \times 85}{0.60 \times 450} \times 60{,}000 = 7{,}600 \text{ lb.}$$

Total weight inside the tube = 60,000 + 7,600 = 67,600 lb.
Power required to operate 22 × 1.44 × 67,600/6,000 = 280 hp.

CHANGES OF MACHINE RATINGS

(*a*) **Enclosed Motors.**—A motor designed to be run open (with windings exposed to the outside air) may usually be run enclosed (with lids closed, decreasing the cooling effect of the outside air) and carry continuously two-thirds of the rated full-load.

(*b*) **Intermittent and Variable Loads.**—Electrical machines, transformers, and other apparatus having heavy windings, which require 6 or 8 hr. to approach their maximum temperature, do not usually heat the windings excessively when they carry:

150 per cent. of continuous full-load rating for 1 hr.
200 per cent. of continuous full-load rating for ½ hr.

This logically implies that the machine is not already heated when the overload occurs; if it is overloaded, following a long full-load period, the size of the machine should be increased a little on that account.

If the motor is loaded only a few minutes at a time, or if the load fluctuates, the average heating of the armature may be obtained as in the case of crane motors.[1]

Change of Speed.—A motor is sometimes run at a higher speed than that for which it was originally designed. For this change it is necessary (1) that the principal field, or a special commutating field be strong enough for commutation at the higher speed; (2) that the mechanical construction of the armature be strong enough to withstand the increased centrifugal force; and (3) that the armature be well-balanced, and the bearings ample, to prevent excessive heating and wear of bearings. Under these conditions, the speed of a D.C. motor can frequently be increased to twice its original speed, by weakening the field. The increased speed increases the ventilation, and thereby reduces the heating of the armature, so that at double the speed the motor will usu-

[1] See "Hoisting, Trolley or Bridge—Intermittent Duty and Variable Duty," Table XIV, p. 175, and the footnote referring to this application.

ally deliver 20 per cent. more power than at the original speed (see p. 23 for allowable torque at higher speed).

If the commutator and winding will stand a higher voltage, the speed may be increased by increased armature voltage, instead of by field control. In that case the armature will not heat excessively, even when the power delivered exceeds 200 per cent. of full-load; usually commutation, rather than heating of the armature, limits the maximum possible load under these conditions.

When lower than rated speeds are obtained by inserting resistance in the armature circuit, the maximum allowable horsepower is reduced about in proportion to the speed, since the armature current is the same at the reduced horsepower as at full horsepower at full-speed.

CHAPTER XXI

COSTS

Even under the most favorable conditions it is not possible to give a simple general expression for costs, that can be applied to all kinds and grades of apparatus. This is especially true under the present fluctuating industrial and commercial conditions. The costs given in the following table should therefore be checked with quotations from manufacturers, before they are used as a basis for installing equipment.

For cost of copper wire, see Table XII, and accompanying notes, pp. 81 and 84. For cost of batteries see p. 51.

Costs of engines, generators and motors depend so much on speed and other features of design, that it is impracticable to express even a close approximation to costs in any simple way. The following expressions are not put in the table, because they are only rough approximations; they will be found to be too high for average conditions:

For 1 to 25 kw., or 1 to 35 hp. D.C. generators or motors running at 1,200 to 400 r.p.m., $75 + $21 per kw., or $75 + $16 per hp.

For 50 to 2,000 kw., or 60 to 2,400 hp. D.C. generators or motors running at 400 to 200 r.p.m., $300 + $8 per kw., or $300 + $6 per hp.

For 60-cycle, 100 to 800 kva. alternators or synchronous motors, running at 300 to 100 r.p.m., $1,000 + $14 per kva.

For 25-cycle, 1,000 to 2,000 kva. alternators or synchronous motors running at 100 r.p.m., $7,000 + $7 per kva.

For 25-cycle alternators or synchronous motors, add 10 per cent. to the cost for 60 cycles.

For 60-cycle induction motors, 25 to 300 hp., $250 + $5 per hp.

For 25-cycle induction motors, 25 to 300 hp., $200 + $9 per hp.

For motor generator sets, sum of motor and generator cost.

For 300 to 1,000 kw. synchronous converters, $4,000 + $15 per kw.

For A.C. or D.C. turbo-generator sets (including turbine), up to 300 kw., $300 + $30 per kw.

For 60-cycle, 500 to 5,000 kw. turbo-generator sets, $5,000 + $10 per kw.

For 60-cycle turbo-generator sets, above 5,000 kw., $30,000 + $6 per kw.

For reciprocating compound steam engines, $500 + $20 per kw. capacity of the generator.

TABLE XVI.—COSTS OF APPARATUS.

Special features and uses	Diameter (or length of side, if not round) in inches	Kind of apparatus	Full scale or normal current or voltage[4]	Accuracy; maximum error in per cent. of full-scale reading.	Approximate net cost in dollars		For description and application of apparatus see page
METERS							
D. C. Switchboard Meters.							152–162
Low price, simple construction, only moderate accuracy; ammeter used without shunt.						$10 + 1.2A$	
	9⅝	Ammeters	5 to 600 amp.	3		$10 + 1.2V$	
		Voltmeters	150 to 750 volts	2½	1 to 25 amp.[1]	4.50	
	3	Ammeters	Any	2	50 to 75 amp.[1] or any[2]	6.00	
						4.50	
Small panels, battery charging, marine, telegraph, telephone, and farm lighting installations.		Voltmeters	1 to 150 volts	2	1 to 25 volts'	4.50	
					50 to 150 volts	6.00	
	5	Ammeters	1 to 75 amp.[1]	2		9.00	
			Any[2]			9.00	
		Voltmeters	5 to 750 volts	1	5 to 300 volts	9.00	
					600 to 750 volts	10.00	
High grade, easily readable...	7 7/16	Ammeters	5 to 75 amp.[1]	2½ (average)		15.50	
			Any[2]			14.75	
		Voltmeters	150–4,000 volts	2½ (average)	150 to 750 volts	$15 + 1.4V$	
					1,000 to 4,000 volts	$28 + 0.45V$	
	9⅝	Ammeters	10 amp.[1]	1		22.68	
			Any[2]			22.25	
		Voltmeters	150 to 750 volts	1		$23 + 1.5V$	

V = potential rating in hundreds of volts. As applied to voltmeters, it refers to the full-scale reading; as applied to other apparatus, it refers to the voltage of the system for which the apparatus is designed.

A = current rating in hundreds of amperes. As applied to ammeters, it refers to the full-scale reading; as applied to other apparatus, it refers to the normal full-load current.

K = rated full-load in kilovolt-amperes. As applied to feeder voltage regulators it refers to the product of amperes and kilovolts across the boosting winding of the regulator—not the kilovolts across the line. (For a three-phase regulator, K is $\sqrt{3}$ times the product, and for a two-phase regulator it is 2 times the product).

N = number of poles of a switch. P = Maximum per cent. each, ohmic and inductive compensation.

[1] The range given applies to cases where the ammeter is self-contained (requiring no external shunt), or used with a special shunt, included in the cost of the meter.

[2] The ammeter or relay can be used with a regular switchboard shunt; its capacity depends on the size of the shunt. The cost of the shunt is not included in the cost of the meter.

TABLE XVI.—COSTS OF APPARATUS.—*Continued*

Special features and uses	Diameter (or length of side, if not round) in inches	Kind of apparatus	Full scale or normal current or voltage[4]	Accuracy; maximum error in per cent. of full-scale reading	Approximate net cost in dollars		For description and applications of apparatus see page
Illuminated dial, for large switchboard panels, or swinging brackets.	12⅛ × 15¾	Ammeters	Any[2]	1		61.50	
		Voltmeters	150 to 750 volts	¾		$63 + 0.80V$	
Negligible temperature coefficient; negligible thermo-electromotive force; thus avoiding errors due to heating.		Ammeter shunts	10 to 20,000 amp.		3,000 to 20,000	$1.3 \times (A - 10)$	
					10 to 3,000	$2 + 0.80A$	
Low price; only moderate accuracy. Shunt made of iron alloy.		Ammeter shunts	100 to 1,500 amp.		100 to 1,000	$0.80 + 0.32A$	
					1,000 to 1,500	$3.00 + 0.10A$	
A. C. Switchboard Meters.							148–165
Low-price, simple construction, only moderate accuracy; ammeter used without current transformer on 2,400 volts or less.	9⅝	Ammeters	5 to 600 amp.	3		$10 + 1.2A$	
			Any[3]			10.50	
		Voltmeters	150 to 750 volts	2½		$10 + 1.2V$	
			Any[3]			10.50	
High grade, perfectly damped, long scales; induction type meters.	7⁷⁄₁₆	Ammeters	Any[3]	1		18.50	
		Voltmeters	150 to 750 volts	1		$19 + 1.25V$	
			Any[3]			21.00	
		Single-phase wattmeters	100 to 400 volts	2		$35 + 1.5V$	
			Any[3]			36.00	
		Polyphase wattmeters	100 to 400 volts	2		$48 + 3.3V$	
			Any[3]			50.75	
	9⅝	Ammeters	Any[3]	1		20.25	
		Voltmeters	150 to 750 volts	1		$21 + 1.25V$	
			Any[3]			22.75	
	9⅝	Single-phase wattmeters	100 to 400 volts	2		$38 + 1.5V$	
			Any[3]			39.25	
		Polyphase wattmeters	100 to 400 volts	2		$54 + 3V$	
			Any[3]			56.25	

[3] Meters and other apparatus connected to instrument transformer secondaries, may be adapted to any line current or voltage, depending on the primary rating and insulation of the instrument transformers. Cost of transformers is not included in the cost of apparatus as listed.

TABLE XVI.—COSTS OF APPARATUS.—*Continued*

Special features and uses	Diameter (or length of side, if not round) in inches	Kind of apparatus	Full scale or normal current or voltage[4]	Accuracy; maximum error in per cent. of full-scale reading	Approximate net cost in dollars	For description and applications of apparatus see page
High grade, perfectly damped, long scales; induction type meters.	7 7/16	Ammeters	5 to 400 amp.	2½ (average)	13.5+0.75*A*	
		Voltmeters	150 to 750 volts	2½ (average)	14+1.2*V*	
			Any[3]		15.75	
High grade, easily readable.	7 7/16	Frequency meters	100 to 500 volts	1	42+0.60*V*	
			Any[3]		42.25	
	9 5/8	Frequency meters	100 to 500	1	43.75+0.60*V*	
			Any[3]		44.00	
Indicating what part of the current is the power component, or what the reactance component.	7 7/16	Single-phase power-factor meters	Any[3]		34.25	
	9 5/8	Single-phase power-factor meters	Any[3]		35.50	
	7 7/16	Polyphase power-factor and reactance factor meters	100 to 400 volts		38+1*V*	
			Any[3]		38.75	
	9 5/8	Polyphase power-factor and reactance factor meters	100 to 400 volts		39+1*V*	
			Any[3]		40.00	
Indicating exact phase difference between machines at all times during synchronizing.	7 7/16	Synchronism indicators (synchronoscopes)	Any[3]		48.75	
	9 5/8	Synchronism indicators (synchronoscopes)	Any[3]		50.00	
	15 7/8	Synchronism indicators (synchronoscopes)	Any[3]		162.50	

[4] In case of wattmeters, power-factor meters, voltage transformers, etc., which do not have a voltage scale, this refers to the voltage to which the potential winding is adapted. In case of current transformers, circuit breakers and switches, it refers to the voltage for which the apparatus is insulated.

TABLE XVI.—COSTS OF APPARATUS.—*Continued*

Special features and uses	Diameter (or length of side, if not round) in inches	Kind of apparatus	Full scale or normal current or voltage[4]	Accuracy; maximum error in per cent. of full-scale reading	Approximate net cost in dollars		For description and applications of apparatus, see page
Indicating voltage to ground, thereby showing whether line is grounded (limited to systems that are not already grounded).	9⅝	Single-phase ground detectors	2,200 to 22,000 volts		2,200 to 6,600 11,000 to 22,000	$33 + 0.20V$ $47 + 0.03V$	
		Three-phase ground detectors	2,200 to 22,000 volts		2,200 to 6,600 11,000 to 22,000	$52 + 0.12V$ $60 + 0.014V$	
		Electrostatic voltmeters	2,200 to 22,000 volts	5		$32 + 0.02V$	
Illuminated dial, for large switchboard panels, or swinging brackets.	12⅛ × 15¾	Ammeters	Any[3]	2		62.50	
	12⅛ × 15¾	Voltmeters	150 to 750 volts Any[3]	1½		$61 + 1.25V$ 62.50	
Vertical edgewise meters for use where a compact arrangement of meters is necessary.	15½ × 3, 4 or 5¼	Ammeters.	Any[3]			44.50	
	15½ × 3, 4 or 5¼	Voltmeters	150 to 750 volts Any[3]			$46.5 + 0.65V$ 47.50	
	15½ × 3, 4 or 5¼	Single-phase wattmeters	Any[3]			46.00	
	15½ × 5¼	Polyphase wattmeters	Any[3]			66.00	
	15½ × 5¼	Frequency meters	Any[3]			61.00	
	15½ × 5¼	Single-phase power-factor meters	Any[3]			55.00	
	15½ × 5¼	Polyphase power-factor meters	100 to 400 volts Any[3]			$54.5 + 1.5V$ 56.00	
Switchboard Integrating Meters. Meter with glass case, for intergrating watt-hours on single-phase switchboard circuits.		Watt-hour meters	100 to 400 volts Any[3]			$29 + 3V$ 31.50	148, 149, 155–158, 164

TABLE XVI.—COSTS OF APPARATUS.—*Continued*

Special features and uses	Diameter (or length of side, if not round) in inches	Kind of apparatus	Full scale or normal current or voltage[4]	Accuracy; maximum error in per cent. of full-scale reading	Approximate net cost in dollars		For description and applications of apparatus see page
Same as the foregoing, except with metal case.		Watt-hour meters	100 to 400 volts Any[3]			26 + 3*V* 28.50	
Meter with glass case for integrating watt-hours on polyphase switchboard circuits.		Watt-hour meters	100 to 400 volts Any[3]			41 + 3*V* 44.00	
Same as the foregoing, except with a metal case.		Watt-hour meters	100 to 400 volts Any[3]			38 + 3*V* 41.00	
Switchboard Graphic Meters.							152, 164
	13¼ × 16½ except D.C. wattmeters, whose dimensions vary with the capacity.	D.C. ammeters	Any[2]	1		118.00	
		A.C. ammeters	Any[3]	1		108.00	
		A.C. or D.C. voltmeters	A.C. or D.C. 140 to 700 volts A.C. only, Any[3]	1		123 + 2.4*V* 127.00	
Relay type (*i.e.*, pen is moved by relay action—not directly by the meter torque) suitable for accurate switchboard records.		Single-phase wattmeters	100 to 500 volts Any[3]	1		111.00 111.00	
		Polyphase wattmeters	100 to 500 volts Any[3]	1		111.00 111.00	
		D.C. wattmeter	100 to 650 volts	1	25 to 8,000 amp. 10,000 to 30,000	185 + 1.8*A* 300 + 0.5*A*	
		Frequency meters	Any[3]	1		138.00	
		Single-phase and polyphase power-factor meters	Any[3]			138.00	

TABLE XVI.—COSTS OF APPARATUS.—*Continued*

Special features and uses	Diameter (or length of side, if not round) in inches	Kind of apparatus	Full scale or normal current or voltage[4]	Accuracy; maximum error in per cent. of full-scale reading	Approximate net cost in dollars		For description and applications of apparatus see page
For above meters; 248 ft. per roll, for feeding at 2, 4 or 8 in. per hr.		Graphic meter paper			Cost per roll, depending on size of order	1.50 to 2.00	
INSTRUMENT TRANSFORMERS							114–120.
Through-type indoor, secondary capacity, 25 to 50 volt-amp., compensated for 10 or 25 volt-amp., for slipping over a cable stud or busbar; nominal secondary current, 5 amp.		Current transformers	600 to 10,000 amp. 3,500 volts		600 to 3,000 amp. 4,000 to 10,000 amp.	$9 + 0.55A$ $30 + 0.4A$	127, 129, 139–141
Dry-type indoor, compact, low priced; capacity 10 volt-amp.; compensated for 10 volt-amp.; nominal secondary current, 5 amp.		Current transformers	5 to 500 amp. 2,500 volts			$9 + 0.7A$	
Dry-type, indoor, capacity 50 volt-amp.; compensated for 25 volt-amp.; nominal secondary current 5 amp.		Current transformers	5 to 1,200 amp. 8,000 volts			$19 + 2A$	
Same as the foregoing, except insulation.		Current transformers	5 to 800 amp. 17,000 volts			$29 + 2A$	
Same as the foregoing, except insulation.		Current transformers	5 to 500 amp. 24,000 volts			$41 + 2A$	
Dry-type, outdoor, capacity 50 volt-amp.; compensated for 25 volt-amp.; nominal secondary current 5 amp.		Current transformers	5 to 500 amp. 8,000 volts			$24 + 2A$	

TABLE XVI.—COSTS OF APPARATUS.—*Continued*

Special features and uses	Diameter (or length of side, if not round) in inches	Kind of apparatus	Full scale or normal current or voltage[4]	Accuracy; maximum error in per cent. of full-scale reading	Approximate net cost in dollars	For description and applications of apparatus see page
Same as the foregoing except insulation.		Current transformers	5 to 500 amp. 17,000 volts		$38 + 2A$	
Same as the foregoing except insulation.		Current transformers	5 to 500 amp. 24,000 volts		$55 + 2A$	
Oil insulated indoor, capacity 50 volt-amp., compensated for 25 volt-amp., nominal secondary current, 5 amp.		Current transformers	5 to 400 amp. 35,000 to 70,000 volts		$0.35V$	
Same as above except outdoor type.		Current transformers	5 to 400 amp.		$0.4V$	
Dry-type, suitable for voltages not exceeding 6,000; capacity 200 volt-amp., compensated for 15 volt-amp.; nominal secondary voltage, 100.		Voltage transformers	200 to 6,000 volts		$13 + 0.25V$	
Oil-insulated, especially suited for voltages that are too high for dry-type transformers, capacity, compensation and secondary voltage same as above.		Voltage transformers	200 to 60,000 volts		$20 + 0.62V$	
To correct the voltmeter indication for ohmic and inductive line-drop, on three-phase, 60-cycle circuit.		Voltmeter compensators	Any[3]		$36.5 + P/8$	128
Same as the foregoing except for single-phase or two-phase.		Voltmeter compensators	Any[3]		$37.75 + P/8$	
For 25-cycle circuit.		Voltmeter compensators			1.25 more than for 60 cycles.	

TABLE XVI.—COSTS OF APPARATUS.—*Continued*

Special features and uses	Diameter (or length of side, if not round) in inches	Kind of apparatus	Full scale or normal current or voltage [4]	Accuracy; maximum error in per cent. of full-scale reading	Approximate net cost in dollars		For description and applications of apparatus see page
RELAYS.							136–141
D.C. protective relays.							
Operate instantaneously — especially suitable for use on 3-wire generator circuits, where the shunt is on the generator and the relay on the switchboard.	8 × 4	Overload relays	Any[2]			16.00	
Operate with inverse time-limit—extremely sensitive, operating on about 4 per cent. of full-load when the current is reversed, especially suited to protecting synchronous converters against reversal of power.	6⅝ × 8⅝	Reverse current relays	Any[2]			46 + 1*V*	
Operate instantaneously—less sensitive than the foregoing, operating on about 50 per cent. of full-load when the current is reversed, or operating from 2 shunts in series on about 25 per cent. reversal; especially suited for battery charging.	4 × 10⅛	Reverse current relays	Any[2]			16.00	
Operate at any desired voltage; especially adapted to battery charging.	2$^{11}/_{16}$ × 5⅜	Over voltage relays	26 to 250 volts			15.00	

TABLE XVI.—COSTS OF APPARATUS.—*Continued*

Special features and uses	Diameter (or length of side, if not round) in inches	Kind of apparatus	Full scale or normal current or voltage[4]	Accuracy; maximum error in per cent. of full-scale reading	Approximate net cost in dollars	For description and applications of apparatus see page
A.C. protective relays.						
Especially suitable for individual outgoing feeders or transmission lines, distribution feeders, motor protection, and differential protection of transformers; operate on the induction principle. Inverse time element, with or without a definite minimum time; the definite minimum time setting is very accurate and can be as desired from zero to 2 sec.		Overload relays	Any[3]		18.00	
Especially suited for use at the receiving ends of parallel transmission lines and at both ends of tie feeders in a ring feeder system.		Reverse power relays	Any[3]		43.00	
For either opening or closing a circuit breaker on either high or low voltage.		Voltage relays	Any[3]	5	22.00	
Auxiliary relays.						
Used in combination with an overload or reverse power relay to introduce a definite time element in the operation.	9⅝	Definite time limit relays	100 to 650 volts, D.C.		$35 + 1V$	
For ringing an alarm when any particular abnormal condition occurs in any circuit.	3 11/16 × 4 13/16	Bell relays	110 to 550 volts, D.C.		$12.30 + 0.2V$	

TABLE XVI.—COSTS OF APPARATUS.—*Continued*

Special features and uses	Diameter (or length of side, if not round) in inches	Kind of apparatus	Full scale or normal current or voltage [4]	Accuracy; maximum error in per cent. of full-scale reading	Approximate net cost in dollars		For description and applications of apparatus see page
SWITCHES AND CIRCUIT BREAKERS. 250-volt D.C. or 500 volt A.C., not fused, single-throw, one-, two-, three- or four-pole.		Front connected knife switches	100 to 2,000 amp. 250 volts, D. C. or 500 volts, A. C		Single-pole, 100 to 1,200 amp.	1.5A	95, 106, 107, 121–123, 131–136
					Two to four poles, 100 to 1,200 amp.	1.2NA	
					Two to four poles, 1,500 to 2,000 amp.	1.44NA	
Same as above, except double-throw.		Front connected knife switches			Multiply prices for single-throw by	1.45	
Same as above, except single-throw, fused.		Front connected knife switches			Multiply prices for unfused, by	1.3 to 1.6[5]	
Same as above, except double-throw, fused at both ends.		Front connected knife switches			Multiply prices for double-throw, unfused, by	1.5 to 2.1[5]	
Rear connected, on marble base, for indoor mounting.		Disconnecting switches	3,300 volts, 100 to 2,000 amp.			2 + 2,5A	123
		Disconnecting switches	6,600 volts, 300 to 1,200 amp.			4 + 4A	
		Disconnecting switches	13,000 volts, 300 to 1,200 amp.			8 + 4A	
		Disconnecting switches	33,000 volts, 300 to 600 amp.			40 + 4A	

[5] The smaller multiplier is for 1,200 amp., the larger multiplier for 100 amp.

TABLE XVI.—COSTS OF APPARATUS.—*Continued*

Special features and uses	Diameter (or length of side, if not round) in inches	Kind of apparatus	Full scale or normal current or voltage [4]	Accuracy; maximum error in per cent. of full-scale reading	Approximate net cost in dollars		For description and applications of apparatus see page
Front- or rear-connected, one-, two-, three- or four-pole, for A.C. or D.C.		Carbon circuit breakers	600 volts, 5 to 300 amp.		Single-pole Two-pole Three-pole Four-pole	$17 + 3A$ $31 + 4.5A$ $50 + 8A$ $63 + 9A$	
		Carbon circuit breakers	750 volts, 400 to 800 amp.		Single-pole Two-pole Three-pole Four-pole	$20 + 7A$ $40 + 10.5A$ $70 + 17A$ $95 + 24A$	
Application to high-tension circuits similar to application of a fuse to low tension—inexpensive and simple. Kva. capacity ranges from 550 on 11,000 volts to 1,320 on 66,000. Single-pole.		Fused type circuit breakers	11,000 to 66,000 volts			$50 + 0.046V$	
Three-pole, single-throw, indoor type, direct control, for switchboard or wall mounting.		Oil switches (non-automatic circuit breakers)	1,500 to 7,500 volts 200 to 300 amp.		4,500 volts, 200 amp.	34 .00	
		Oil switches (non-automatic circuit breakers)			1,500 volts, 300 amp.	43.50	
		Oil switches (non-automatic circuit breakers)			7,500 volts, 300 amp.	55	

TABLE XVI.—COSTS OF APPARATUS.—*Continued*

Special features and uses	Diameter (or length of side, if not round) in inches	Kind of apparatus	Full scale or normal current or voltage[4]	Accuracy; maximum error in per cent. of full-scale reading	Approximate net cost in dollars		For description and applications of apparatus see page
Same as the foregoing except 2-pole.		Oil switches (non-automatic circuit breakers)			Multiply price for 3-pole by	0.85	
Same as the foregoing except 4-pole.		Oil switches (non-automatic circuit breakers)			Multiply price for 3-pole by	1.2	
Same as the foregoing except 2-, 3-, or 4-pole, double-throw.		Oil switches (non-automatic circuit breakers)			Multiply price for 2-, 3-, or 4-pole single-throw by	1.25	
For remote control, and other mounting, add to any of the foregoing 5.50 to 8.50 (depending on kind of mounting).							
Similar to the foregoing but of small ampere capacity.		Oil switches (non-automatic circuit breakers)	4,500 volts, A.C. 60 amp.		Single-throw 2-pole	11.25	
					Single-throw 3-pole	16.25	
					Single-throw 4-pole	21.50	
Simple, reliable, inexpensive; instantaneous breaking capacity on 3-phase, 2,000 kva., single-throw.		Automatic and non-automatic oil circuit breakers	2,500 volts or less, A.C. 5 to 100 amp.		750 volts, 5 to 50 amp., 2 pole	25.00	
					750 volts, 5 to 50 amp., 3-pole	28.50	
					750 volts, 5 to 50 amp., 4-pole	35.50	
	For 75 or 100 amp.				Add to the 5 to 50 amp. cost	1 per pole	
	For 2,500 volt-circuits.				Add to the 750 volt cost about	15	

TABLE XVI.—COSTS OF APPARATUS.—*Continued*

Special features and uses	Diameter (or length of side, if not round) in inches	Kind of apparatus	Full scale or normal current or voltage[4]	Accuracy; maximum error in per cent. of full-scale reading	Approximate net cost in dollars		For description and applications of apparatus see page
Heavier construction than the foregoing, details worked out more elaborately; larger instantaneous breaking capacity, ranging on 3-phase from 13,000 to 36,000 kva. 3-pole, single-throw.		Automatic and non-automatic oil circuit breakers	13,200 volts or less 10 to 2,400 amp.		4,500 volts, 300 to 2,400 amp.	0.3A	
					7,500 volts, 300 to 1,600 amp.	0.4A	
					13,200 volts, 300 to 1,600 amp.	0.5A	
Same as foregoing except 2-pole.		Automatic and non-automatic oil circuit breakers			Multiply price for 3-pole by	0.7	
Same as foregoing except 4-pole.		Automatic and non-automatic oil circuit breakers			Multiply price for 3-pole by	1.3	
Same as foregoing except double-throw, 2-, 3-, or 4-pole.		Automatic and non-automatic oil circuit breakers	2,500 volts or less, 300 amp. or less		Multiply price for corresponding single-throw breaker by	1.5	
					For breakers of less than 300 amp. capacity, the cost is about the same as for 300 amp.		
TRANSFORMERS							43–50
60 cycles, 1 to 200 kva., single-phase, high efficiency, low temperature rise.		Transformers	3,300 volts or less		1 to 50 kva.	40 + 10K	
					75 to 200 kva.	350 + 4K	

TABLE XVI.—COSTS OF APPARATUS.—*Continued*

Special features and uses	Diameter (or length of side, if not round) in inches	Kind of apparatus	Full scale or normal current or voltage[4]	Accuracy; maximum error in per cent. of full-scale reading	Approximate net cost in dollars.		For description and applications of apparatus see page
Same as the foregoing except 25 cycles.		Transformers	2,200 volts or less		1 to 50 kva. 75 to 200 kva.	$60 + 12.5K$ $430 + 6K$	
60 cycles, 1 to 100 kva. single phase, moderately high efficiency, moderate temperature rise.		Transformers	2,200 volts or less		1 to 50 kva. 50 to 100 kva.	$30 + 8.4K$ $160 + 5.4K$	
60 cycles, 10 to 100 kva., single phase, high efficiency and low temperature rise.		Transformers	16,500 volts		10 to 50 kva. 50 to 100 kva.	$230 + 9.5K$ $450 + 5K$	
Same as the foregoing except 10 to 50 kva., 25 cycles.		Transformers	16,500 volts		10 to 50 kva.	$300 + 13.2K$	
60 cycles, 3 to 100 kva., 3-phase, somewhat more compact and simpler to connect than 3 single-phase.		Transformers	2,200 volts		3 to 50 kva. 50 to 100 kva.	$100 + 11.2K$ $260 + 8K$	
LIGHTNING ARRESTERS.		Multigap arrester	50,000 volts or less		Per pole	$8 + 0.3V$	142–147
Used in conjunction with other arresters		Horn-gap arrester			Per pole	$5 + 0.04V$	
		Condenser arrester	1,500 volts or less		Per pole	12.00	
		Multipath arrester	400 to 750 volts		Per pole	3.30	
		Aluminum arrester	2,000 volts up		Per pole	$30 + 0.4V$	
		Choke coils			Up to	$25 + 90A$	

TABLE XVI.—COSTS OF APPARATUS.—*Continued*

Special features and uses	Diameter (or length of side, if not round) in inches	Kind of apparatus	Full scale or normal current or voltage[4]	Accuracy; maximum error in per cent. of full-scale reading	Approximate net cost in dollars		For description and applications of apparatus see page
CURRENT AND VOLTAGE REGULATORS.							
For A.C. and D.C. generators.		Generator voltage regulator	D.C. 125 to 550 volts A.C. Any[3]		Up to	1000	126–128
Automatic induction regulator, motor operated.		Feeder voltage regulators				530 + 15.6*K*	111–113
For series Mazda circuits, 60 cycles, 4 to 68 kva.		Constant current regulating transformers	Primary voltage 2,000 to 2,400; secondary current 5.5 to 7.5 amp.			160 + 12*K*	109–111, 164
PLUG AND INSTRUMENT SWITCHES.							159–165
For generator field.		Plug switch	125 volts, 200 amp.			6.50	
For series arc lamp circuits.		Plug switch	2,200 to 4,000 volts, 10 to 100 amp.			7.00 to 14.25	
For ground detector circuits, multiple-point form, 1, 2, 3, and 4 point.		Plug switch	1,000 to 3,300 volts		1,000 volt plug	1.25	
					1,000 volt receptacle, per point	0.80	
					3,300 volt plug	1.90	
					3,300 volt receptacle, per point	1.20	
For ground detector, bayonet form.		Plug switch			3,300 volt plug	1.25	
					3,300 volt receptacle	2.25	
For synchronizing.		Plug switch	500 volts or less, 1 amp.		Plug, 2 to 6 points	0.70 to 1.75	
					Receptacle, 2 to 6 points	1 to 2.80	

TABLE XVI.—COSTS OF APPARATUS.—*Concluded*

Special features and uses	Diameter (or length of side, if not round) in inches	Kind of apparatus	Full scale or normal current or voltage[4]	Accuracy; maximum error in per cent. of full-scale reading	Approximate net cost in dollars		For description and applications of apparatus see page
For voltmeters, 1 to 8 points.		Plug switch	600 volts or less		Plug, 4, point	1.25	
					Receptable, per point	0.30	
For ammeters.		Plug switch	5 amp.		Plug	2.25	
					Receptacle	5.60	
For ammeter, for 2- and 3-phase circuits, with 2 or 3 current transformers.		Dial switch			Three-phase, 3-wire with 2 transformers	6.75	
					Two-phase, 2 transformers	16.75	
					Three-phase 4-wire, 3 transformers	17.50	

CHAPTER XXII

PROBLEMS

PROBLEMS ON CHAPTER I

1. Diagram of D.C. Connections.—DATA: A shop has the following 220-volt D.C. motor equipment:

On Feeder No. 1.—Two shunt motors driving shafts from which groups of machines are driven.

On Feeder No. 2.—Ten shunt motors, each driving a lathe, and four compound motors each driving a planer.

On Feeder No. 3.—Ten compound motors for individual drive for eight punch presses and two shears.

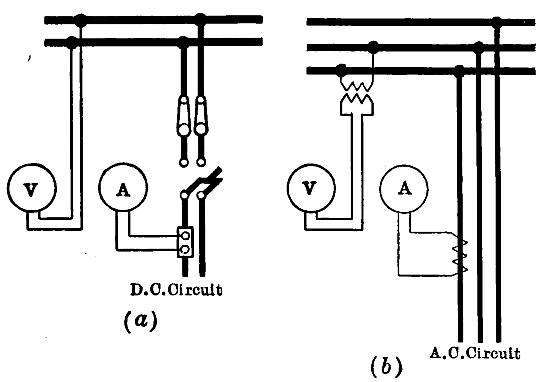

FIG. 107.—Representation of voltmeters and ammeters on D.C. and A.C. circuits.

A D.C. switchboard ammeter is usually made for use with a shunt; an A.C. voltmeter with a voltage transformer; and an A.C. ammeter with a current transformer. Some modifications of these connections are discussed in the text and used in later problems.

Lighting Feeders.—The shop has four 220-volt lighting feeders, each ending in a panel board. Each panel board has six outgoing circuits, and each circuit is controlled by a two-pole switch and protected by a two-pole fuse-block.

Generators.—Power for motors and lighting is furnished by two 220-volt compound wound generators which are to be run either singly or in parallel.

REQUIRED.—Draw a diagram, showing directly, or indicating by notes, the buses, feeders, and other connections and equipment for controlling the motors and generators, and for furnishing power to the motors and lamps.

Put an ammeter in series with each generator, and each feeder circuit. Make such voltmeter connections, to one or more voltmeters, that the voltage can be measured across the buses and across each generator before it is connected to the buses. (See Fig. 107*a*, for method of connecting voltmeters and ammeters in the diagrams.)

2. Diagram of A.C. Connections.—DATA: A factory has the following three-phase 440-volt motors:

On Feeder No. 1.—Ten 50-hp. squirrel-cage induction motors, driving shafts for group-driven machines. (See Fig. 9, page 31, and Fig. 23, *c*, *f*, page 49, for suitable arrangements of auto-transformers and connections, to obtain low voltage for starting squirrel-cage induction motors.)

On Feeder No. 2.—Ten 100-hp. synchronous motors driving reciprocating pumps. The motors are provided with squirrel-cage induction motor windings (which makes them self-starting), in addition to the regular synchronous motor windings. The external A.C. connections are the same as for squirrel-cage motors. In addition D.C. connections are necessary to excite the fields. Power is obtained from the exciter buses for exciting the fields of the motors as well as of the generators.

On Feeder No. 3.—Four 75-hp. induction motors with wound rotors, for conveyors.

Lighting Feeders.—Besides these power feeders, there are nine 110-volt 60-amp. single-phase lighting feeders, obtaining power from three lighting transformers.

Power is furnished by three-phase 440-volt generators, excited from exciter buses by two exciters which are connected to operate either singly or in parallel.

For solving this problem, assume the following: (*a*) The combined kilowatt capacity of all the generators is to be equal to the total kilowatt input of all the motors at rated full-load, assuming a motor efficiency of 80 per cent.; plus the kilowatts required for lighting.

Power factor is ordinarily taken into account in determining the size of A.C. generators; this and several other points are neglected in the present problem, but are considered in later problems.

(*b*) At least two generators are to be installed. There may be more than two if the total power required is so great that each generator has a capacity of 1,000 kw.

(*c*) The combined capacity of all transformers is to be equal to the rated capacity of all equipment connected to their secondaries.

(*d*) Three transformers are to be installed, unless special conditions make some multiple of three desirable.

All these assumptions are not far from standard practice. They are taken up more fully in connection with later problems.

REQUIRED.—(*a*) Determine the number of generators and the size of each, and the size of each transformer.

(*b*) Draw a diagram showing all connections, fully labelled. Show only one ammeter connection and one voltmeter connection in each circuit in which you consider them desirable for satisfactory operation of the plant. (In practice sometimes there is provided an ammeter connection in each line, and a voltmeter connection across each pair of lines.) See Fig. 107*b*, for meter connections.

PROBLEM ON CHAPTER II

3. Safe Equipment.—This problem is to be based not only on the text and foregoing problems, but also, as far as possible, on the student's previous observation.

Data.—A small shop requires power for motors and lighting. This is to be purchased from an electric power company whose 2,200-volt, three-phase, three-wire feeders pass the building. Induction motors are to be used throughout the shop.

Required.—What voltage would you specify for power? For lighting? What provision would you make for safety to equipment and operators? Draw a diagram of connections from the 2,200 volt line to one or two motors and lamps. Where there is any other possible arrangement of equipment, give reasons for your choice.

PROBLEMS ON CHAPTER III

4. Cement Plant.—Data: A cement plant uses a total of 3,000 kw. for power and lighting. About 80 per cent. of the power is used at the main plant, which adjoins the power house. The remainder of the power is used at the quarry, which is 1 mile from the power house.

Required.—Answer the following questions and give reasons for your choice.

(*a*) Should an A.C. or a D.C. system be installed? (If you consider both A. C. and D.C. desirable, for what purposes should each be used?)

(*b*) If an A.C. system is selected, what should be the number of phases, and the frequency?

(*c*) What should be the voltage of the system? (Or, if there is more than one voltage, what should the several voltages be?)

5. Machine Shop.—Data: Power for a small machine shop is to be purchased from an electric power company, which furnishes it at 2,200 volts, on a three-phase, three-wire system. The power is used for lighting, and for direct-connected motors driving the following machines: 6 engine lathes, 2 planers, 2 drill presses, 1 saw, 1 milling machine, 1 punch, 1 shear, 2 emery wheels.

Required.—Answer the same questions as in Problem 4. (*d*) If you select a D.C. system, how would you obtain it? (*e*) If you select A.C., how would you vary the speed of the lathes and drill presses?

6. Machine Shop.—If a generator is to be installed to furnish power to the shop of Problem 5, how would the questions be answered, assuming that the generator may be either A.C. or D.C., and of any desired voltage?

7. Machine Shop.—DATA: A railroad repair shop requires power for driving a large number of engine lathes, boring mills, planers, and drill presses, several wheel and axle-lathes, rivet headers, a turn table, cranes, and a large wood shop. The wood shop is about 2,000 ft. from the power station. The turn table and yards are to be lighted, and all the buildings are to be lighted inside.

REQUIRED.—Answer the same questions as in Problems 4 and 5.

PROBLEMS ON CHAPTER IV

8. Pump.—DATA: A motor is to drive a reciprocating pump, pumping water to a reservoir at a height of 200 ft. The pump has an efficiency of 75 per cent., and is required to deliver 100 cu. ft. per min. continuously. D.C. power is available for the motor. (Weight of water is 62.5 lb. per cu. ft.)

REQUIRED.—What kind and size of motor would you use?

9. Hoist.—DATA: A motor is used to drive a hoist that lifts a load of 10 tons at the rate of 100 ft. per min. The efficiency of the hoist is 75 per cent. The motor is used for 1 hr. at a time.

REQUIRED.—What kind of a motor would you use? How much power must it deliver for 1 hr.? How much would it deliver continuously?

10. Variable Speed—Dust.—DATA: A motor is to be installed in a very dusty place. It must be large enough to deliver any power up to 25-hp. continuously, to a machine that runs at any speed from 25 to 100 r.p.m. A 220-volt D.C. system is available for power. When the machine is adjusted for a certain load, it should maintain a speed that is approximately constant. Assume that the efficiency of gear reduction per pair of gears is 95 per cent., taking into account bearing friction. The gear reduction must not exceed 1:7 per pair of gears.[1]

REQUIRED.—(*a*) Suggest in detail a suitable motor-driving mechanism (by gear or other mechanical means). (*b*) Give as full information as you can, by which the motor can be ordered. (*c*) What current will the motor take? (*d*) What horsepower can it deliver when the enclosing lids are removed?

11. Variable Torque and Speed.—DATA: A shunt motor drives a shaft at various speeds as required and is to exert a torque at each speed as follows:

50 to 150 r.p.m.	4,000 lb.-ft. torque.
151 to 300 r.p.m.	3,000 lb.-ft. torque.
301 to 400 r.p.m.	2,000 lb.-ft. torque.

[1] See paragraph on p. 166, entitled *The Best Available Speed of Motor.*
S. 15: 221; 23: 28–34.
A. pp. 612–615.

The motor must be large enough to exert this torque continuously. The field current at rated speed (without field rheostat) is 2 per cent. of the armature full-load current. The motor is connected to a 220-volt D.C. circuit.

REQUIRED.—(*a*) Suggest a satisfactory arrangement for obtaining these results; (*b*) Specify the motor horsepower and the maximum resistance required in any rheostats that are to be provided.

PROBLEMS ON CHAPTER V

12. Small Starting Torque.—DATA: A machine runs at 200 r.p.m., and requires a torque of 800 lb.-ft. It is located where men are working who are not familiar with electric circuits. A 2,200-volt, three-phase, 60-cycle circuit is available for power. No speed control is required, and there is only a small starting torque. The speed reduction per pair of gears must not exceed 1:6.

REQUIRED.—Give as full information as you can for purchasing the motor that you would install. Give reasons for your choice.

13. Large Starting Torque.—DATA: A 220-volt, three-phase, 60-cycle, 25-hp. squirrel-cage induction motor runs a machine having large starting friction; so that the motor must exert a starting torque that is 150 per cent. of the rated running torque.

REQUIRED.—(*a*) What voltage must be provided for starting? If this voltage is provided by an auto-transformer, what is the starting current in the motor, and in the line? (*b*) What would these currents be if the motor started at 27 per cent. of full-load torque? Note the advantage of starting light if possible.

14. Large Starting Torque.—DATA: The same as in Problem 13, except that a phase-wound motor is installed. Assume, in accordance with the current curve in Fig. 7, that above full load the primary current is nearly proportional to the torque.

REQUIRED.—Find the starting current taken from the line at 150 per cent. of rated running torque, and compare with that in Problem 13*a*.

15. Pump.—DATA: A reciprocating pump is to be operated by an A.C. motor, and a 440-volt, three-phase, 60-cycle circuit is available. Four plans are under consideration with reference to the pump and motor installation:

(*a*) According to the first plan the pump is to be connected directly to the piping system pumping into the reservoir, so that in starting it must overcome its own starting friction and the inertia of the column of water, and in addition it must work against the water pressure.

(*b*) The second plan is that the pump be installed in or near the generating station, pumping into the reservoir as before, but that it be provided with a by-pass for the water making it possible to start with but little torque on the motor.

(*c*) The third plan is the same as the second, except that the motor is to be on a rather long, heavily loaded transmission line carrying other loads at low lagging power factor, and it is proposed to use a motor that will improve the power factor more than an induction motor will do.

(*d*) The fourth plan is the same as the first, except that the reservoir will be omitted, so that fluctuations in the amount of water used must vary the speed of the motor.

The pressure in the water mains is 60 lb. per sq. in. The average demand for water is 1000 cu. ft. per min., and the reservoir is large enough to take care of all fluctuations. The maximum demand, which will last for an hour at a time, is 4000 cu. ft. per min. The pump efficiency is 70 per cent.

REQUIRED.—Specify the kind and size of motor to be provided according to each plan.

PROBLEMS ON CHAPTER VI

16. Machine Shop.—DATA the same as in Problem 7.

REQUIRED.—Work out a different system, based on this chapter, that would meet all requirements. Is this preferable to the arrangement worked out in Problem 7? Give reasons.

17. Battery Charging from A.C. Power.—DATA: A factory purchases electrical energy at 2 cts. per kw.-hr. A 110-volt, three-phase 60-cycle circuit is available in a garage of the factory, and is to be used for charging automobile batteries. This will require 9.5 amp. at 10 volts, for each of fifteen automobiles, 3 hr. per day, 6 days in the week, throughout the year.

REQUIRED.—Work out an arrangement for charging the batteries, draw a diagram of connections, and estimate the cost per year for electrical energy.

PROBLEMS ON CHAPTER VII

18. A.C. Transmission.—DATA: A factory has a 440-volt three-phase 60-cycle power plant. A branch of the factory 1 mile distant is to use 100 kilowatts at 90 per cent. power factor. Assume that the line-drop will be 10 per cent., line reactance being negligible.

REQUIRED.—What would you specify for voltage of the transmission line? (See Chapter III.) Specify the voltage ratio, size, and number of transformers to be installed at each end of the line, and draw a diagram showing all connections from the buses at the main power house to the substation buses at the branch factory.

19. Machine Shop.—DATA: The machines in a machine shop using a total of 200 kw. at 85 per cent. power factor are to be driven by A.C. motors. A 2,200-volt two-phase 60-cycle system is available as a source of power. It is to be expected that this will later be changed to a three-phase system.

REQUIRED.—What system would you adopt for the motors? Give full information for purchasing the transformers.

20. Motor Starter.—DATA: One of the machines in Problem 19 requires a 50-hp. squirrel-cage induction motor, which starts with full-load torque.

REQUIRED.—Specify the number of auto-transformers to be provided for starting, and the voltage and short-time current capacity that is required in each winding of each auto-transformer. Draw a complete diagram of connections, indicating on it the current capacities of the several parts of the equipment.

PROBLEMS ON CHAPTER VIII

21. Storage Battery for Off-peak Load.—DATA: An office building is provided with a power plant, in which the generators are running during the day. A storage battery is to be installed to furnish power for lighting when the generators are shut down. The battery capacity must be sufficient to light 100 60-watt lamps for 6 hr. An end-cell switch is provided for regulation of the voltage on discharge. The lighting of the building is from a 110- and 220-volt three-wire system. It is permissible if desired to arrange switches by which the circuits are changed to a 110-volt two-wire system when they are fed from the storage battery.

REQUIRED.—(*a*) Specify the kind of battery that is required, the total number of cells, the number of end-cells, and the ampere-hour capacity of each cell.

(*b*) Draw a diagram showing connections to the battery, and all necessary electrical equipment for furnishing power, and for controlling and protecting the battery.

22. Storage Battery Truck.—DATA: A battery truck is to be used for carrying material from section to section of a factory. The truck must make four trips daily, over a distance of 2 miles. The truck must be large enough to carry 5 tons, but the average load carried will not exceed 2 tons. A three-phase, 60-cycle, 220-volt circuit is available for obtaining power to charge the storage battery.

REQUIRED.—(*a*) Specify the kind of battery, the number of cells, and the ampere-hour capacity of each cell.

(*b*) Specify the kind of apparatus that you would use for charging, and the A.C. and D.C. voltage and current capacity.

(*c*) Draw a complete diagram of connections for charging.

PROBLEMS ON CHAPTER IX

23. Lamp Economy.—DATA: Tables I and II, in Supplement to Bulletin 20 of National Lamp Works.

REQUIRED.—(*a*) Compute the amount of light in lumens per dollar invested in lamps, for 25-, 40-, 60- and 100-watt, 110-volt lamps, and plot a curve with sizes of lamps (in watts) as abscissæ and lumens per dollar invested in lamps, as ordinates.

(*b*) Plot a similar curve on the same sheet, for 220-volt lamps.

(*c*) Plot on the same sheet, curves between watts and lumens per watt for 110- and 220-volt lamps. (Make these curves dotted, or otherwise distinguished from (*a*) and (*b*).

(*d*) *Conclusions.*—Of these eight kinds of lamps, which is the most economical to use, considering only the cost of lamps? Which is the most economical, considering only the cost of energy? (Obviously other considerations sometimes make it economical to use neither of these lamps.)

24. Shop Lighting.—DATA: A shop 50 ft. wide by 90 ft. long has a lighting system consisting of four rows of 110-volt, 100-watt Mazda lamps, with eight lamps in a row. The rows are uniformly spaced, and the lamps are uniformly spaced in each row. Dome reflectors are provided for direct lighting, making the illumination practically uniform. Average conditions exist as to the effect of dust on the reflectors.

REQUIRED.—Find the illumination on the working plane,

(*a*) When the lamps are new and reflectors clean.

(*b*) After 1,000 hr. of use when reflectors are clean.

(*c*) When lamps are new, but reflectors have not been cleaned for 6 weeks, and

(*d*) After 1,000 hr. of use, when reflectors have not been cleaned for 6 weeks.

PROBLEMS ON CHAPTER X

25. Size of D.C. Conductor.—DATA: A D.C. 220-volt, 250-hp. motor is 300 ft. from the buses. The line leading to the motor is a rubber-covered copper cable. Market quotations for this kind of wire are on the 20-ct. base, and there is a discount of 50 per cent. on the wire. Net cost of labor and supplies is assumed to be the same for any size of wire that will be used. The motor is running 24 hr. per day, 365 days per year. Energy costs 1 ct. per kw.-hr.

REQUIRED.—(*a*) What size of cable is required for safety?

(*b*) What size of cable must be used, in order that the line drop at full-load shall not exceed 10 per cent.?

(*c*) What is the most economical size of wire?

(*d*) Which of these three sizes should be provided?

26. Size of D.C. Conductor.—DATA the same as in Problem 25, except that the motor is in operation only 8 hr. per day, 6 days in the week, throughout the year.

REQUIRED.—Find the sizes of wire for safety, voltage drop, and economy, as in Problem 25.

27. Size of D.C. Conductor.—DATA the same as in Problem 26, except that the motor carries full-load, 2 hr. per day; one-half load 3 hr.; and one-quarter of full-load 3 hr. per day.

REQUIRED.—Obtain results as in Problem 26.

PROBLEMS ON CHAPTER XI

28. A.C. Line Voltage Regulation.—DATA: A single-phase line has a resistance of 1 ohm and reactance of 1 ohm.

REQUIRED.—What is the decrease in voltage caused by 100 amp. flowing in the line, if the power factor of the load is 100 per cent.? 80 per cent.? 60 per cent.? (Use the approximate solution.)

29. Size of A.C. Conductor.—DATA the same as in Problem 25, except that the motor is a three-phase, 60-cycle induction motor.

REQUIRED.—What size of wire should be provided, in order to be large enough for all requirements? [Suggestion: Reactance is *not* inversely proportional to area, so that the solution for size of wire for allowable line drop is somewhat complicated. A good method of procedure is to find first the size required for safety and economy, and then to find by trial whether the voltage drop is excessive. If it is excessive, find by trial a larger size that does not have an excessive drop. Use the approximate solution in computing voltage drop.]

PROBLEMS ON CHAPTER XII

30. Generator Compounding.—DATA: A 550-volt D.C. generator furnishes power to a feeder whose center of distribution is 2,000 ft. from the generator. The feeder delivers 300 kw. The size of the feeder is 500,000 cir. mils.

REQUIRED.—What must be the per cent. overcompounding of the generator, to maintain constant voltage at the center of distribution?

31. Maximum Demand.—DATA: A factory has in it 20 200-hp. shunt motors, 30 100-hp., 50 25-hp., 100 10-hp., and 100 5-hp.; also 400 60-watt lamps. The demand factor during the daytime is 55 per cent. for motor loads, and 40 per cent. for lighting.

REQUIRED.—How much power is demanded of the generating station?

32. Number and Size of Generators.—DATA the same as in the numerical example on page 98, except as follows: Interest is at 5½ per cent., depreciation 5 per cent., and insurance and taxes each 1 per cent.; other costs for switchboard, wiring, and equipment are $6 per kw. of total generator capacity; power is required 8 hr. per day, 6 days per week.

REQUIRED.—Find the best number and size of generators, and the cost per kilowatt for power, including fixed charges.

PROBLEMS ON CHAPTER XIII

33. Size of Alternator and Engine.—Data: A three-phase engine type generator is required to furnish steady power to 200 1-hp. induction motors, running at full-load.

Required.—The kilovolt-ampere capacity of the generator, and the horsepower of the engine driving it.

34. Combined Load at Several Power Factors.—Data: The generator of Problem 33 is also required to furnish power to four 100-hp. induction motors, running at full-load, and fifty 100-watt lamps.

Required.—The kilovolt-ampere capacity of the generator. [Suggestion: Find for each part of the load, the power component of the kilovolt-amperes (= kva. × power factor), and the "reactive" component (= kva. × sin θ, if cos θ is the power factor).[1] Add together the power components to find the total power component, and the reactive components to find the total reactive component. The total kilovolt-ampere capacity must be the square root of the sum of the squares of the two components.]

35. Combined Synchronous and Induction Motor Load.—Data: The motor and lighting loads are the same as in Problem 34, except that some of the induction motors are replaced by synchronous motors, whose fields are adjusted so that the power factor of the generator load is 100 per cent.

Required.—Find the necessary kilovolt-ampere capacity of the generator.

PROBLEMS ON CHAPTER XIV

36. Constant-current Regulating Transformer.—Data: A constant-current regulating transformer operating from a 2,200 volt circuit is to furnish power for 100 60-watt 6.6 amp. series lamps. The line drop in the circuit is 25 volts. The power factor of the load is practically 100 per cent. At full-load, the transformer efficiency is 93 per cent., and the power factor of the primary 84 per cent.

Required.—The kilovolt-ampere capacity, and the primary and secondary current and voltage capacities.

37. Feeder Voltage Regulator.—Data: A three-phase feeder has a voltage of 2,300 at the buses, a line resistance of 0.1 ohm, and a line reactance of 0.25 ohm per line. The feeder is required to deliver power from zero to 8 kw., at any power factor from 60 per cent. (lagging) to 100 per cent. An induction regulator is to be used to maintain constant voltage at the end of the line.

Required.—The current capacity, the boosting voltage, the per cent. boosting, and the total three-phase kilovolt-ampere capacity of the regulator.

[1] See brief table of sines and cosines on page 90.

PROBLEMS ON CHAPTER XV

38. Instrument Transformers.—DATA as in Problem 37: A watt-hour meter is used to record the energy delivered by the feeder. The meter has 100-volt potential windings and 5-amp. current windings.

REQUIRED.—What should be the theoretical transformer ratio of the current and voltage transformers, according to these data?

39. Instrument Transformers.—DATA: If voltage and current transformers cannot be obtained that produce exactly 100 volts and 5 amp. respectively, in their secondaries at rated voltage and full-load, the next higher or lower rating is selected, and the meter is calibrated to suit (see list of transformers on pp. 116, 120). For the most accurate meter indications, the voltage elements of the meter in Problem 38 should have between 90 and 125 per cent. of the rated voltage, and at full-load the current elements should have between 75 and 150 per cent. of the rated current.

REQUIRED.—Select current and voltage transformers of commercial sizes, suitable for this service.

PROBLEMS ON CHAPTER XVI

40. Switches.—DATA: A 220-volt D.C. generating plant contains four 1,000 kw. generators, and the following power feeders:

Four 500 kw. feeders.

Four 300 kw. feeders.

Four 200 kw. feeders.

REQUIRED.—Give as full information as possible, as to the switches to be installed for the control of these circuits.

41. Rheostats.—DATA: A 25-hp. motor on a feeder in Problem 40 is to run normally at 600 r.p.m. Field and armature rheostats are to be provided for varying the full-load speed. There are to be enough steps in each rheostat to vary the speed, by steps of 100 r.p.m., from 100 to 1,200 r.p.m.

REQUIRED.—Give all possible specifications for the rheostats.

42. Balancer-set Outfit.—DATA: In the plant of Problem 40 are a balancer set and eight, three-wire 15-amp. lighting feeders. The lighting system is so arranged that the unbalancing of the current will not exceed 15 per cent. of the maximum possible lighting current. The armature current of the balancer set is 8 per cent., and the field current 2 per cent. of the machine full-load current, at no load.

REQUIRED.—(*a*) Give full information as to the switches to be provided in addition to those of Problem 40.

(*b*) Specify the kilowatts and voltage of each machine of the balancer set.

(*c*) Give full information regarding the motor starting rheostat.

(*d*) Draw a complete diagram of connections of the balancer set. Note that if the neutral line is closed before the resistance is all cut out of the armature rheostat, the voltage is unbalanced, and all the lamps on one side of the circuit may be destroyed. Provide if possible some device making this condition impossible.

43. Line-drop Compensator.—DATA as in Problem 37. In addition, a voltmeter and a voltage regulating relay are to be connected to current and voltage transformers and to a line-drop compensator, in the generating station, to indicate and regulate the voltage at the end of the feeder.

REQUIRED.—(*a*) Specify the per cent. compensation of the compensator, and all transformer ratios.

(*b*) Draw a complete diagram of connections of instrument transformers, compensator, voltage regulating relay, and induction voltage regulator. [Suggestion: The diagram may be simplified by notes referring to diagram of Problem 37.]

PROBLEMS ON CHAPTER XVII

44. Feeder Protection and Voltage Regulation.—DATA: The feeder of Problem 37 is to be protected by a circuit-breaker that carries the rated full-load without excessive heating. The circuit-breaker is tripped by a relay that operates in case an overload occurs, exceeding double the normal current. The relay receives its current from current transformers. It can be set to operate on any current from 3 to 6 amp.

Required: (*a*) Specify the current and voltage rating of the circuit-breaker, and the current transformer ratio, selecting transformers of customary rating.

(*b*) Draw a diagram of connections of the voltage regulator, circuit-breaker, relay, and current transformers operating the relay.

45. Overload Protection.—DATA as in Problems 40 to 42.

REQUIRED.—Specify fully the equipment for overload protection.

PROBLEMS ON CHAPTER XVIII

46. Lightning Protection.—DATA as in Problem 37. In addition, the feeder is to be protected against lightning. The line is in a mountainous district where lightning discharges are very severe. It is proposed to put arresters at each end of the line, and every 1,500 ft. along the line.

REQUIRED.—Select suitable lightning arrester equipment, and draw a diagram showing the complete connections.

47. Lightning Protection.—DATA: A 2,200-volt, three-phase, 60-cycle power plant furnishes power for coal mining. Power is used outside each mine, for machine work, pumping, ventilating, and hauling, and inside the mine for mining, hoisting, and hauling. Motor generator sets are located in the mines and elsewhere as required, to obtain power at 275 volts, D.C., for hauling and other purposes.

REQUIRED.—Select suitable lightning arrester equipment, and draw a diagram showing connections.

PROBLEMS ON CHAPTER XIX

48. Meters.—DATA as in Problems 40 and 42.

REQUIRED.—(*a*) Draw a diagram showing the circuits, including all meters and ground detecting and meter switching apparatus, and specify the full scale indication of each meter.

49. Meters.—DATA as in Problem 47. There are three generators in the power plant.

REQUIRED.—Lay out suitable feeders, and show all necessary meters, meter switches, ground detecting and synchronizing apparatus.

PROBLEMS ON CHAPTER XX

50. Machine Shop Motors.—DATA: A machine shop is to be equipped with motors for individual drive for the following machines:

Engine lathe, 16-in. swing, for heavy duty.
Engine lathe, 12-in. swing, for average duty.
Planer, 6-ft. bed, 42 in. wide between housings.
Boring mill, 6 ft. diameter of table, for average duty.
Pair of emery wheels, 16 in. diameter, for heavy duty.
Vertical drill press (upright drilling machine), 32-in. table.
Punch press for punching a 1½-in. hole in ½-in. soft steel.
Lever shear for cutting ¼ in. by 48-in. stock.

REQUIRED.—Specify the horsepower of motor for each application.

51. Crane—Hoisting Motor.—DATA: A 50-ton travelling crane is required to hoist full-load at 15 ft. per min., and to lower it at the same speed, with dynamic braking. The motor is hoisting one-third of the time, lowering one-third, and idle one-third.

REQUIRED.—(*a*) What power is the motor required to deliver during hoisting?

(*b*) What is the equivalent power during lowering, in its effect in heating the motor?

(*c*) What size of motor is required?

52. Crane—Trolley Motor.—DATA as in Problem 51. In addition, the weight of the trolley is 20 tons; maximum trolley speed is 120 ft. per min.; average acceleration and retardation is 4 ft. per sec. per sec. The trolley is accelerating during one-third of the time, retarding during one-third, travelling uniformly during one-sixth, and either stationary of drifting[1] (without power) during one-sixth.

REQUIRED.—(*a*) The power required during steady travel.

(*b*) The power required during acceleration.

(*c*) The equivalent of the power during lowering, in its effect in heating the motor.

(*d*) The size of trolley motor.

53. Crane—Bridge Motor.—DATA as in Problems 51 and 52. In addition, the weight of the bridge is 40 tons; maximum bridge velocity is 300 ft. per min. No power is used during retardation, and acceleration is small enough so that power during acceleration is practically the same as during steady travel. Period of acceleration and steady travel, 30 sec. Period of retardation and rest, 45 sec.

REQUIRED.—(*a*) The power required during steady travel.

(*b*) The size of the motor. [Suggestion: No variation of power is considered, except as it changes from zero to the maximum. Since there is only one value, the expression for *intermittent*, instead of *variable* power can be used, if desired.]

54. Acceleration of Motor Rotation.—DATA as in Problem 52. In addition, the weight of the gear and motor armature is 1,000 lb.; outside diameter of the armature is 16 in.; diameter of trolley track wheels is 10 in.; and gear ratio from motor to track wheel is 2:1.

REQUIRED.—How much additional power is required during acceleration, on account of accelerating the rotation of the armature and gear?

GENERAL PROBLEMS

55. Railroad Repair Shop.—DATA: A small railroad repair shop (see Fig. 108) is to be provided with D.C. power for motors, lighting and battery charging, for the following equipment:

Motor drive for

Four 26-in. lathes for heavy duty.

Three 50-in. lathes for average duty.

One lathe used on machinery steel—cutting speed, 60 ft. per min., 3/8-in. cut; 1/4-in. feed.

One lathe used on soft cast iron—cutting speed, 40 ft. per min.; 1/2-in. cut; 1/4-in. feed.

One wheel lathe for heavy duty on 84-in. wheels, with separate motor for tail stock.

One 12-ft. boring mill.

One 6-ft. boring mill.

[1] Strictly, if it is drifting without power, it is losing velocity, so that the power during retardation will be less. Practically the error is small in assuming that there is no change of velocity during a small amount of drifting.

One 36 in. × 8-ft. planer for average duty.
One 42 in. × 16-ft. planer for average duty.
One 60 in. × 20-ft. planer for average duty.
One 14-in. slotter.
One 3/8 in. × 96-in. shear.

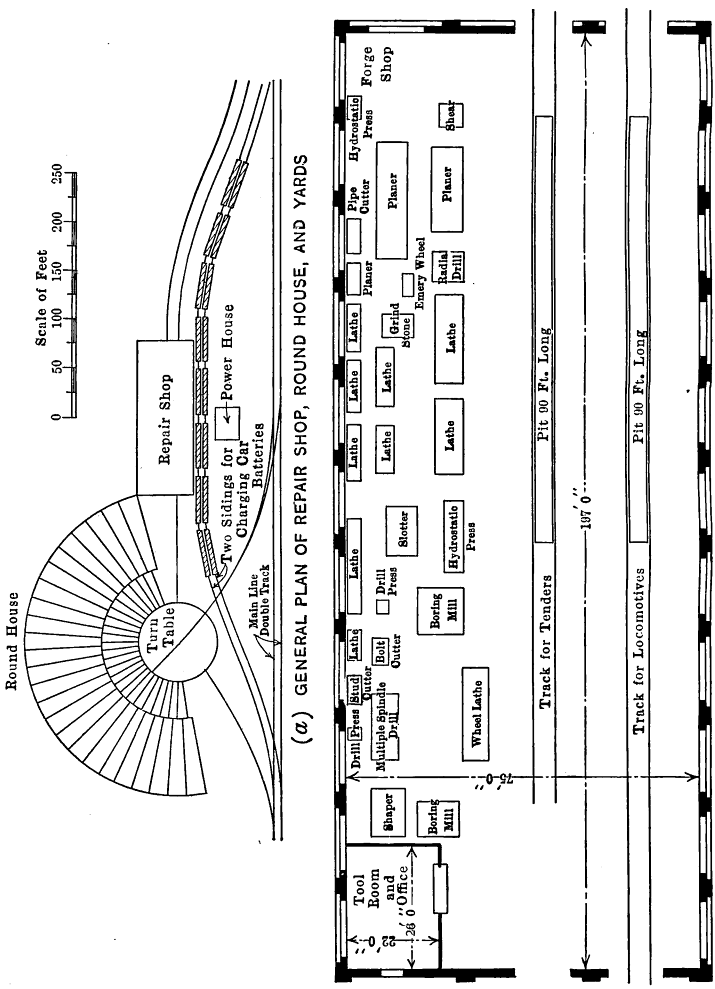

FIG. 108.—A small railroad repair shop and round house.

One multiple-spindle drilling machine, for 10 1-in. drills.
One radial drill for heavy duty, 10-ft. arm.
Two upright drills, 22-in. table.
One 16-in. shaper.
One 2¼-in. bolt cutter.

One 2-in. stud cutter (same power required as for the same size of bolt cutter).

One 6-in. pipe cutter.

One 16-in. emery wheel.

One 60-ton hydrostatic wheel press.

One small hydrostatic press requiring 5-hp. motor.

One 80-ton crane—hoisting and lowering 5 ft. per min.; trolley travel 30 ft. per min.; bridge travel 100 ft. per min.; acceleration negligible; weight of trolley, 25 tons; weight of bridge, 70 tons. Each motor is working only a few minutes out of an hour.

One 100-ft. turn table requiring 35-hp. motor.

Lighting.—General illumination—also special illumination as required, in pits, inside locomotives, etc.

(*a*) In the main shop.

(*b*) In the round house.

(*c*) On the turn table.

(*d*) In the yards.

Battery charging for train lighting, for two trains each composed of

One baggage car.

One 60-ft. mail car.

Two 16-section Pullman sleepers.

Four coaches.

In addition to other demands, the batteries on the Pullman cars are to be adequate for lighting 2 hr. before the train is made up, and 1 hr. at the end of the trip.

The total time of the trip is 8 hr. in each direction. Each train makes the round trip every day. If the axle-generator system is adopted, it is still necessary, on account of frequent and long stops, to give the batteries a charge at the end of each round trip, sufficient for 2 hr. service after the train starts.

Generators, Switchboard Equipment and Wiring.—For corresponding sizes of generators, the cost of generators and other equipment per cent. fixed charges, and cost of energy are as in Problem 32. The demand factor of the total load is 55 per cent. The plant is in operation 24 hr. per day, 300 days per year.

Required.—Draw a complete diagram of connections (condensed by notes); select the voltage or voltages of the system; specify the kind of motor for each application and horsepower of each; the number, size and kind of generators; the size, kind and voltage of each machine of each motor-generator set; and the size and location of all lamps. Give all possible information regarding meters, switches, circuit-breakers, rheostats, and other electrical equipment that should be provided in the power plant and shop, and the size and number of cells in each battery.

56. Cement Making Plant.—Data: The mechanical process of cement making is, in brief, as follows: Limestone and shale are quarried, crushed, dried and stored ready for use. They are then mixed in suitable proportions, and reduced by several additional processes to a fine powder. This powder is passed through a kiln and melted to a clinker formation, and certain chemical changes take place. The clinker is then sometimes exposed to the weather for a few weeks, but this weathering may be eliminated. A small amount of gypsum is then added, and the material is again pulverized. It is then in its final state and is stored ready for shipment.

Following is a list of machines and operations requiring motors in a typical cement-making plant;[1] the list is in the order of handling the cement (see Fig. 109). Wherever 5 hp. or less is required, a 5-hp. motor is installed for simplicity of layout, and to reduce the number of spare motors to be kept on hand. Where the horsepower is not given in the list, it is to be worked out as a part of the problem.

In the quarry, 1, 3_a, 3_b, crushers (150, 75 and 30 hp.; 2, 4, belt elevators (capacity 100 tons per hour, lift 60 and 40 ft. respectively); and 5, belt conveyor (5 hp.).

In the dryer department, 6, tram conveyor (10 hp.); 7, rotating the cylindrical dryer (25 hp.); 8, belt elevator, (10 hp.); and 9, belt conveyor (5 hp.) to separate storage tanks for shale and for limestone.

In the mix department, 10_a and 10_b, belt conveyors for shale and limestone, respectively (5 hp. each) to the mixing bin; 11, belt elevator (5 hp.) to the ball mills.

In the raw department, 12_a, 12_b, ball mills (75 hp. each); 13, belt conveyor and belt elevator (5 hp.); 14_a, 14_b, 14_c, Kent-Maxecon mills (50 hp. each); 15, screw conveyors (5 hp.) $16_{a,b}$, belt elevators (5 hp.); $17_{a,b}$, tube mills for raw material;[2] 18, belt elevator (5 hp.); 19, 20, belt conveyors (10 and 5 hp. respectively) to the kilns.

In the kiln department, 21_a to 21_e, rotating the kilns (20 hp. each); 22, Peck carrier (10 hp.); 23, belt conveyor (5 hp.) to clinker storage department.

In clinker storage department, 24, 25, belt conveyors (5 hp. each); 26, belt elevator (5 hp.); 27, belt conveyor (5 hp.); 28, rolls (10 hp.); 29, cable (75 hp.).

In the clinker department the processes are the same as in the raw department, beginning with the Kent-Maxecon mills—Nos. 14 to 20.

In the coal department are one 60-hp. and one 25-hp., two 10-hp. and three 5-hp. squirrel-cage motors.

In the machine shop are located one 15-hp. motor for line shaft and one 25-hp. motor for air compressors.

In the stock house are five 15-hp. and two 5-hp. squirrel-cage motors.

[1] In nearly all details the motors listed are as in the plant of The Cayuga Cement Corporation, Portland Point, N. Y.; information was furnished by courtesy of Mr. W. H. Kniskern, General Manager. A few small motors have been omitted from the list, but none that would affect the layout of the system.

[2] Assume data as on p. 182, unless otherwise specified.

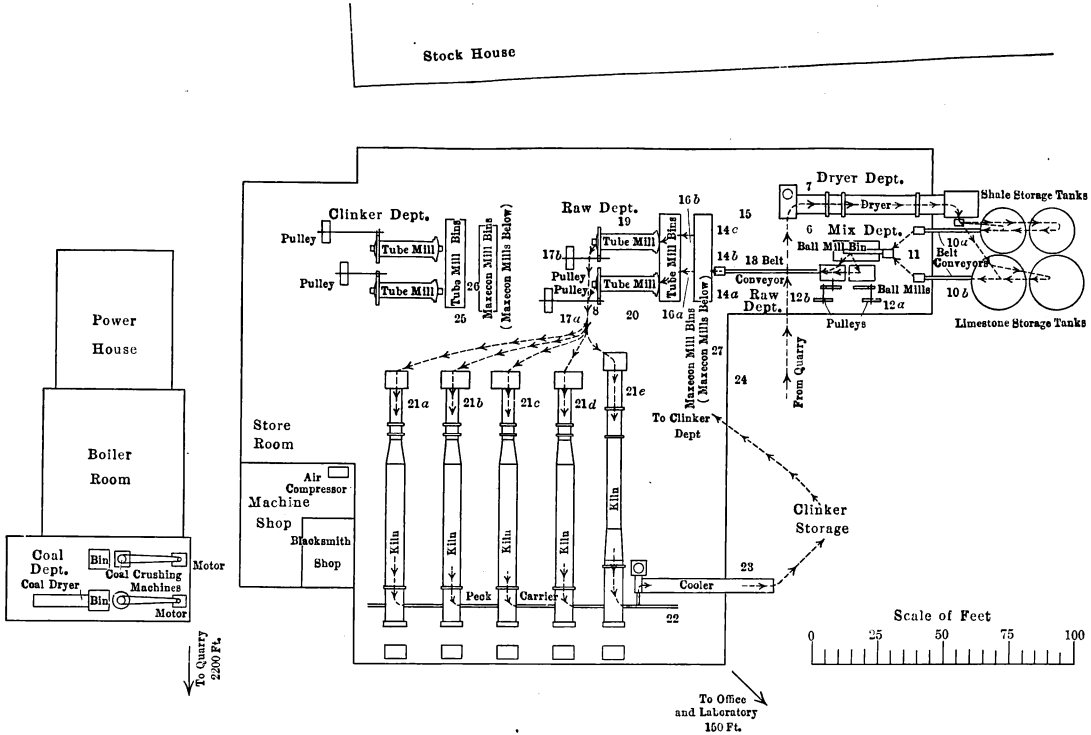

FIG. 109.—Main Plant of the Cayuga Cement Corporation, Portland Pt., N. Y.

The arrows and dotted lines show the progress of the cement through the plant. The numbers show the locations of the various motors. The numerical order of motors corresponds to the order of progress of the cement. Where the cement goes by more than one path the motor numbers are given sub-letters.

In the laboratory is one 5-hp. motor.

Special provision for speed regulation or large starting torque is unnecessary, except as follows: The starting torque for tube mills is considerably more than the running torque; and the speed of rotation of each kiln must be varied depending on the temperature of the kiln.

Lighting.—Power required for lighting is as follows:

Office and laboratory, 1 kw.

Stock house, 1 kw.

Clinker storage and other yard lighting, 1 kw.

Quarry and crusher plant, 5 kw.

Main plant, power house, boiler room, coal department, average 0.2 watt per sq. ft. of building area.

Generators, Switchboard Equipment and Wiring.—The plant is in operation an equivalent of 24 hr. per day, 280 days per year. The demand factor of the load is 90 per cent.

Cost of turbo-generators, engines and exciters is as indicated on page 185. Cost of switchboard, wiring and other equipment in the power plant is $8 per kw. of total A.C. generator capacity.

Interest is at 6 per cent., depreciation 6 per cent., insurance 0.5 per cent., and taxes 1 per cent.

Copper wire suitable for the required wiring is quoted on the 18-ct. base with a discount of 52 per cent. The cost of installing, including supplies is 30 cts. per lb.

Cost of energy delivered to the switchboard, for operation and maintenance, including fuel, labor, and supplies (but not including fixed charges on turbines and generators), for various sizes of turbo-generators, is as follows:

Kw. capacity of each unit	3,000	2,000	1,500	1,000	750	500
Cost of energy in cents per kilowatt-hour	0.45	0.5	0.52	0.55	0.6	0.7

Required.—Draw a complete diagram of connections of (*a*) the power plant (condensed by notes), (*b*) one power feeder, including all motor connections (some of which have squirrel-cage, and some wound rotors), (*c*) one lighting feeder, leading to a panel board and branching from there to the various lights, and (*d*) the feeder to the quarry—not necessarily showing more than one motor on that feeder. The diagram is to include the switchboard connections to all the lighting and power feeders, suitably labelled to show to what part of the plant they lead.

Specify the size of motor in each case where the size is not given. Specify the kind of motor for each case (if nearly all the motors are of one kind, it is sufficient to specify all except that one kind).

Give as full information as possible regarding all generators, switches, circuit-breakers, rheostats, meters and other equipment shown in the diagram.

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