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DYNAMO ELECTRIC MACHINERY;

ITS CONSTRUCTION, DESIGN,
AND OPERATION

DIRECT CURRENT MACHINES

BY

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PREFACE.

THIS book is intended to be used primarily in connection with instruction on courses of electrical engineering in institutions for technical education. It is laid out on the lines of the lectures and the instruction as given in the Polytechnic Institute of Brooklyn. It is intended equally as much for the general reader, who is seriously looking for information concerning dynamo electrical machinery of the types discussed, as well as a book of reference for engineers.

The first two chapters are devoted to a brief but logical discussion of the electrical and magnetic laws and facts upon which the operation of this class of machinery depends. Calculus methods have been employed in a few places in these chapters, but the results arrived at by use of them are in such a form that they can be utilized by the reader who is unfamiliar with the processes of the calculus.

In the chapter on design it has seemed advisable to express the flux density in lines per square centimeter. Both the square centimeter and the square inch are used in practice. The alteration of the formulas to square inch units is obviously simple.

We wish to express our thanks to the various manufacturing companies who have so courteously given information, and who have kindly loaned electrotypes of their apparatus.

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PREFACE TO THE SECOND EDITION.

THE cordial reception accorded this volume upon its appearance has resulted in a rapid exhaustion of the edition. Its adoption as a text-book by many educational institutions has convinced the author that others concur with him in his judgment as to what should be embodied in such a book; and he is encouraged in the preparation of a second volume which will treat of alternating current machines and which will appear shortly. Such errors as had inadvertently crept into the first edition are here corrected, in so far as they have been brought to the attention of the author.

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DYNAMO ELECTRIC MACHINERY.

CHAPTER I.

ELECTRICAL LAWS AND FACTS.

1. **Mechanical Units.** — *Force* is that which tends to produce, alter, or destroy motion. The units of force are the pound and the dyne. The *dyne* is that force, which acting on one gram for one second, will produce a velocity of one centimeter per second.

Work is the production of motion against resistance. The units of work are the foot-pound and the erg. The *foot-pound* is the work done in lifting a body weighing one pound one foot vertically. The *erg* is the work performed by a force of one dyne in moving a body one centimeter in the direction of its acting. The joule is a larger unit much used, and is equal to 10^7 ergs.

Energy is the capacity to do work. Energy is divided into *Kinetic* energy and *Potential* energy. A body possesses kinetic energy in virtue of its motion, while potential energy is due to the separation or the disarrangement of attracting particles or masses. A wound up spring has potential energy because of the strained positions of the molecules, while a weight raised to a height has potential energy because of the separation of its mass from the attracting mass of the earth. The potential energy of a body is measured by the work required to put the body into its strained condition. Kinetic energy is measured by the product of the weight into the square of the velocity divided by twice the acceleration due to gravity, or

$$\text{Kinetic Energy} = \frac{Wv^2}{2g}.$$

Power is the rate of performance of work. Its units are the horse-power and the watt. A *horse-power* is 33,000 foot-pounds per minute. A *watt* is 10^7 ergs per second. One horse-power is equivalent to 746 watts. The number of watts in an electrical circuit carrying a certain number of amperes of current under a pressure of a certain number of volts is expressed by the product of the amperes into the volts. If we let T equal the torque or twisting moment and ω equal the angular velocity $(= \frac{2\pi n}{60}$ where n is the number of revolutions per minute), then the horse-power

$$\text{H.P.} = \frac{60\,\omega T}{33000} = \frac{2\,\pi n T}{33000}.$$

In a belt-driven machine the torque in the shaft is equal to the difference in tension of the two sides of the belt multiplied by the radius of the pulley in feet, hence $T = (F - F')\,r$.

2. Absolute and Practical Units. — Since distinction must continually be made between the absolute units and the practical units, throughout this work the capital letters I, E, and R will be used for quantities expressed in practical units, the ampere, the volt, and the ohm; the lower case letters i, e, and r for quantities expressed in absolute units of current, pressure, and resistance respectively.

The absolute unit of *current* is such that, when flowing through a conductor of one centimeter length, which is bent into an arc of one centimeter radius, it will exert a force of one dyne on a unit magnet pole (§ 10) placed at the center.

The absolute unit of *difference of potential* exists between two points when it requires the expenditure of one erg of work to move a unit quantity of electricity from one point to the other. This unit of quantity is the quantity which, in a second, passes any cross-section of a conductor in which a unit current is flowing.

The absolute unit of *resistance* is offered by a body when it allows a unit current to flow along it between its two terminals, when maintained at a unit difference of potential.

$$\text{Current, } I = \frac{1}{10} i.$$

$$E.M.F., E = 10^8 e.$$

$$\text{Resistance, } R = 10^9 r.$$

It is convenient and rational to make a distinction between electromotive force and difference of potential. Electromotive force is produced when a conductor cuts magnetic lines of force, or when the electrodes of a primary battery are immersed in a solution. But a difference of potential may exist merely because of an electric current. Between any two points of a conductor carrying a current there is that which would send a current through an auxiliary wire connecting these points, and we call it difference of potential. If the current in the original conductor be doubled, the difference of potential between the same two points will be doubled, showing that this difference of potential exists because of the current flowing in the original conductor. The word *pressure* is used for either difference of potential or for *E.M.F.* with obvious relevancy.

3. Ohm's Law. — Ohm's law is expressed by the formula

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

where I is the number of amperes flowing in an undivided circuit, E the algebraic sum of all the electromotive forces in that circuit, and R the sum of all the resistances in series in that circuit.

The form of the equation $E = IR$, as applied to a portion of a circuit, is much used under the name of Ohm's law. In this case, however, E is not *E.M.F.*, but difference of potential, as explained in the last article.

If, in a house lighted by electricity, the service maintains a constant pressure of 100 volts at the mains where they enter from the street, and no lights be turned on, then at every lamp socket in the house there will be a pressure of 100 volts. If now a lamp be turned on, it will be working on less than 100 volts, because of the *drop* or *fall of potential.* If many lamps be turned on, a considerable drop may occur. The drop is caused by the resistance of the wires carrying the current from the place of constant potential to the place where it is used, and the volts lost have been consumed in doing useless work in heating the wires. That the drop is proportional to the current flowing is shown by a simple application of Ohm's law.

Let R be the resistance of the line, and E_d the volts drop caused thereby when a current I flows. Then

$$E_d = IR,$$

from which it is evident that the drop varies as the current when the resistance in the line is constant.

4. Resistance of Conductors.—The resistance R of a conductor is expressed by the formula $R = \frac{\sigma l}{A}$, where σ is a constant called the resistivity, and depending upon the material and the temperature of the conductor, l is the length in centimeters, and A the cross-section in square cms. The reciprocal of the resistivity, $\frac{1}{\sigma}$, is called the conductivity of a substance.

The conductivity of copper depends on its purity, and on its physical condition, soft copper having 1.0226 times the conductivity of hard copper. Lake copper has a high conductivity because of its pureness. The same is true of electrolytic copper. This latter is now very largely used, though for a while there was a prejudice against it because it was said to be brittle. Temperature affects the resistance of metals. In pure metals the increase of resistance for a rise of 1° C. is about .004 times their resistance at 0° C. Various alloys of iron, nickel, and manganese have a high value for σ, and do not have so high a temperature coefficient as given above. Iron heated in contact with copper gives a large thermal *E.M.F.*, which militates against its alloys being used for resistances in measuring instruments.

If in the foregoing expression for R the centimeter and square centimeter be the units of length and cross-section respectively, then the following list gives the value of σ for various metals in microhms (1 microhm $= \frac{1}{1000000}$ ohm).

Copper	at 0°C, ...	1.594
Iron	" "	9.5
Steel	" "	13.0
18% German Silver	" "	27.
30%	" "	45.

A *circular mil* is a circle $\frac{1}{1000}$ inch in diameter, and a wire one foot long and one circular mil cross-section is called a *mil-foot.* The resistance of a mil-foot at 0° C. of

Copper	= 9.59	ohms,
Iron	= 58.	ohms,
Steel	= 82.	ohms.

The American Institute of Electrical Engineers has adopted as its standard resistivity for soft copper one given by Matthiessen. A wire of standard soft copper, of uniform cross-section, of one meter length, and weighing one gram, should have a resistance of 0.141729 international ohms at 0° C. A commercial copper showing this resistivity is said to have 100 per cent conductivity. Copper is frequently found having a conductivity of 102 per cent. It is in these cases almost invariably electrolytic copper.

5. Insulating Materials. — Materials which are to be used for insulating from each other the various electrical circuits of dynamo electric machines should possess the following properties: —

They should have a high insulation resistance, and this resistance should be maintained high over the range of temperatures to be found in machines. They should furthermore have a dielectric strength sufficient to preclude any possibility of their being perforated by the voltages liable to exist between the conductors which they separate. This strength must also exist throughout all probable ranges of temperature. They must possess such physical properties as will permit of mechanical manipulation, as they must be oftentimes bent and twisted. Of course the chemical constitution should not be altered by any change of temperature to which they would be submitted.

Mica possesses the highest insulation resistance and the largest dielectric strength to be found. It requires 1000 volts to perforate a sheet 1 mil in thickness. Its chemical constitution is unaffected by high temperatures. It is not, however, mechanically strong.

Preparations of fibrous materials with linseed oil, which, after being dried, have been thoroughly baked, are fairly good insulators. As water is generally present in their pores, their insulation resistance, upon heating, decreases until the temperature has reached 100° C., and then it increases. These preparations are mechanically flexible. Preparations of fibrous material with shellac are good insulators, but crack upon bending.

Vulcanized fibers are made by treating paper fiber chemically, and, when dried, they have a fairly high insulation resistance, but they readily absorb moisture, and, upon drying, are liable to warp and twist. They furthermore become brittle when heated.

Sheets of insulation made up from pieces of scrap mica cemented together by linseed oil or preparations of shellac, when carefully constructed with lapped joints, exhibit nearly as good insulating and dielectric properties as sheet mica. While not perfect mechanically, these sheets permit of bending better than pure mica.

Vulcabeston, which is a preparation of asbestos and rubber, exhibits fairly good insulating and mechanical qualities, and is especially fitted for higher temperatures. Its dielectric strength is about $\frac{1}{100}$ of that of mica.

6. Divided Circuits. — If a current *I* be flowing through

R, the undivided part of the circuit shown in Fig. 1, and if I_1 and I_2 be the currents flowing in the shunt resistances R_1 and R_2, then $I = I_1 + I_2$, and, since the pressure E upon each shunt is the same, by Ohm's law,

$$I_1 = \frac{E}{R_1} \text{ and } I_2 = \frac{E}{R_2}$$

$$\text{or } I_1 : I_2 :: \frac{I}{R_1} : \frac{I}{R_2}$$

The currents in the branches of a divided circuit are inversely as the resistances of the branches.

If R_e be a single resistance, that substituted for the shunted resistances R_1 and R_2 will leave I unchanged, then, by Ohm's law,

$$\frac{E}{R_e} = \frac{E}{R_1} + \frac{E}{R_2}$$

$$\text{or } R_e = \frac{R_1 \, R_2}{R_1 + R_2} = \frac{I}{\frac{I}{R_1} + \frac{I}{R_2}}$$

The resistance equivalent to a number of shunted resistances is equal to the reciprocal of the sum of the reciprocals of the separate resistances.

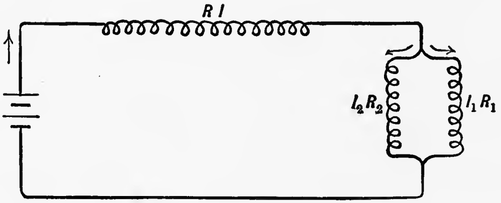

Fig. 1.

7. Power of Electric Current. — A difference of potential e between two points requires e ergs of work to bring a unit quantity of electricity from one point to the other. A unit of quantity is one absolute unit of current flowing for one second. Hence a current i flowing for t seconds with a difference of potential e does eit ergs of work. Likewise a current I flowing t seconds gives It coulombs of quantity, and with a difference of potential of E volts does $EIt \times 10^7$ ergs of work. Hence the *work per second* or the *power* is $EI \times 10^7$ absolute units. The practical unit of power is the *watt*, and equals 10^7 absolute units. Hence, remembering that by Ohm's law $E = IR$, the power of a current in

$$\text{Watts} = EI = I^2R.$$

For commercial currents and voltages the watt is a needlessly small expression, hence the kilowatt (= 1,000 watts) is generally used as the unit of electrical power. It is represented by the abbreviation K.W. The horse-power is equal to 746 watts, or approximately three-fourths of a K.W.

8. Heat Developed by a Current. — When a current I does work in overcoming a resistance R, the work performed is converted into heat. By the last article the work thus done per second, or the power expended, will be I^2R watts. Since this rate of production of heat is often of no service, this expenditure of power is generally called the *I^2R loss.*

This production of heat causes a rise of temperature in the conductor, and the temperature will continue to rise till the heat generated per second by the I^2R loss is exactly counterbalanced by the rate of dissipation of heat by conduction, convection, and radiation.

The necessary resistances of electrical machines involve the production of heat in their operation (as does also friction and reversal of magnetism), which causes a rise of temperature. As insulating materials can survive only moderately high temperatures, such machines must be designed to operate without becoming too hot. This is accomplished by decreasing the I^2R loss, by increasing the radiating surface, and by supplying ventilation.

9. **Fuses.** — These are devices intended to protect circuits from destruction or damage due to an excessive flow of current through them. They protect them by being themselves destroyed. They are generally made of lead or alloys of lead. Lead is liable to become oxidized after having been installed for some time. It is then liable to form a tube of hard oxide, which is sufficiently strong to hold molten lead in its interior, so as to maintain an electrical contact in the circuit which should be broken. Some alloys are not open to this objection. These alloys, in the form of wires, strips, or ribbons, are fastened at each end to copper terminals which are slotted to fit into fuse receptacles. The wire with its terminals is called a fuse *link*. Such a link is shown in Fig. 2.

Fig. 2.

Copper wires are sometimes used as fuses on trolley cars, but the high melting point of copper prohibits its use as a protective device on house circuits.

The current which will fuse a wire of lead alloy depends in magnitude upon the length of the wire. Short lengths of a wire of given cross-section and given material will carry stronger currents than longer lengths. The heat which is generated in the short ones escapes more rapidly, owing to the larger masses of metal commonly forming the terminals of the fuse. Fuses are rated to carry a given amperage, and the rating is stamped upon the copper terminals. According to the national code the fuses must, however, be able to carry indefinitely without melting such a number of amperes that the rated capacity is but 80 per cent of it. This permits the fuse to carry without melting 25 per cent above the rated capacity.

Fig. 3.

For high voltages, and for large amperages, inclosed fuses are sometimes used, in which the fusible conductor is surrounded by a packing of finely divided powder in which borax is included as an element most desirable. Such a fuse is shown in Fig. 3.

CHAPTER II.

MAGNETIC LAWS AND FACTS.

10. Strength of Magnet Pole. — A unit magnet pole is one which will repel an equal like pole, when at a distance of one centimeter, with a force of one dyne.

It follows from this definition that a pole m units strong will repel a like *unit* pole with a force of m dynes. The force exerted between two magnetic poles varies inversely as the square of the distance between them. Hence the force exerted between two magnetic poles of strengths m and m' when d centimeters apart is defined by the equation

$$F = \frac{m\,m'}{d^2}.$$

11. Intensity of Magnetic Field. — A magnetic field is of unit strength or intensity when a unit magnet pole placed therein is acted upon by a force of one dyne, or when a magnet pole m units strong is acted upon by a force of m dynes. The strength of a field is usually represented by $\mathcal{H}$.

12. Magnetic Field and Lines of Force. — The space around a magnet where its action is felt is termed the field of that magnet. This field may conveniently be considered as permeated by *lines of force*. These lines represent the *direction* of the force exerted by the magnet, and by their closeness to each other show the *magnitude* of this force.

The student must not get the impression that, because the lines spread apart, a point in the field could be chosen where there would be no line. These lines may well be considered as tubes or pencils of force, filling all the space around the magnet.

The lines of force contained in any plane passed through the magnet pole compose a *magnetic spectrum*, which can be made visible by the familiar experiment of sprinkling iron filings on a paper, which is laid over a magnet, and by gently tapping it.

By convention one line of force per square centimeter is considered to represent a field of unit strength, the square centimeter being so taken that it is at all points perpendicular to the lines cutting it. Hence the strength or intensity $\mathcal{H}$ of any field can be expressed by the number of lines of force per square centimeter.

Suppose a sphere of one centimeter radius to be circumscribed about a unit magnet pole. Another unit pole at any point on the surface of this sphere will be acted upon by a force of one dyne. Hence there exists a unit field at any point on this surface. But there are 4π square centimeters on this surface, and each square centimeter will be cut by one line of force. Therefore, *there emanate from a unit magnet pole* 4π *lines of force*. Similarly a magnet pole of strength m sends out $4\pi m$ lines of force.

A magnetic field is said to be *uniform* when it has the same $\mathcal{H}$ at every point therein, or when the lines of force are parallel.

13. Electro-Magnetic Induction. — In 1831 Faraday and Henry independently discovered that when a conductor was moved in a magnetic field, an electromotive force was set up in the conductor. This phenomenon is the foundation of all modern electrical engineering.

An absolute unit of *E.M.F.* is produced when a conductor cuts one line of force per second. If the conductor cuts two lines in the second, or one line in half a second, then two units are produced.

If, in the short interval of time, dt seconds, $d\phi$ lines be cut, then during that interval the value of the induced *E.M.F.* will be

$$e = -\frac{d\phi}{dt},$$

or,

$$E = -\frac{1}{10^8}\frac{d\phi}{dt} \text{ volts.}$$

The negative sign is used because the induced *E.M.F.* tends to send a current in such a direction as to demagnetize the field. When of no consequence the negative sign will hereafter be omitted.

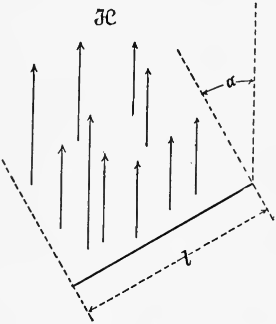

Fig. 4.

If a conductor, Fig. 4, l centimeters long moves parallel to itself with a uniform velocity of v centimeters per second across a uniform magnetic field of strength $\mathcal{H}$, its path making an angle a with the direction of the lines of force, then the number of lines cut per second is $\mathcal{H}lv \sin a$, and since the rate of cutting is uniform, the *E.M.F.* at any instant is

$$e = \mathcal{H}lv \sin a.$$

If there be a non-uniformity in the rate of cutting lines, due either to an uneven field or an irregular motion, then the average value of the induced *E.M.F.* associated with the cutting of ϕ lines in the time, t seconds, will be $e_{av} = \frac{\phi}{t}$. For suppose the time t to be divided into p equal and small periods having a duration of Δt seconds. Furthermore, suppose that during these successive periods $\Delta\phi'$, $\Delta\phi''$, $\Delta\phi'''$, etc., lines be cut respectively. Then the induced *E.M.F.*'s during these periods, which may be represented by e', e'', e''', etc., respectively, will be as follows: —

$$e' = \frac{\Delta\phi'}{\Delta t}.$$

$$e'' = \frac{\Delta\phi''}{\Delta t}.$$

$$e''' = \frac{\Delta\phi'''}{\Delta t}.$$

$$\ldots\ldots = \ldots\ldots$$

Adding these p equations, and then dividing by p, gives the equation above, viz.,

$$e_{av} = \frac{\phi}{t} \text{ or } E_{av} = \frac{\phi}{10^8 t} \text{ volts.}$$

The average value of the induced *E.M.F.* is therefore independent of the magnitude of the instantaneous values.

If a loop of wire revolve, uniformly or otherwise, in a magnetic field which is uniform or otherwise, its sides cut lines of force at various rates. The instantaneous *E.M.F.* in the whole loop will be as before.

$$e = \frac{d\phi}{dt},$$

where ϕ is the number of lines that links with, or that passes through, the loop. If the loop be of n turns, then the pressure will be n times as great, or during the interval dt,

$$E = -\frac{n\,d\phi}{10^8 dt}.$$

14. Direction of Induced E.M.F. — The direction of flow of a current induced in a closed circuit by moving it in a magnetic field is best represented by drawing the conventional representation of the three dimensions of space. If the flux be directed upwards, and the motion of the conductor be to the right, then the *E.M.F.* will tend to send a current toward the reader. If any one of these conditions be changed it necessitates the change of one of the others, and conversely the change of any two leaves the third unaltered. About the same idea is represented in Fleming's Rule, which is as follows: —

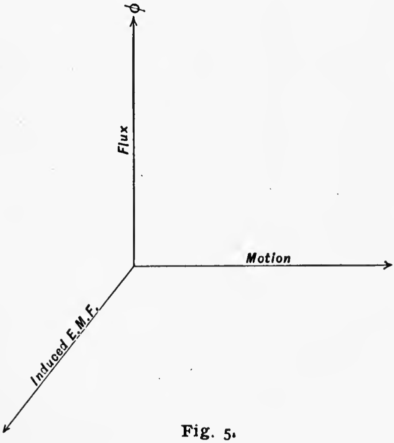

Fig. 5.

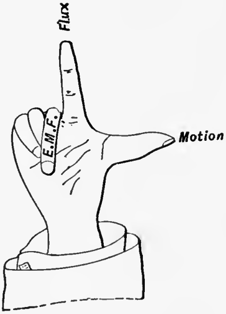

Fig. 6.

Let the index finger of the right hand point in the direction of the flux, and the thumb in the direction of the motion. Bend the second finger at right angles with the thumb and index finger, and it will point in the direction of the *E.M.F.*

Another rule is : —

Stand facing a north magnetic pole. Pass a conductor downward. The current tends to flow to the left.

15. Inductance. — Nearly every electrical circuit which has a current flowing in it has lines of force linked with it, due to that current. When the circuit is opened the disappearance of the lines is accompanied by a cutting of the circuit by those lines, and the cutting results in the production of an *E.M.F.* This is called the *E.M.F.* of *self-induction.* Its magnitude is dependent upon the rapidity with which the field disappears, and upon a constant determined by the geometric shape of the circuit and the character of the medium in which it is placed. This constant is called the *self-inductance* or the *coefficient of self-induction* of the circuit. It is generally represented by the letter *L*, and is that coefficient by which the time rate of change of current in the circuit must be multiplied in order to give the *E.M.F.* induced in the circuit. Its absolute value is numerically represented by the number of lines of force linked with the circuit per absolute unit of current in that circuit. Its practical unit is 10^9 times as large as the absolute unit, and is called the *henry.* In a given circuit it varies as the square of the number of turns of wire. Two circuits may exercise a mutually inductive action upon each other, and an *E.M.F.* may be induced in one by a change of current in the other. This is called the *E.M.F.* of *mutual induction.* In magnitude it depends upon the shape and position of the two circuits, and upon the character of medium in which they are placed. It is also dependent upon a constant which is called the *mutual inductance* or *coefficient of mutual induction* of the two circuits. It is generally represented by the letter M. It is that coefficient by which the time rate of change of the current in one of the circuits is multiplied in order to give the *E.M.F.* induced in the other circuit. Its absolute value is numerically equal to the number of lines of force linked with one of the circuits per absolute unit of current in the other circuit. Its practical unit is the same as the practical unit of self-inductance, that is the henry, and is 10^9 times as large as the absolute unit. The coefficient of mutual induction varies directly as the number of turns of wire in either circuit.

16. Quantity of Electricity Traversing a Circuit Due to a Change of Flux Linked with it. — In many dynamo tests, and in many magnetic investigations, it is necessary to measure, generally by means of a ballistic galvanometer, the quantity of electricity traversing a circuit due to a change of flux linked with it. If the circuit have a resistance of r and in dt time the flux linked with n turns changes by $d\phi$, then the instantaneous current

$$i = \frac{\frac{n d\phi}{dt}}{r}.$$

But the quantity, $dq = idt$, hence

$$dq = \frac{n d\phi}{r},$$

which is independent of time. So if the flux change from ϕ_1 to ϕ_2, then

$$q = \frac{\phi_1 - \phi_2}{r} n,$$

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or $$Q = \frac{n}{100} \frac{\phi_1 - \phi_2}{R} \text{ microcoulombs.}$$

17. Work Performed by a Conductor Carrying a Current and Moving in a Magnetic Field. — Let a conductor carrying a constant current i be moved in a direction perpendicular to itself and to the lines of force of a magnetic field. Suppose it to move for dt seconds, and in that time to cut $d\phi$ lines of force. Then the induced *E.M.F.* e will be $-\frac{d\phi}{dt}$. The quantity of electricity dq that has to traverse the circuit against this *E.M.F.* during the time dt will be idt. Since potential is a measure of work, the work required to carry dq units of electricity against a difference of potential e is edq ergs. Hence the work in ergs,

$$dw = edq = idt \times \frac{d\phi}{dt} = id\phi.$$

Therefore the current i, in cutting ϕ lines of force, performs the work

$$w = i\phi \text{ ergs.}$$

From this it is seen that the work done by a conductor carrying a current and cutting lines of force is independent of the time it takes to cut them.

In the above discussion, if the field be not uniform or the motion be not uniform, the value of e will not be the same for each instant of time. But since the result obtained is independent of time, it is immaterial how the lines are arranged, and how the rate of cutting varies.

18. Magnetic Potential. — The magnetic potential at any point is measured by the work required to bring a unit magnet pole up to that point from an infinite distance.

The difference of magnetic potential between any two points is measured by the work in ergs required to carry a unit magnet pole from one to the other. The difference of magnetic potential is a measure of the ability to send out lines of force, or to set up a magnetic field.

19. Magnetomotive Force of a Circular Circuit Carrying a Current. — A thin circular conductor carrying a current forms a *magnetic shell.* If a unit magnet pole be taken from the top side of a shell, and carried around to the bottom side, work must be done, and this work is a measure of the difference of potential between the two sides of the shell.

It is immaterial whether the pole be carried from one side of the shell to the other, or the shell be turned bottom side up around the pole. In the latter case it is clear that all the lines emanating from the pole will be cut once, and once only, by the conductor, wherefore 4π lines will have been cut.

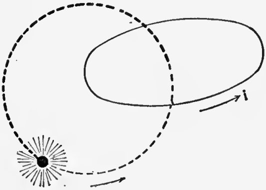
Fig. 7.

If current i flows in the conductor, then, by § 17,

$$\text{Work in ergs } i\phi = 4\,\pi i.$$

If there be n turns of the conductor, each line of force will be cut n times, and the work will be $4\pi ni$ ergs.

Hence the difference of potential between the two sides of a thin magnetic shell is $4\,\pi ni$ or $\frac{4\pi nI}{10}$.

In this expression $\frac{4\pi}{10}$ is a constant, and it is convenient to regard nI as a single variable. In connection with it the term *ampere-turns* is employed, and this is frequently written nI.

Here the same argument holds as in §17, that the intensity of field and the rate of cutting lines will vary as the pole is in different parts of the path. But the total number of lines cut is the same in any case, so the expression for work and potential is true, no matter what path the pole takes.

20. Force Exerted on a Field by a Conductor Carrying a Current. — When a conductor moves in a field perpendicular to itself and to the lines of force, then, from § 17,

$$\text{Work} = i\phi \text{ ergs.}$$

If the conductor be l centimeters long, and traverses a distance of s centimeters through a uniform field of strength $\mathcal{H}$ ($\mathcal{H}$ lines per sq. cm.), then

$$\phi = ls\mathcal{H},$$

and the

$$\text{Work} = ils\,\mathcal{H} \text{ ergs.}$$

But

$$\text{Work} = \text{force} \times \text{distance} = Fs = ils\mathcal{H}.$$

$$\therefore\ F = il\mathcal{H} = \frac{Il\mathcal{H}}{10} \text{ dynes.}$$

21. The Solenoid. — A uniformly wound, long, straight coil, carrying a current i, produces a uniform field $\mathcal{H}$ at its center. This coil is called a *solenoid*, and may be considered as composed of *magnetic shells* arranged at equal distances from each other. It takes $4\pi i$ ergs to move a unit magnet pole from one side of a shell to the other (§ 19), and $4\pi in$ ergs to pass it through the n consecutive shells of the solenoid. If these n shells occupy a length on the solenoid of l centimeters, then

$$Work = force \times distance = \mathcal{H}l = 4\pi in \ ergs,$$

and the magnetizing force, that is, the strength or intensity of field, in the solenoid is

$$\mathcal{H} = \frac{4\pi nI}{10\,l}.$$

22. Permeability. — The same difference of magnetic potential between two points will produce more lines of force in iron than in air. Iron is then said to be more permeable than air, or to have a greater *permeability.* If a difference of magnetic potential could set up, at a certain place, a field of strength $\mathcal{H}$, with air as a medium, and one of strength $\mathcal{B}$, with some other substance as a medium, then the ratio $\frac{\mathcal{B}}{\mathcal{H}}$ expresses the permeability of that substance. This ratio is usually represented by μ. As $\mathcal{H}$ varies directly with the magnetic difference of potential, it becomes a measure of it. Therefore $\mathcal{H}$ is called the *magnetizing force and* $\mathcal{B}$ *the flux density*, the *magnetic density*, or the *induction per square centimeter.* For air, vacuum, and most substances $\mu = 1$. For iron, nickel, and cobalt μ has a higher value, reaching, in the case of iron, as high as 3000. Bismuth, phosphorus, water, and a few other substances, have a permeability very slightly less than unity.

A substance for which $\mu = 0$ would insulate magnetism. There is no such substance.

The total magnetic flux, ϕ, which passes through an area of A square centimeters, in which the magnetic density is $\mathcal{B}$, is represented by the equation

$$\phi = A\mathcal{B}.$$

The permeability of air is constant for all magnetizing forces. This is not the case with iron and other substances which have a permeability greater than unity. The value of μ, $\mathcal{B}$, and $\mathcal{H}$, which are connected by the relation $\mathcal{B} = \mu\mathcal{H}$, are given in the following table for average commercial wrought iron, for cast iron, and for steel. The relations which exist between $\mathcal{B}$ and $\mathcal{H}$ are also shown in Figs. 8, 9, and 10. These curves are technically known as $\mathcal{B}$–$\mathcal{H}$ curves.

DATA FOR $\mathcal{B}$–$\mathcal{H}$ CURVES.

AVERAGE FIRST QUALITY METAL.

$\mathcal{H}$	Ampere-turns per Centimeter Length.	Ampere-turns per Inch Length.	Wrought and Sheet Iron.		Cast Iron.		Cast Steel.	
			$\mathcal{B}$	Kilo-lines per Sq. In.	$\mathcal{B}$	Kilo-lines per Sq. In.	$\mathcal{B}$	Kilo-lines per Sq. In.
10	7.95	20.2	11800	74	3900	25.2	12000	77
20	15.90	40.4	14000	90	5500	35.5	13800	89
30	23.85	60.6	15200	98	6500	42.0	14600	94
40	31.80	80.8	15800	102	7100	45.7	15400	99
50	39.75	101.0	16400	106	7700	49.5	16000	103
60	47.70	121.2	16800	108	8200	53.0	16400	106
80	63.65	161.6	17200	111	8900	57.2	16700	108
100	79.50	202.0	17600	114	9300	60.0	17600	113
125	99.70	252.5	17800	115	9700	62.4	18200	117
150	119.25	303.0	18000	116	10100	65.8	18600	120

$\mathcal{H} = 1.258$ (nI per cm.) $= .495$ (nI per in.). $\mathcal{B} = .155$ (ϕ per sq. in.).

23. Things Which Influence the Shape of the $\mathcal{B}$-$\mathcal{H}$ Curve. — In general all substances mixed with or alloyed with iron lower its permeability. In steel and cast iron the permeability seems to be in inverse proportion to the amount of carbon present. Carbon in the graphitic (not combined) form lowers the permeability less than carbon when combined. In cast iron and cast steel such substances as tend to give softness and greater homogeneity to the metal

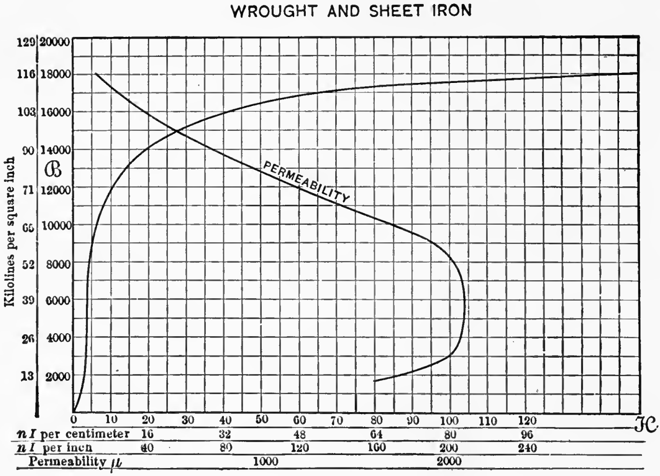
WROUGHT AND SHEET IRON
Kilolines per square inch
129 116 103 90 71 65 52 39 26 13
𝔅
20000 18000 16000 14000 12000 10000 8000 6000 4000 2000
PERMEABILITY
0 10 20 30 40 50 60 70 80 90 100 110 120
ℋ
n I per centimeter 16 32 48 64 80 96
n I per inch 40 80 120 160 200 240
Permeability μ 1000 2000

Fig. 8.

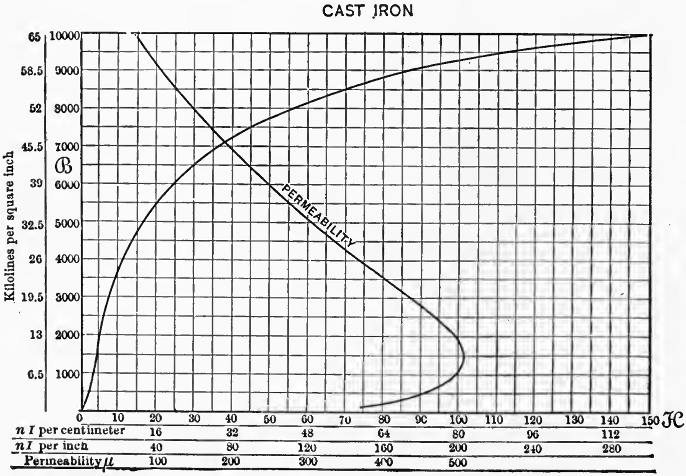
CAST IRON
Kilolines per square inch
65 58.5 52 45.5 39 32.5 26 19.5 13 6.5
𝔅
10000 9000 8000 7000 6000 5000 4000 3000 2000 1000
PERMEABILITY
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150
ℋ
n I per centimeter 16 32 48 64 80 96 112
n I per inch 40 80 120 160 200 240 280
Permeability μ 100 200 300 400 500

Fig. 9.

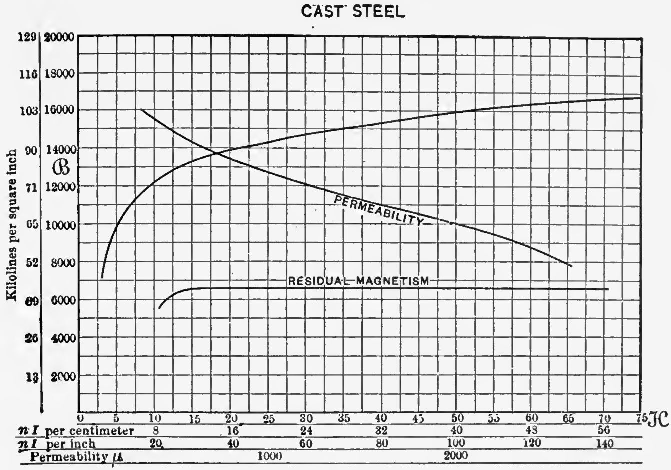

Fig. 10.

when present in limited amounts, say 2 per cent, increase the value of μ. Aluminum and silicon act in this way.

The physical condition of the metal also affects its permeability. Chilling in the mold, when casting, lowers it, as does tempering, or hardening the metal by working it. On the other hand, annealing increases the permeability.

A piece of iron or steel, subjected to a small magnetizing force, has its permeability increased by increasing the temperature until a *critical temperature* is reached, when it falls off rapidly to almost *unity*. For stronger magnetization the permeability does not rise so high at the critical temperature, and does not fall off so sharply after it. The value of this critical temperature lies between 650° C. and 900° C., depending on the test piece.

24. Reluctance and Permeance. — In the flow of magnetic lines of force the reciprocal of the *permeability*, $\frac{1}{\mu}$, is called the *reluctivity*. The total *reluctance*, tending to oppose the passage of magnetic lines under the influence of a magnetic difference of potential, is directly as the length and the reluctivity of the medium and inversely as its cross-section. Hence the total magnetic resistance or

$$\text{Reluctance} = \frac{\text{length}}{\text{cross-section}} \text{ reluctivity.}$$

Reluctivity is usually represented by $\rho (= \frac{1}{\mu})$. Hence for a medium of cross-section A square centimeters and length l centimeters, the reluctance

$$\mathcal{R} = \frac{l}{A} \rho.$$

Permeance is the reciprocal of the reluctance, hence the permeance

$$\mathcal{P} = \frac{A}{l\rho} = \frac{A}{l} \mu$$

It must be remembered that ρ and μ are not constant for some substances, but depend for their values upon the strength of the magnetizing force $\mathcal{H}$ which is acting upon the substances.

25. Relation Between Magnetomotive Force, Magnetic Flux, and Reluctance.—These quantities are related to each other the same as are *E.M.F.*, current, and resistance, viz.,

$$\text{Flux} = \frac{\text{Magnetomotive Force}}{\text{Reluctance}}.$$

In this respect electric current and magnetic lines are similar. However, while electric circuits, in the main, exist in media of zero electric conductivity, and therefore permit of accurate calculations, there being no appreciable leakage, magnetic circuits must be situated in media which have permeabilities of at least unity. In the latter case much leakage is present, and precise calculations are out of the question. In the designing of dynamo electric machinery, however, one or more paths of low reluctance are presented to the magnetizing force, and these are protected by being so shaped that leakage paths offer a comparatively high reluctance.

26. Hysteresis. — If a piece of iron become magnetized, and the magnetizing force be then removed, the iron does not become completely demagnetized. A certain magnetizing force in the opposite direction must be used to bring it to a neutral state. This phenomenon has been termed *hysteresis*. Because of hysteresis a $\mathcal{B}$–$\mathcal{H}$ curve taken with continuously *increasing* values of $\mathcal{H}$ to the maximum and

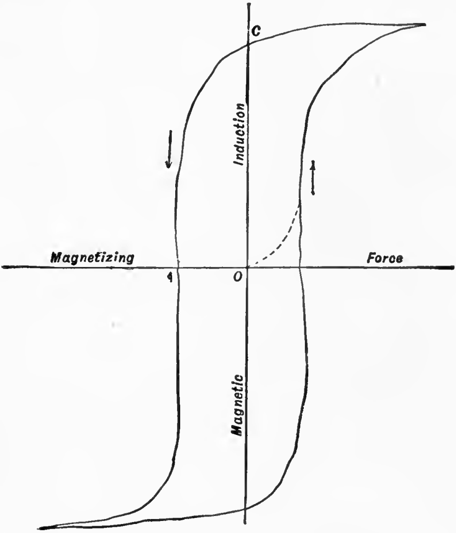

Fig. 11.

then with continuously decreasing values of $\mathcal{H}$ to a negative maximum, and so on, will assume the shape shown in Fig. 11. The distance $O\ A$ represents the *coercivity*, that is, the magnetizing force necessary to bring the iron from a magnetic to a neutral state. The distance $O\ C$ represents the *retentivity*, that is, the amount of magnetic induction left in the iron after the magetizing force has been removed. The area inclosed by the curve represents the energy lost in carrying the iron through one cycle, i.e., from a maximum magnetization to a maximum in the opposite direction and back to the orginal condition.

For suppose the magnetization to be due to a current I flowing in a solenoid of n turns. If, in a short interval of time dt, a change of $d\phi$ be made in the flux which is linked with the solenoid, then this change will induce an $E.M.F.$ in the solenoid which during the interval of time dt will be equal to

$$E = \frac{n d\phi}{10^8 dt} \text{ volts.}$$

During this time work must be performed to maintain this current I, and its magnitude is

$$EIdt = \frac{nId\phi}{10^8},$$

for Idt represents the quantity of electricity which is transferred from one point to another, between which there exists a difference of potential E. Now $\phi = A\mathcal{B}$ (§ 22) and hence $d\phi = Ad\mathcal{B}$. Furthermore, $nI = \frac{10\,\mathcal{H}l}{4\,\pi}$ (§ 21). Hence the work during the time dt is

$$EIdt = \frac{Al}{10^7 4\pi}\,\mathcal{H}\,d\mathcal{B} \text{ joules.}$$

Supposing the magnetizing force to vary cyclically, taking T seconds to make one cycle, then the work per cycle is

$$EIT = \frac{Al}{10^7 4\pi} \int_{-\mathfrak{B}_{max}}^{+\mathfrak{B}_{max}} \mathcal{H}\, d\mathfrak{B} \text{ joules.}$$

If the number of cycles completed in one second be f, then $f = \frac{1}{T}$, and the work in joules per second, that is, the power in watts, equals

$$EI = \frac{fAl}{10^7 4\pi} \int_{-\mathfrak{B}_{max}}^{+\mathfrak{B}_{max}} \mathcal{H}\, d\mathfrak{B} = \frac{0.796}{10^8} f \text{ volume} \int_{-\mathfrak{B}_{max}}^{+\mathfrak{B}_{max}} \mathcal{H}\, d\mathfrak{B}.$$

The integral expression is evidently the area contained by the hysteresis loop.

27. Steinmetz's Law. — The value of the integral expression is dependent upon $\mathfrak{B}_{max}$, upon the retentivity of the kind of iron, and upon its coercivity. Steinmetz has shown that for all practical purposes the value of the integral may be expressed by the empirical formula

$$\frac{1}{4\pi} \int_{-\mathfrak{B}_{max}}^{+\mathfrak{B}_{max}} \mathcal{H}\, d\mathfrak{B} = \eta \mathfrak{B}_{max}^{1.6},$$

where η is a constant depending upon the kind of iron. Its value is given in the following table: —

HYSTERETIC CONSTANTS.

Best soft iron or steel sheets	0.001
Good soft iron sheets	0.002
Ordinary soft iron	0.003
Soft annealed cast steel	0.008
Cast steel	0.012
Cast iron	0.016
Hard cast steel	0.025

The hysteretic constant, if at first small, grows with age. Its increase can be hastened by continued heating. The increase may amount to 200 per cent. Annealing, while it increases the permeability, also increases the hysteretic constant, if it be originally very small.

The magnitude of the hysteretic constant is largely dependent upon the mechanical structure of the iron. To attain the smallest value the iron should not be of homogeneous structure, but should be more compact in directions perpendicular to the direction of the flux than in transverse directions.

CHAPTER III.

ARMATURES.

28. Dynamos. — Dynamos may be defined as machines to convert mechanical energy into electrical energy by means of the principle of electromagnetic induction. In all commercial machines the mechanical energy is supplied in the form of rotation, and the electrical energy is delivered either as "direct current" or "alternating current." These machines are also frequently called *generators.*

29. Principle of the Action of a Dynamo. — If a loop of wire be revolved in a magnetic field about an axis perpendicular to the lines of force, as in Fig. 12, then each side (but not the ends) of the loop is a conductor moving across the lines of a magnetic field, and as such will have an *E.M.F.* induced in it. Since the motion of one conductor is up while that of the other is down, the directions of the induced *E.M.F.*'s in the two sides will be opposite to each other, and since they are on opposite sides of a loop, the pressure will be cumulative; i. e., instead of neutralizing each other, the two pressures will be added to each other. If now the two ends of the wire from which the loop is made be respectively connected with *slip rings*, and a circuit be completed through contacts sliding on them, a current will flow. When the loop, in its revolution, reaches a position (as illustrated in Fig. 12) such that the conductor that was previously moving upward begins to move downward, then the direction of the induced *E.M.F.* will be changed in both sides of the loop, and the direction of the current through the circuit will be changed. For each complete revolution the current changes direction twice. It is an *alternating current,* and the supposed machine is an *alternating current dynamo,* or simply an *alternator.*

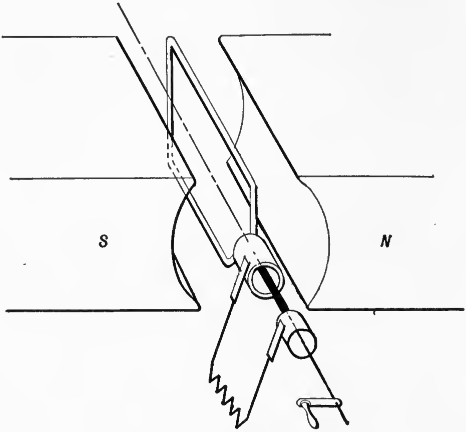

Fig. 12.

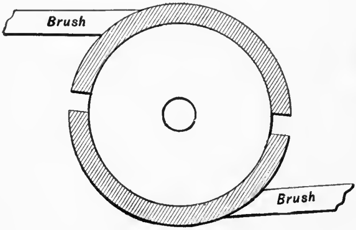

Fig. 13.

30. The Principle of the Commutator. — A commutator is used on the shaft of a machine when it is desired to get a direct or *rectified* current. For the single loop in the above case, the commutator (Fig. 13) would consist of two similar cylindrical parts of metal, insulated from each other, and affording sliding contact for two brushes. One end of the wire of the loop is attached to one piece of the commutator, and the other to the other.

The brushes are so placed that at the instant the induced *E.M.F.* in the loop changes its direction, the brushes slide across from one *segment* of the commutator to the other, and thus the current, while reversed in the loop, is left flowing in the same direction in the outside circuit. If the loop were wound double before the ends were attached to the commutator segments, and if the speed of revolution and the strength of the magnetic field were both maintained constant, twice the *E.M.F.* would be produced, but no more commutator segments would be necessary (Fig. 14).

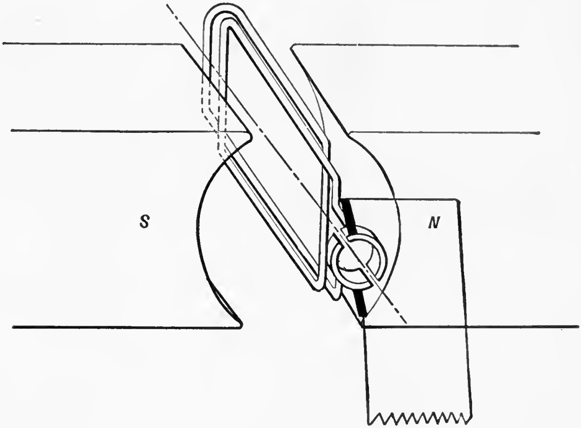

Fig. 14.

In the above cases at the instants of commutation there would be no *E.M.F.* produced, and hence the current would fall to zero twice every revolution. If two coils were placed 90° apart, one or the other would always be cutting lines of force. Hence at no time could the pressure be zero.

To satisfactorily collect current from this arrangement requires four commutator segments and a system of connections similar to that shown in Fig. 15. In this case the *E.M.F.* would fluctuate, but not so badly as in the previous case. If we increase the number of loops, and correspondingly increase the number of commutator segments, we decrease the fluctuation of the *E.M.F.* until it becomes practically constant. In a bipolar machine with 12 commutator segments the fluctuation is 1.7 per cent of the total *E.M.F.*

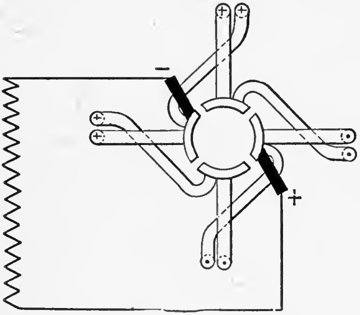

Fig. 15.

31. The Armature. — In a dynamo, the loops of wire in which *E.M.F.* is induced by movement in a magnetic field, together with the iron core that sustains them, with the necessary insulation, and with the parts connected immediately thereto, constitute the *armature* of a dynamo. The conductors in which the *E.M.F.* is generated are called the *inductors*. An armature in which both sides of the loop of wire cut lines of force, as in the cases just described, is called a *Drum Armature*. A kind of armature less generally used is the *Ring Armature*, illustrated diagrammatically in Fig. 16. Here

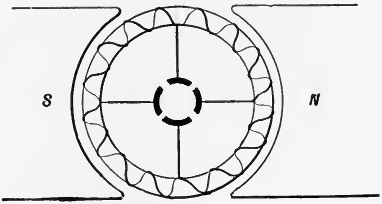

Fig. 16.

the lines of force emanating from the N. pole of the field magnets flow through the iron core of the ring, and very few across the air space inside the ring. Hence when wires are wound on the ring, and the whole is revolved about an axis perpendicular to the plane of the ring, only the wires on the outside face of the ring cut lines of force, those on the inside serving only to complete the electrical circuit. So a smaller portion of the wire on a ring armature is in action than on a drum armature.

A drum armature of large diameter and of short length in the axial direction has more wire exposed on its ends than on its periphery. The pole pieces are sometimes placed at the ends, and the armature is then called a *Disk Armature.* This type is seldom used in this country.

32. The Field Magnets. — Almost all dynamos have their magnetic fields produced by electro-magnets. These are called the field magnets. In small machines these are usually bipolar, i.e., having one N. and one S. pole, with

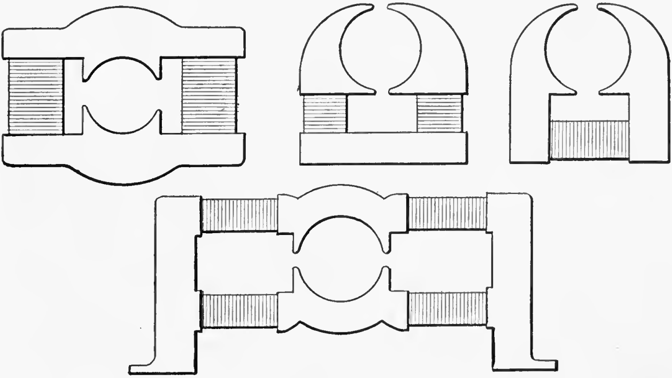

Fig. 17.

the armature revolving between. In large machines it is usual to use multipolar field magnets, in which any even number of poles alternately N. and S. are arranged in a circle with their faces concentric with the armature.

Bipolar machines are made in many forms, a few of which are shown in Fig. 17.

The magnetizing coils may be on both legs of the magnet, on one leg, or on the *yoke* which connects the two legs. In the double horse-shoe type there are four windings, one on each of the four legs. Such a field is sometimes said to be of the *consequent pole* type.

33. Capacity of a Dynamo. — By § 13, in a bipolar machine the average pressure between brushes equals the product of the number of lines cut into the number of inductors cutting them, divided by the time in seconds of one revolution. Since each line is cut twice in one revolution by each conductor, the formula for the *E.M.F.* produced by the machine is

$$E = \frac{V}{60}\frac{\phi S}{10^8}$$

where V is the number of revolutions per minute, ϕ the total flux through the loops, and S the number of inductors. In drum armatures $S =$ twice the number of loops; in ring armatures $S =$ the number of loops.

The capacity of a machine is measured by the watts it can send out, hence the capacity varies as EI. It is seen from the foregoing formula that the E of any machine may be increased by increasing either V, ϕ, or S.

The value of V is limited, (1) by considerations of mechanical safety and economy, and (2) by the desirability, in the case of a dynamo, of directly connecting it to the steam engine or other prime mover, and in the case of a motor the connection of it to the machine it operates. The speed of small machines is greater than that of larger ones; but the peripheral velocity, that is, the velocity of a point on the exterior of the armature, for all sizes, lies between 25 and 100 feet per second on belt-driven machines, and between 25 and 50 feet per second on direct connected machines. On large (say 2,000 K.W.) multipolar machines, having great diameter of armature, these values are often exceeded.

The value of ϕ depends upon the size of the machine, and the permeability of the metal of its frame. To get a large and economical $\mathcal{B}$ the metal parts of the field magnets are designed to have a very low magnetic reluctance. The air-gap between the pole pieces and the armature, and the space occupied by the revolving inductors, are each made small. The armature inductors are wound upon an iron core of low magnetic reluctance. These cores are frequently slotted and the windings laid in the slots. Besides reducing, to a certain extent, the magnetic reluctance by this construction, a good mechanical means is furnished for driving and protecting the inductors. Wires wound on the exterior of a plain cylinder, or *smooth core*, under the influence of high speeds and the "magnetic drag" which they experience have a serious tendency to rub one another, and chafe the insulation to its final destruction. The armatures having slotted cores, which are also called *toothed core armatures*, are to be recommended for generators that will be obliged to work under wide variations of load. They cost more to build than smooth-core armatures.

The numbers of inductors S on an armature can be increased by decreasing the size of the wire. Sufficient cross-section must, however, be left in the inductors to carry the maximum current of the machine without causing a heating of the armature to such a point as to endanger the insulation. Good practice calls for from 400 to 800 circular mils cross-section of armature conductor per ampere. The smaller values are for intermittently acting machines — elevator motors for example. The larger values are for machines that run continuously, such as central-station generators.

34. Eddy or Foucault Currents in Armature Cores. — It is evident that an imaginary axial lamina of the iron core of an armature is a conductor moving in a field, and therefore has in it an induced *E.M.F.* Since this lamina in itself forms a closed circuit, currents, called *Foucault* or *eddy currents*, will flow in it, Fig. 18, and their energy will appear in the form of heat, which will produce an undue elevation of temperature of the armature. To avoid this the iron of the core is laminated at right angles to the axis of revolution, and the laminae are insulated from one

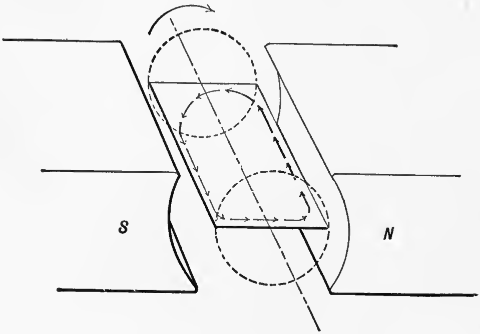

Fig. 18.

another. The heating due to eddy currents is proportional to the square of the thickness of the disks or laminae. Commercial and mechanical reasons limit the decrease of thickness. In good practice the thickness of armature disks varies from .01″ to .06.″

For insulation between the disks reliance is usually placed on the iron oxid that forms on them during their manufacture. Generally every six disks or so a further insulation is interposed by the use of shellac, japan, or paper. Milling slots in laminated armature cores after setting up causes burrs. These bridge the insulation between the disks, and militate against the advantages sought after by lamination. For small armatures the disks are punched whole from sheet-iron, with the teeth and holes for the shaft. These punchings are assembled on the shaft, and held in place by brass collars set down on either side of the pile by nuts on the shaft or by similar devices. In large machines, parts or segments of the whole periphery are punched separately, and these are assembled with joints staggered. These large laminae are not directly attached to the shaft, but are mounted upon a spider, which in turn is connected with the shaft. A complete spider and core is shown in Fig. 19.

In large armatures it is usual to make ducts or ventilating passages in the core by occasionally separating the disks by the interposition of blocks of insulating material. Such ventilation carries off the heat, and lessens the rise of temperature of the armature when in operation.

35. Rating of Machines.—The American Institute of Electrical Engineers recommends that all electrical and mechanical power be expressed, unless otherwise specified,

Fig. 19.

in kilowatts; that the full-load current of an electric generator be that current which, with the rated full-load voltage, gives the rated kilowatts; that all guaranties on heating, regulation, and sparking should apply to the rated load, except where expressly specified otherwise; that direct current generators should be able to stand an overload of 25 per cent for one-half hour without an increase of temperature elevation exceeding 15° C. above that specified for full load; and that direct current motors should, in addition, be able to stand an overload of 50 per cent for one minute.

Concerning the normal permissible elevation of temperature the following statements are taken from articles 25 to 31 of the Institute's Standardization Report: —

"Under regular service conditions, the temperature of electrical machinery should never be allowed to remain at a point at which permanent deterioration of its insulating material takes place.

"The rise of temperature should be referred to the standard conditions of a room temperature of 25° C., a barometric pressure of 760 mm. and normal conditions of ventilation; that is, the apparatus under test should neither be exposed to draught nor inclosed, except where expressly specified.

"If the room temperature during the test differs from 25° C., the observed rise of temperature should be corrected by $\frac{1}{2}$ per cent for each degree C. Thus, with a room temperature of 35° C., the observed rise of temperature has to be decreased by 5 per cent, and with a room temperature of 15° C., the observed rise of temperature has to the increased by 5 per cent. The thermometer indicating the room temperature should be screened from thermal radiation emitted by heated bodies, or from draughts of air. When it is impracticable to secure normal conditions of ventilation on account of an adjacent engine, or other sources of heat, the thermometer for measuring the air temperature should be placed so as fairly to indicate the temperature which the machine would have if it were idle, in order that the rise of temperature determined shall be that caused by the operation of the machine.

"The temperature should be measured after a run of sufficient duration to reach practical constancy. This is usually from 6 to 18 hours, according to the size and construction of the apparatus. It is permissible, however, to shorten the time of the test by running a lesser time on an overload in current and voltage, then reducing the load to normal, and maintaining it thus until the temperature has become constant.

"In apparatus intended for intermittent service, as railway motors, starting rheostats, etc., the rise of temperature should be measured after a shorter time, depending upon the nature of the service, and should be specified.

"In apparatus built for conditions of limited space, as railway motors, a higher rise of temperature must be allowed.

"In electrical conductors, the rise of temperature should be determined by their increase of resistance. For this purpose the resistance may be measured either by galvanometer test or by drop-of-potential method. A temperature coefficient of 0.4 per cent per degree C. may be assumed for copper. Temperature elevations measured in this way are usually in excess of temperature elevations measured by thermometers.

"It is recommended that the following maximum values of temperature elevation should not be exceeded:—

COMMUTATING MACHINES.

Field and armature by resistance, 50° C.
Commutator and brushes by thermometer, 55° C.
Bearings and other parts of machine, by thermometer, 40° C.

"Where a thermometer, applied to a coil or winding, indicates a higher temperature elevation than that shown by resistance measurement, the thermometer indication should be accepted. In using the thermometer, care should be taken so to protect its bulb as to prevent radiation from it, and, at the same time, not to interfere seriously with the normal radiation from the part to which it is applied.

"In the case of apparatus intended for intermittent service, the temperature elevation, which is attained at the end of the period corresponding to the term of full load, should not exceed 50° C. by resistance in electric circuits. In the case of railway, crane, and elevator motors, the conditions of service are necessarily so varied that no specific period corresponding to the full-load term can be stated."

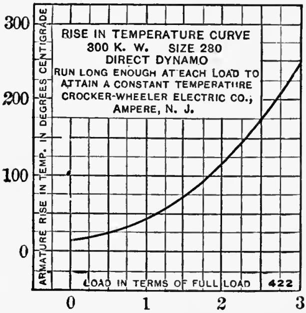

Fig. 20.

The manner in which temperature elevation is affected by size of load and duration of full load is shown in Figs. 20 and 21. The temperature of stationary surfaces rises about 80° when radiating one watt per square inch. The rise is but 15° to 20° when the

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surface is rotating at 3,000 feet per minute in such a manner as the surface of an armature rotates, and amounts

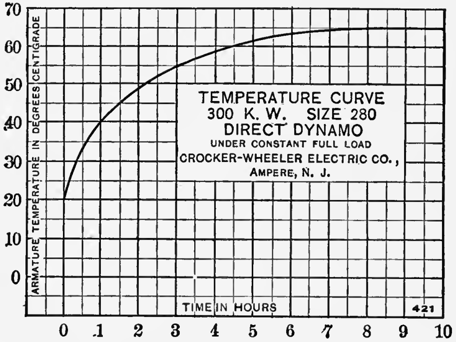

Fig. 21.

to but 10° to 12° at a speed of 6,500 feet per minute. Within limits, the ratio of rise of temperature to radiation per unit surface is linear.

36. Definitions Concerning Armature Windings. — In some dynamos the inductors and commutator segments are not all electrically connected with each other. In such cases the winding is called an *open-coil winding*. This definition must not be made to include the double or multiple windings to be described later, where two or more closed-coil windings on the same core are not electrically connected to one another. Fig. 22 shows a primitive open-coil winding. In this type only those inductors on whose commutator bars the brushes may for the moment be resting are in series with the external circuit. All the other inductors are cut out and idle.

Open-coil windings are used chiefly on arc-lighting dynamos, and will be further discussed in a following chapter devoted to such machines. *Closed-coil windings* are much more generally used. In this case all the inductors are engaged all the time, save when short circuited at commutation, in adding *E.M.F.* to the circuit. Although there are many kinds of closed-coil windings, they are all alike in that the inductors form one or more endless circuits completely around the armature core.

Before showing some of the many types of closed-coil winding it will be well to define some of the terms used.

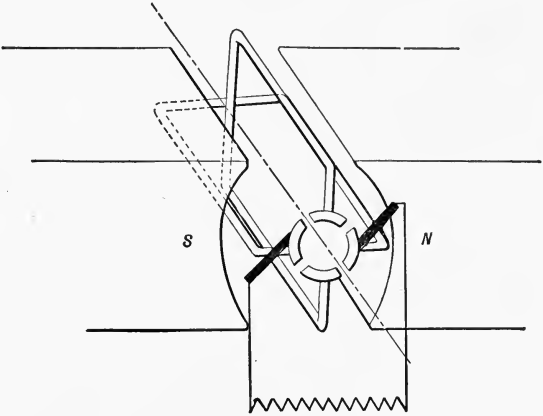

Fig. 22.

By *inductor* is meant that part of the winding conductor which lies on the face of the armature that sweeps past the pole pieces, and is that part of the conductor in which *E.M.F.* is induced. In the following descriptions when one inductor is mentioned there may be in reality a number of wires; and, again, a loop said to be formed by two inductors may be a loop of many turns, but the connections and placing would be the same as if actually there were only one inductor. It simplifies the diagrams to treat the subject in this manner.

That part of an armature winding which is electrically connected directly between two consecutive commutator segments is called a *coil.*

A *two-circuit* winding is one in which the current, on entering the armature at one brush, finds two paths by which it reaches the other brush. Since a closed-coil winding is endless, there must invariably be two paths when two brushes are used.

A *four-circuit* or *multi-circuit* winding is one in which the current finds four or more paths through the armature. There are at least two circuits for every pair of brushes used in collecting the current, unless the commutator bars are cross-connected, as in Fig. 25.

If a winding is so arranged that one commutator bar under a brush carries all the current from one side of the armature to that brush, then the winding is said to be *single.* If, however, the windings are so arranged that two or more bars convey this current to the brush at once, or if the current is commutated at two or more points on the contact surface of the brush, then the winding is said to be *double* or *multiple.* Triple and quadruple windings are not infrequent on machines which carry very heavy currents.

A *singly-re-entrant* winding is one in which, by successive angular advances, all the coils have been laid when an advance of 360° has been made. To be *doubly-re-entrant* wound the angular advance between successive coils, in the order of their winding, is doubled; and the whole winding is not complete until the armature has been gone around, angularly, twice, i.e., through an advance of 720°. On the second time around the coils fill up the interstices left by the doubled pitch of the first round. *Triply* and *quadruply re-entrant* windings are used. In these the circuit passes around the armature three or four times. Any closed-coil winding, single or multiple, may be singly or multiply re-entrant, the re-entrancy being reckoned as great as that of any single winding on the armature.

The two principal types of closed-coil armatures are the gramme or ring armature, and the drum.

37. Ring-Armature Windings. — As the name implies, the ring-armature core consists of an annular ring around which the armature conductors are wound in a continuous spiral, or two or more separate but interleaved spirals in multiple windings. These are tapped off at equal intervals to the commutator bars. In ring armatures there is but one inductor per loop of wire, the return being on the inside of the ring where there is no magnetic flux. This winding, though less generally used than the drum winding is simpler and much more easily illustrated, and will be treated first.

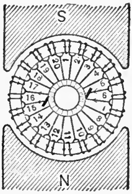

Fig. 23.

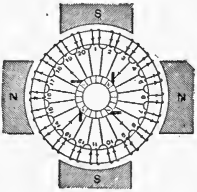

Fig. 24.

Fig. 23 shows the simplest of all dynamo armature windings. It is a bipolar, singly-re-entrant, two-circuit, single winding.

Fig. 24 shows a four-pole, four-circuit, singly-re-entrant, single winding. The number of coils should be a multiple of the number of poles to electrically preserve a balance in the four branches or circuits.

Fig. 25 is the same as Fig. 24 save that the commutator bars are cross-connected. The current that would flow out of two brushes in the previous case, now flows out of one brush. This form is seldom used, since it reduces by half the brush contact surface, and thus doubles the heat loss in the transition of the current from the commutator to the brush.

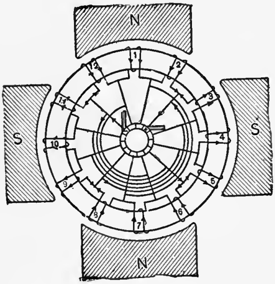

Fig. 25.

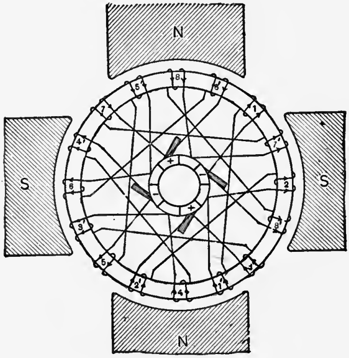

Fig. 26.

Fig. 26 shows a four-pole four-circuit singly-re-entrant, single winding, where only half as many bars are used as there are coils. A disadvantage is that coils of considerable difference of pressure are adjacent, thus increasing the difficulty of properly insulating them. Ordinarily, if it be desired to halve the number of bars, it is better to unite two adjacent coils in series, and treat them as one. But if the magnetic distribution be uniform, this method of connecting two coils that are in different parts of the field in series averages up the inequalities and facilitates sparkless commutation.

Fig. 27 shows a bipolar, two-circuit, singly-re-entrant, double winding. The advantages of the double winding are: the current is commutated at two points of the bearing-surface of the brush, and therefore is only half as heavy at any one point as when only a single winding is used; and the successive bars of one winding are separated by the width of one bar plus two insulations, thus making the short circuiting of a coil by dirt, arc, or injury very unlikely.

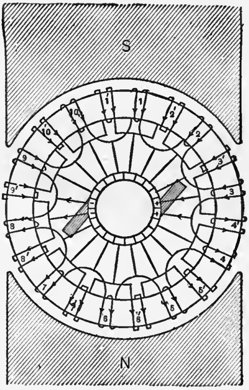

Fig. 27.

In multipolar windings a distinction is made between the "short-connection" and the "long-connection" types. In the *short-connection* type coils in adjacent fields are connected in series, while in the *long-connection* type coils twice as far apart are connected together.

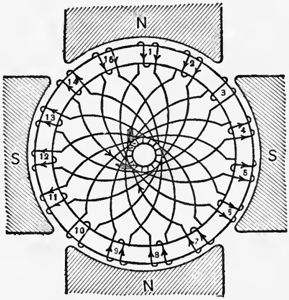

Fig. 28.

Fig. 28 shows a long-connection, two-circuit, four-pole single winding. Here only slight differences of potential exist between contiguous coils.

Fig. 29 represents a ten-pole, long-connection, two-circuit, single winding. In these long-connection types, which are all more or less highly re-entrant, small mention is made of the re-entrancy. Strictly according to definition, the winding in Fig. 29 is re-entrant nine times.

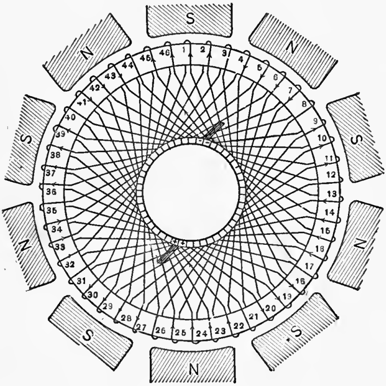

Fig. 29.

Fig. 30 is a four-pole, *short-connection*, two-circuit, single winding. Besides the complication of the windings, this form as well as all other short-connection windings, is open to the objection that the contiguous coils have, periodically, the full *E.M.F.* of the machine between them, making heavy insulation necessary.

Fig. 31 gives a four-pole, two-circuit double-wound

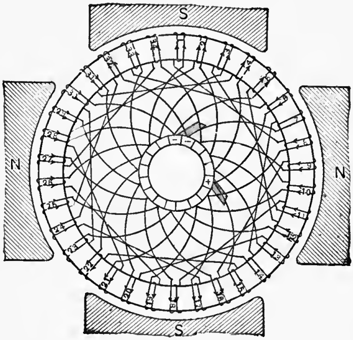

Fig. 30.

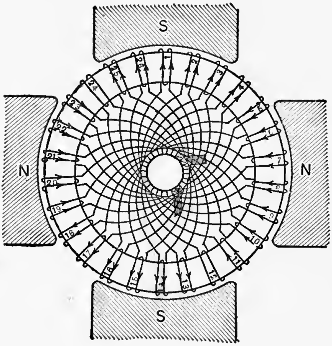

Fig. 31.

armature, and Fig. 32 gives a similar winding for a six-pole machine.

38. Drum Armature Windings. — Windings for drum armatures are more varied and more complex than those for ring armatures, and are much harder to portray diagrammatically. But few will be shown.

The most simple of these windings is shown in Fig. 33. The diagram shows the drum and inductors in section, with the connections of the commutator end in full lines and those of the back (pulley) end in dotted lines. Those inductors marked with a + are supposed to carry a current in the direction from the observer into the paper, and those with a point are supposed to carry a current from the page to the observer. Those not marked are parts of coils short-circuited by the brushes. This winding was devised by von Hefner-Alteneck, and may be used on any bipolar armature having half as many commutator bars as slots, or, if it be smooth core, as many bars as coils. If *n* be the number of bars and 2*n* the number of slots, then the wire is started at bar 1, passed back through slot 1, across the pulley end to slot *n* (or sometimes *n* ± 2, in the

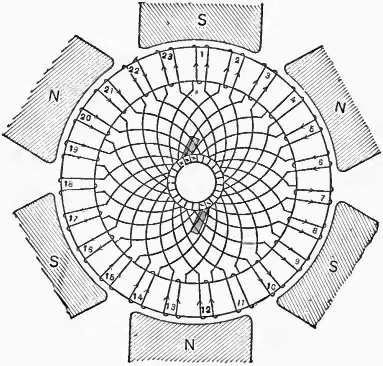

Fig. 32.

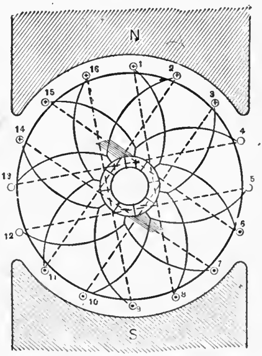

Fig. 33.

figure $n = 8$). It is then brought forward through slot n, and attached to bar 2. From bar 2 it passes back through slot 3, across the back end and forward through slot $n + 2$ and connects to bar 3. Thus passing back through the odd-numbered slots and forward through the even-numbered slots, n coils can be made to fill the $2n$ slots and each can be attached to its own commutator bars.

Fig. 34 is very similar to the last, save that the wires are laid two layers deep, thus allowing the conductor that passed through slot 1 to return through slot $n + 1$ which is diametrically opposite. Both this winding and the last are classed as two-circuit single windings.

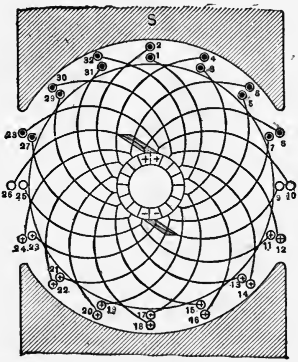

Fig. 34.

In a bipolar machine a *chord-wound* drum armature is one in which the two inductors of one loop are appreciably less than 180° apart, so that the wire at the back end is a chord rather than a diameter of the circle of the drum. The advantages of this winding are that, on a given drum, it decreases the total length of wire necessary to give a definite number of inductors, and that it reduces the bunching and overlapping of the wires at the pulley end of the drum. The disadvantage is that it is impossible to secure a perfectly electrically balanced winding by this method. This objection does not hold in the case of multipolar generators, hence all multipolar drums are chord wound.

In the following figures the numbered radial lines will represent armature inductors, the lines inside of them will represent their connections to the commutator segments, and the lines outside of them will represent the cross connections between inductors at the pulley end. The brushes are placed inside the commutator for convenience and clearness.

Fig. 35 represents a six-circuit, single winding with 80 inductors and 40 segments. In practice the inductors, instead of all lying beside each other, would probably be wound one on top of another in one slot.

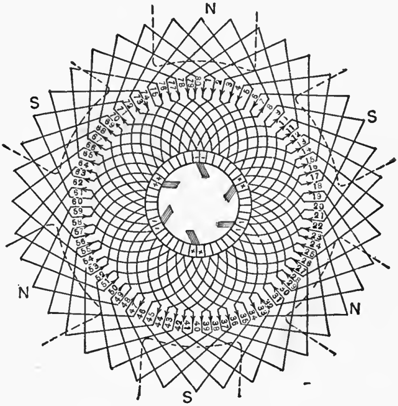

Fig. 35.

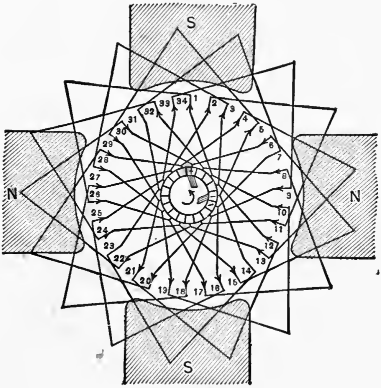

Fig. 36.

Fig. 36 shows a rather simple single winding. Although it is four pole it is but two circuit, in which it resembles Fig. 37, which is, however, a triple winding.

Fig. 38 gives a six-pole, two circuit, double winding.

In winding armatures, double or triple cotton insulated copper wire is generally used. Care must be taken to well insulate the wires, both from each other and from the core.

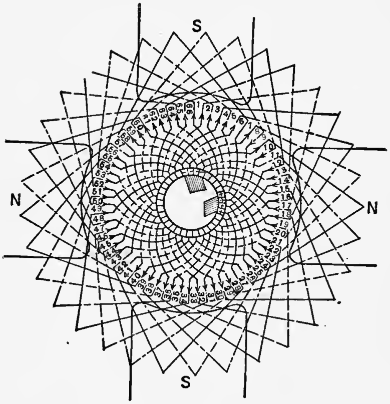

Fig. 37.

Many of these styles of winding create very complex masses of wire on the ends of the drum, and great care must be exercised both in regard to insulating and fastening at these points, so that the movement of the wires under the influence of the "magnetic drag" may not chafe the insulation and short-circuit the conductors. Mica is the best insulator, and is used where flat sheets are needed; but its great cost, and the difficulty of manipulating it, result in the extensive use of canvas, oiled paper, rubber tape, vulcanized fiber, and many patented manufactured insulators. Much reliance is placed upon the liberal use of japan and shellac, especially in conjunction with canvas.

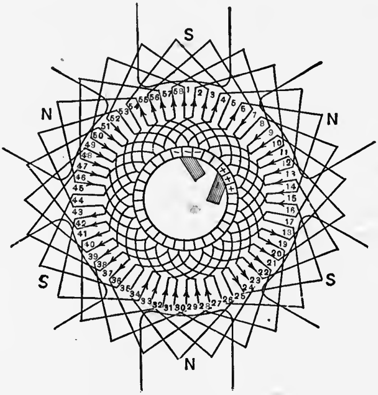

Fig. 38.

Where very large wires are used on the surface of an armature, eddy currents are set up in them by reason of one side of the wire being in a stronger field than the other. To avoid this a number of smaller insulated wires are wound in parallel, to take the place of the larger one, or what is more economical of space, thin copper bars set edgewise take the place of the round wire.

In the winding of multipolar armatures it is possible to use *formed coils*, which are wound on a separate collapsible forming block, and are afterward applied to the core. This method is advantageous in that better insulation can be assured, and damaged or burned-out coils can be replaced without disturbing all of the windings. Fig. 39 shows a General Electric Company's formed coil, and Fig. 40 some of the Crocker Wheeler coils.

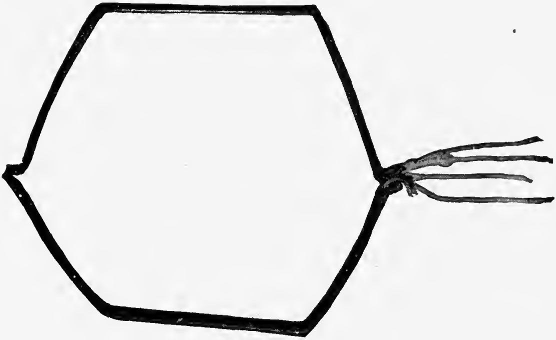

Fig. 39.

All armatures, whether wound with wire, or formed coils, or shaped conductors, must be banded around to prevent dislodgement of the conductors under influence of centrifugal action. The wire used for this purpose is generally of hard-drawn brass or of phospher bronze, and on railway motors of steel. It is wound over insulating strips forming a band of several turns. The completed turns are often sweated together with solder.

Many manufacturers punch a small recess in each side of the teeth near the face. A strip of maple wood is fitted

Fig. 40.

Fig. 41.

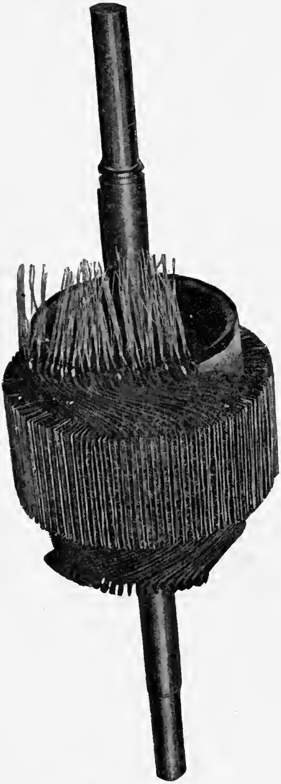

Fig. 42.

into the recesses, and acts like a cover to the slot, firmly holding the windings in place, and presenting a neat appearance.

Figs. 41, 42, 43 show respectively a core, a partially wound, and a completed General Electric Company's armature. Figs. 44 and 45 show small Westinghouse types.

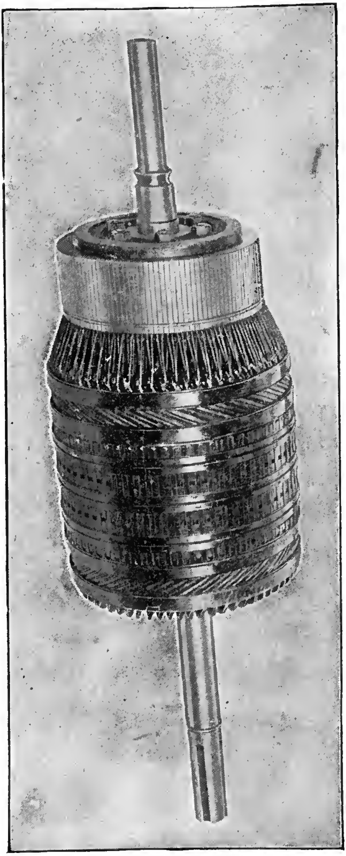

Fig. 43.

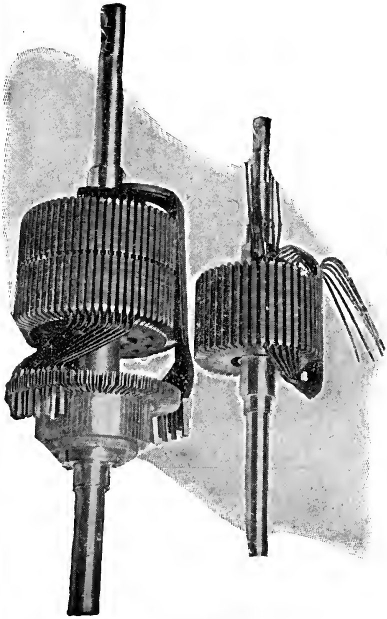

Fig. 44.

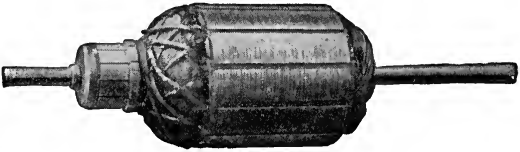

Fig. 45.

39. Commutators. — The segments or bars of a commutator are always of drop-forged, or hard-drawn copper. The insulation between them is always of mica. There are various grades of mica; and for insulating purposes the amber-colored mica, which must be free from iron, is to be preferred. Besides being a good insulator, amber mica has the additional advantage that it wears at the same rate as copper; thus after long use it leaves neither elevations nor depressions on the commutator surface.

In fastening the bars considerable ingenuity is displayed; for they must not displace themselves with reference to the windings, neither must one bar lift so as to be above the level of its neighbors. If the latter occurs, then, when the bar comes under a brush, it will lift it; and as the high spot moves out from under the brush the contact is broken until the spring can reseat the brush. This causes excessive wear and destructive sparking.

After a commutator has been for a time in use, it becomes grooved and pitted, a condition which causes further sparking and wear, and the commutator must be turned down again to a true surface. The design of a commutator should allow of good operation after it has been subjected to this treatment.

Mechanical friction and the electrical losses that accompany commutation will raise the temperature of the commutator about 5° C. above that of the armature. To secure successful operation a commutator must be designed with a sufficient number of bars, so that the difference of potential between two adjacent bars shall not exceed 10 volts. This would mean that a 100-volt bipolar machine should have at least 20 bars. The potential between the brushes or around *half* the commutator is 100 volts, hence half the commutator must have 10 bars. There is no general rule for the length of a commutator bar, but one may roughly say that there should be at least one inch per 100 amperes.

Commutators should be designed so as to expose a sufficient area to radiate the heat which is communicated to them. Except in the case of some special commutators, which are supplied with cooling devices, at a peripheral speed of 2,500 feet per minute, the radiation of one watt per square inch of peripheral radiating surface will result in a rise of temperature of 20° C. The permissible rise of 55° C., therefore, allows a radiation of 2.75 watts per square inch. The heat to be radiated is due to the following causes: —

a. Friction between the brushes and the commutator bars. This is equal to $\left(\frac{2 \times \pi \times 746}{33{,}000}\right)$ times the product of the following quantities: The radius of the commutator in feet, the speed in revolutions per minute, the coefficient of friction between the brushes and the commutator (0.3 for carbon brushes and 0.25 for copper brushes), and the sum of the pressures of all the brushes upon the commutator. This latter should amount to 1.25 lbs. per square inch of rubbing surface. Copper brushes permit 200 amperes per square inch of rubbing surface, and carbon brushes 40 amperes.

b. The contact resistance between the brushes and the commutator. As there is always a drop of about one volt at each point of contact, and as there is a drop at both the positive and negative terminals, the watts represented by these contact resistances are numerically equal to twice the current of the machine.

c. The energy represented in the sparking at the brushes and the heat due to waste currents in the short-circuited segments. These two losses cannot be accurately calculated, but may be estimated as equal to about 6 per cent of the total commutator loss.

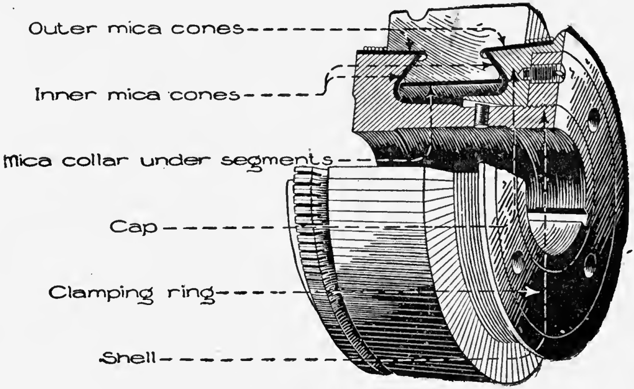

Fig. 46.

Fig. 46 gives a broken-away view of a General Electric commutator, showing the methods of attachment and insulation.

40. Collecting Devices. — These consist of the *brushes*, the *brush holders*, and the *rockers*.

Brushes for high potential machines are of carbon. Carbon against copper causes less wear than copper against copper, and further, the greater resistance of a carbon brush results in less sparking when it bridges two commutator bars than would the lower resistance of a copper brush. Combination brushes of carbon and copper are sometimes used. Carbon brushes are set at an angle generally, though some makers set them radially; and in motors that must be reversed, as is the case with railroad and elevator motors, they are invariably set radially. A surface contact of one square inch per 40 amperes is usual for carbon brushes.

On low-potential machines copper brushes, set at an angle of 45° with the tangent to the commutator surface at the point of contact, are invariably used. This is because there is less natural tendency to spark on low voltages, and because the resistance of carbon brushes would be too great a fraction of the whole resistance of the circuit, and cause a wasteful drop of potential. Copper brushes must have their ends filed to give sufficient surface contact, and this is generally done with the aid of a *jig*, illustrated in Fig. 47. The abrasion of carbon brushes is accomplished by means of glasspaper.

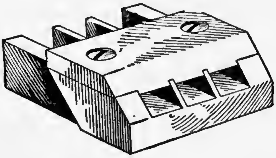

Fig. 47.

Brush holders should permit of a low-resistance contact between the brush and the leads, they should provide adjustment as to position and tension of the brushes, and they should be arranged so that none of the springs shall get hot and lose temper while in performance of its duties. The tension on carbon brushes varies from 1 to 10 lbs. per square inch of contact surface. The lower limit is to be found in large central station generators, and the higher limit in small machines and in motors which are subjected to frequent and sudden strains, as railway motors. The coefficient of friction between brush carbon and copper varies from 0.28 to 0.32.

Figs. 48 and 49 plainly show a Crocker Wheeler rigging with parallel-motion brush holders. Fig. 50 shows a form of General Electric holder.

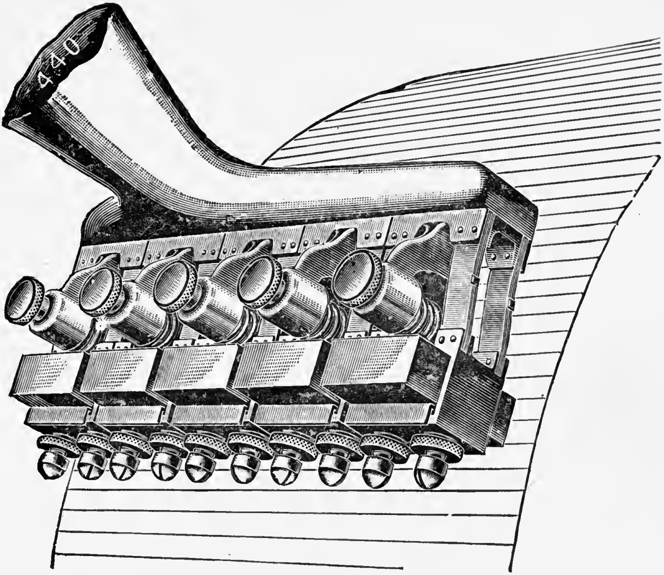
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Fig. 48.

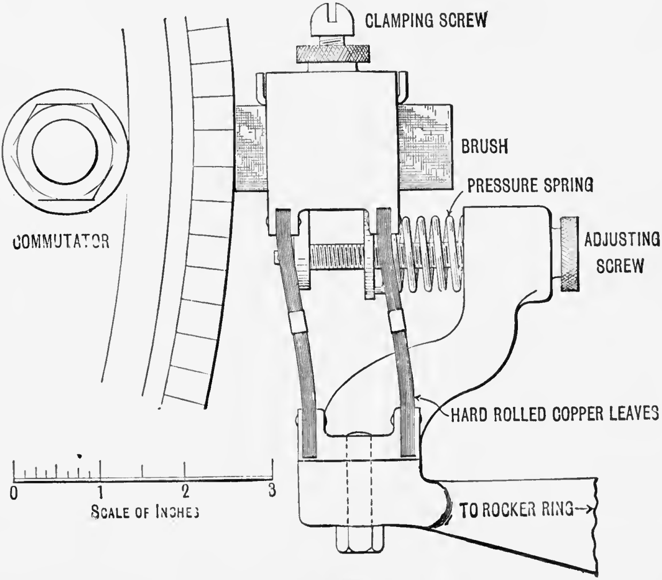

CLAMPING SCREW
BRUSH
PRESSURE SPRING
ADJUSTING SCREW
COMMUTATOR
HARD ROLLED COPPER LEAVES
TO ROCKER RING
0
1
2
3
SCALE OF INCHES

Fig. 49.

Rockers are rings or attachments carrying the brush holders, and they are mounted concentric with the commutator. They are made to give all the brushes of the machine, or sometimes all the positive brushes or all the negative brushes at once, a motion around the axis, thus adjusting all brushes by one movement. Fig. 51 shows such a rocker.

41. Shafts, Bearings, and Oilers. — Since armature shafts generally have high speeds, and almost always are subject to sudden large variations of load, the shafts, the bearings, and the oiling facilities must be well designed. Wiener gives the following approximate diameters of steel shafts for drum armatures: —

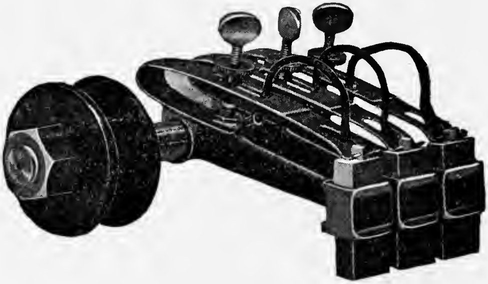


Fig. 50.

For 100 watts	$\frac{3}{8}$ inch,
For 1,000 watts	2 inches,
For 10,000 watts	$4\frac{3}{4}$ inches,

all to be turned down at the bearings.

It is necessary that the bearing-boxes be exactly in line, and a form of self-alignment bearing is frequently used. If undue wear in the bearings occur, the armature is apt to sag till it strikes a pole piece, which will damage the armature. Many machines use ordinary oil cups to secure lubrication, while others make use of some device, as is shown in Fig. 52. The shaft revolves in a cylindrical brass with a spherical enlargement at its middle which rests upon

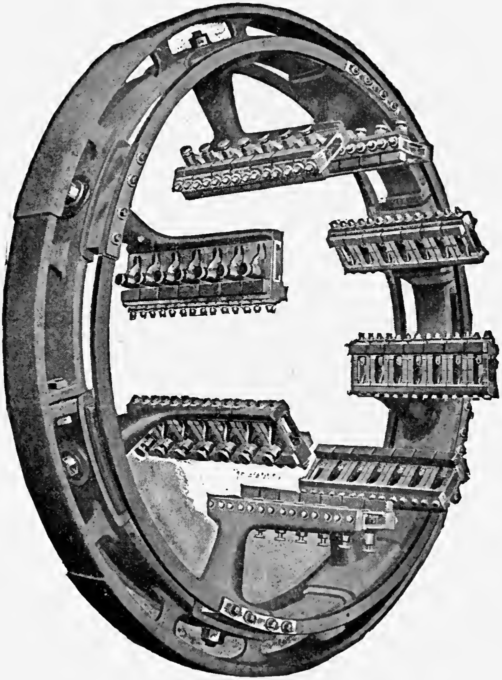


Fig. 51.

a corresponding spherical bed of Babbit metal. This secures self-alignment. Two slots are cut radially in the brass, and allow two rings to rest upon the shaft. These rings are also of brass, and have an inside diameter slightly larger than the outside diameter of the brass cylinder.

The pillow block is hollowed away under these rings, the hollows serving as receptacles for the storage of oil. As the shaft revolves, the rings also revolve at such a rate as to carry a steady stream of oil up into the slots, thereby lubricating the bearing.

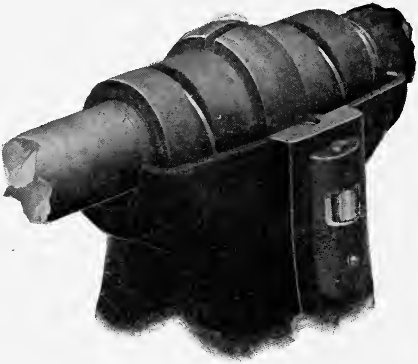


Fig. 52.

CHAPTER IV.

FIELD MAGNETS.

42. **Parts of Field Magnets.** — The parts of a dynamo, exclusive of the armature, which make up the magnetic circuit, belong to the field magnets. Fig. 53 shows a conventional bipolar horse-shoe type with the parts plainly marked. The *field cores* are the iron centers in the *magnetizing* coils. The *yoke* connects the cores together at one end while the other ends terminate in the *pole pieces*, one being a north magnetic pole, the other a south. The side of the pole piece embracing the armature is styled the *pole face*, and the latter's projecting edges are fittingly called the horns. Some dynamos have the magnetizing coils on the *yoke*, thus making the latter serve also as core. In different types different numbers of pieces prevail, thus all the parts (save the coils) might be cast in one piece or each might be made separately.

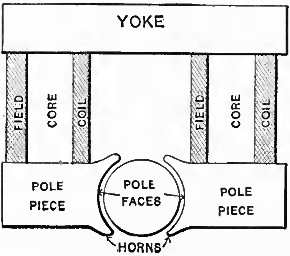


Fig. 53.

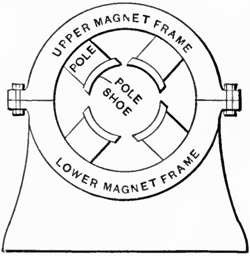


Fig. 54.

In multipolar machines the designation of the parts is somewhat different than in the case of bipolar machines. The particular designation often depends upon the manufacturer. Fig. 54 gives the designation used by the Crocker Wheeler Company.

43. Magnetic Material. — The materials used for field magnetic circuits are three, — cast iron, wrought iron, and cast steel. The selection of material for a given machine is governed by considerations of (*a*) weight, (*b*) first cost, (*c*) economy and satisfactory regulation when in operation.

Cast iron has the great advantage of cheapness; but it is poor magnetically, hence more weight and bulk must be employed to perform the same service as the magnetically superior wrought iron. It costs more in copper to magnetize a cast-iron core, because more turns will be required, and each turn will be longer than if the core were of better material.

Wrought iron is the best magnetic material available. It is used either in forgings, or in the form of plates punched from the sheet. In either form it is expensive; but since less weight in a given machine is necessitated when this metal is used, it is often chosen where portability is required, as in the case of the marine dynamos, electric railroad motors, and particularly motors for automobiles.

Cast steel is intermediate between cast iron and wrought iron, both in cost and in magnetic properties, and is much employed in good practice. The use of different metals in different parts of the frame is very general. For instance, a cast-iron yoke is used with cast-steel cores and pole pieces, or a cast-iron or steel yoke is used with wrought-iron cores and pole pieces.

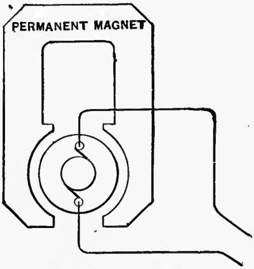
44. Shape of Field Magnets. — There is a great variety of shapes of field magnets. Formerly each manufacturer had a type peculiarly his own, and this led to many forms, some of little merit. These freak types are now disappearing, and a few general types are adopted more or less by all makers. In all forms, however, the *polar span*, or part of the armature circle that is covered by pole faces, is from 65 per cent to 75 per cent, or from 234° to 270°. In general a small number of poles in the field magnets requires less copper in the exciting coil than does a larger number, and also the fields can be excited more economically. But in large bipolar machines successful operation under varying loads requires a large *air gap* between the pole face and the armature. This increases the magnetic reluctance and the energy necessary for excitation. Multipolar machines do not require so large an air gap. Furthermore, increasing the number of poles gives the mechanical advantage of allowing a lower armature speed without lowering the potential of the output. Multipolar machines will run cooler than bipolars of the same economy of operation.

Speaking generally, though it is by no means a rule, bipolar fields are used up to about 10 K.W., four-pole fields from 10 K.W. to 100 K.W., six-pole fields from 100 K.W. to 300 K.W., and beyond that point eight or more poles are generally used.

45. Methods of Excitation of Fields. — Dynamos are classified according to the five methods of exciting the fields of the machine. They are: — the *Magneto*, the *Separately Excited*, the *Shunt Wound*, the *Series Wound*, and the *Compound Wound*.

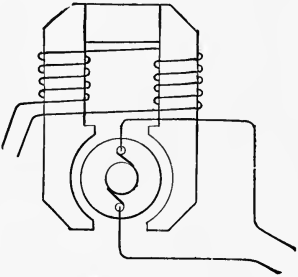
The magneto generator, Fig. 55, is one in which the field is a permanent steel magnet, generally of horse-shoe type.

The separately excited dynamo, Fig. 56, has, as its name implies, its field coils traversed by a current other than that produced by the machine. Alternating current machines are nearly always of this type.



MAGNETO DYNAMO

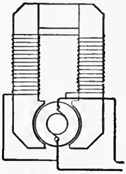
Fig. 55.



SEPARATELY EXCITED DYNAMO

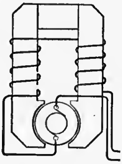
Fig. 56.

The shunt-wound machine, Fig. 57, has a large number of turns of fine wire wound on its core, and the ends are connected to the terminals of the machine, thus being in *shunt* with the outside circuit. The ampere turns requisite for excitation are obtained by passing a small number of amperes through a large number of turns.



SHUNT WOUND DYNAMO

Fig. 57.

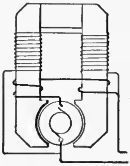


SERIES WOUND DYNAMO

Fig. 58.

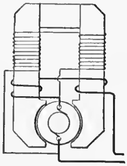
The series-wound generator, Fig. 58, has all the current that is produced by the armature passed through large conductors wound with fewer turns around the cores. The exciting coils are then in *series* with the external circuit. The ampere turns required for excitation are obtained by passing a large current through a small number of turns.

The compound machine, Fig. 59, is one in which there are both shunt and series coils on the field magnets. This method of winding is used for purposes of regulation under varying loads, as will be explained later. Compound windings are of two classes, the *long shunt* and the *short shunt*. In the former, the current used in the shunt windings is also passed through the series windings along with the main current. In the latter, the current from the shunt coils passes directly back to the armature, avoiding the series turns. Figs. 59 and 60 clearly show the two methods. The short shunt is generally preferred.



COMPOUND WOUND
DYNAMO LONG SHUNT

Fig. 59.



COMPOUND WOUND
DYNAMO SHORT SHUNT

Fig. 60.

46. Field Coils. — The coils of a dynamo must, without undue elevation of temperature, supply sufficient ampere turns to give the required excitation. This temperature rise will not be excessive when about 0.35 watt is radiated per square inch of outer surface of the coil. If no account be taken of the ends of the pole and coil, 0.6 watt may be allowed per square inch. The field coils have no ventilation due to their own motion as have armatures, hence about 1000 circular mils per ampere must be allowed in the wire which composes such coils. The cost of copper is needlessly increased, if more than the necessary cross-section be allowed.

Fig. 61.

Field coils are usually wound on brass or iron spools, shaped to slip over the cores. Sometimes, especially in the case of small machines, the coils are wound on frames, which can be collapsed and removed. The coils of series machines and the series coils of compound machines are often wound with copper ribbon instead of wire, or are even made up of forged copper conductors, having a rectangular cross-section. This is because the heavy currents require such large cross-section of conductor that if made of wire much space would be lost between the wires. The rear coil in Fig. 61 is a series coil of shaped conductors. This figure shows both the shunt and the series coil, as wound by the Westinghouse Company, for a compound multipolar railway generator. The binding which is seen on the shunt coils in both illustrations should not be mistaken for the wires of these coils. Field coils are wound with double cotton-covered copper wire. Further insulation between coil and core, and between series and shunt coils, is effected by the use of fiber, fuller board, and mica.

47. Magnetic Leakage. — Since air is not an insulator of magnetism, but is simply much less permeable than iron, it is evident that some of the lines of force generated by the field coils will not follow around the desired path through pole pieces and armature, but will take a path through the air and be of no utility in creating *E.M.F.* in the revolving armature. Fig. 62 roughly represents some of the paths such lines may take.

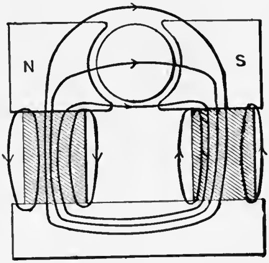


Fig. 62.

If ϕ_t be the total flux caused by the field coils and ϕ_a be the flux that passes through the armature, then the coefficient of magnetic leakage,

$$\lambda = \frac{\phi_t}{\phi_a},$$

and is always greater than unity.

In practice λ varies from 1.25 to 1.4 in single horse-shoe fields, and in the Edison type of inverted horse-shoe and in double horse-shoe fields it varies from 1.5 to 1.75. In multipolar machines λ varies from 1.1 to 1.5.

To find the coefficient of magnetic leakage of small or moderate sized machines proceed as follows: —

Arrange the field-coils for separate excitation by a current that can be conveniently commutated. Suppose the machine to have a field of the double horse-shoe type, as in Fig. 63. Take a few turns of fine insulated wire about the middle of one coil, as *c*, *d*, and connect the ends to a ballistic galvanometer of low sensibility. A low-reading Weston voltmeter will answer. Suddenly commutate the current in the field coils. The change in direction of the flux in the core, from $+ \phi$ to $- \phi$, will induce *E.M.F.* in the test coil, which will give a throw to the voltmeter needle. The deflection is directly proportional to the flux in the core. Repeat with the other coil, and the sum of the deflections obtained from *cd* and *ef* is directly proportional to the total flux produced ϕ_t. Now make a test coil of the same number of turns and of the same resistance about the armature, in such a position *ab* that it includes the area

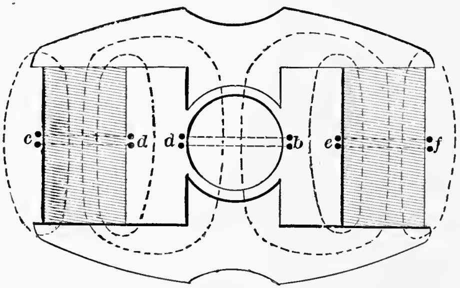


Fig. 63.

of the armature that is cut by the greatest number of lines of force. Upon commutating the current a throw of the needle will result, which is proportional to the flux in the armature ϕ_a. Hence the coefficient of magnetic leakage,

$$\lambda = \frac{\phi_t}{\phi_a} = \frac{\text{defl. at } cd + \text{defl. at } ef}{\text{deflection at armature}}.$$

The exciting current must remain constant during the investigation.

The location of the different leakage paths may be found by using test coils on different parts of the frame. The difference between the throws observed at any two places is a measure of the leakage between those two places.

Clearly the number of lines choosing paths through the air will decrease as the permeability of the iron circuit increases. An increase in the reluctance of the main magnetic circuit will increase the leakage loss.

Armature cores vary in permeability under varying conditions of load. As the load increases, this change produces an increase in the reluctance of the main magnetic circuit. This results in an increase of the loss by leakage. The coefficient of magnetic leakage is, therefore, different with different loads.

48. Pole Pieces and Shoes. — In general practice the field cores and the frame of a generator are worked at a flux density of at least 15,000 lines per sq. cm.

This is too high a value to use in the air gap. Therefore pole shoes are put on the ends of the pole pieces to distribute this flux over a wider area where it has to pass through the air, and to thus decrease the total reluctance of the magnetic circuit.

49. Effect of Joints in the Magnetic Circuit. — Since no two pieces of metal can be put together with a perfect joint, there is always an increase of reluctance in a magnetic circuit when a joint is introduced therein. Professor Ewing found by experiment that at low magnetizations ($\mathcal{H} = 7.5$) the increase of reluctance of a certain bar of iron due to a joint was above 20 per cent, and that for high magnetizations ($\mathcal{H} = 70$) the loss due to one joint was less than 5 per cent. The difference is probably due to the fact that the pieces under strong magnetizations attract themselves so powerfully as to make a more perfect joint. Ewing also found that a single cut in a bar acted upon the reluctance of the bar as though the length of the bar had been increased by amounts given in the following table: —

For $\mathcal{H} =$	7.5	15	30	50	70
Equivalent length of 1 cut in cms. of iron . . .	4	2.53	1.10	0.43	0.22

CHAPTER V.

OPERATION OF ARMATURES

50. Process of Commutation.—The simple process of commutation as described in § 30 is attended with some difficulties in practice. Consider one coil of a plain ring armature with the commutator bars attached thereto as in Fig. 64. In position *A*, when the brush is on only one of the bars in question, the action of the other coils of the armature will be to force current in this one coil in the direction indicated by the arrow. *B* is considered to be the positive brush. In position *D*, when the brush has passed over to the other bar entirely, the direction of the current in this coil is in the other direction. Now this change of direction must occur when the coil is in a weak field, for it is observed that the coil is short circuited while in position *C*, the circuit being completed through the coil, the bars and the brush spanning the mica insulation at o. If now at this moment the coil should be in a strong field, and should be cutting many lines of force, too large an

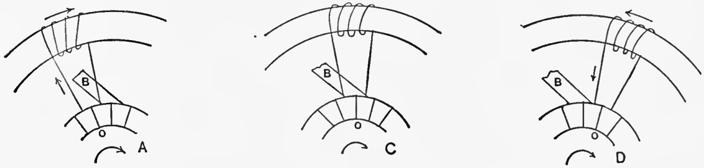


Fig. 64.

E.M.F. would be produced, and as the resistance of the circuit indicated is very low, an excessively strong current might flow. When the brush slips past o the circuit is broken, and a more or less serious sparking occurs according to the strength of the current flowing at the instant of break. Commutation must then be effected when the coil is in such a position as not to cut many lines of force. It follows that every commutating machine must have at least two places where the effective field has a zero value. Fig. 65 gives a rectified curve of the magnetic distribution under the pole pieces and around the armature of a well-designed bipolar machine, the ordinates of the curve giving the flux density in the air gap.

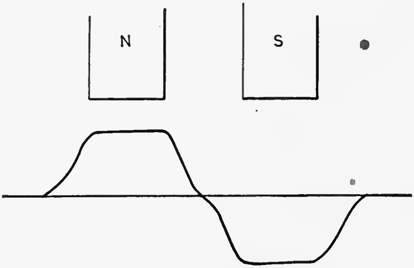


Fig. 65.

The *neutral plane* is a plane passed through the axis of the armature and a point in the field immediately surrounding the armature, where the inductively effective component has a zero value. The coil in position *C*, Fig. 64 is supposed to be in the neutral plane.

The *commutating plane* is a plane passed through the axis of the armature and through the points of contact of the brushes. The segments are supposed to be connected with parts of the armature windings lying on the same radius.

51. Influence of Self-Induction of the Commutated Coil. — When the coil in Fig. 64 is in position *A* the current flowing in it produces magnetic flux in the ring independent of any inductive action of the field magnets of the dynamo, and links the flux with itself. When the coil is in position *D*, there is also a magnetic flux and linkage, but its direction has been changed. Therefore, in passing through the position *C*, the current in the coil and the accompanying flux linked with the coil have decreased to zero, and have afterwards risen in value in the opposite direction.

This change of flux produces an E.M.F. in the coil independent of any action of the field magnets (see § 15). This *E.M.F.* is called an electromotive force of self-induction and tends to continue the flow of a current which has been started, and tends to prevent any increase or decrease in the strength of the current and to prevent the stopping or starting of the current. The value of this self-induced pressure with a given flow of current varies as the square of the number of turns in the coil, as the cross-section of the coil, and as the permeance of the magnetic circuit. Because of self-induction it is evident that, if commutation take place in the neutral plane, there is a liability that the currents in the short-circuited coils may persist in flowing until after the passage of the brush, thereby producing sparking. This trouble is to be avoided by revolving the plane of commutation until the field acts sufficiently upon the short-circuited coil to induce an opposing *E.M.F.*, whose integrated value during the time of commutation is double the integrated value of the *E.M F.* of self-induction. Such an *E.M.F.* will reverse the current in the coil during the time of commutation, and deliver the coil on the outside of the brush with the same current as its new companions have, and consequently without sparking. If the resistances of the coil, of the brush, and of transition be not negligible a greater integrated value of *E.M.F.* must be induced.

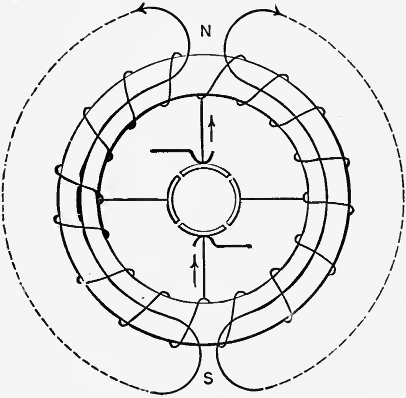


Fig. 66.

52. Cross-Magnetizing Effect of Armature Currents. — Independent of field magnets the current flowing in the armature conductor will magnetize the armature core. The poles thus produced will be in the plane of commutation. Fig. 66 shows the magnetizing effect of the armature turns on a ring armature. Fig. 67 shows a cross-section of a drum armature and its windings with the resulting magnetization.

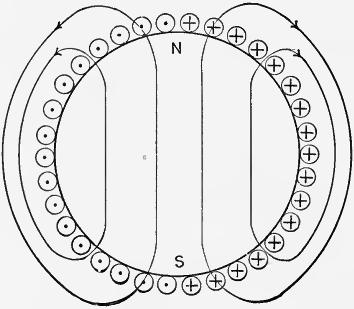


Fig. 67.

Thus, when there is a load on a dynamo and the armature conductors are carrying a heavy current, there are two coexistent magnetic fields. This condition results in a skewing of the lines of force, as is shown in Fig. 68. As the lines are skewed the neutral plane is shifted. To produce sparkless commutation the commutating plane must also be shifted. This causes a further skewing of the lines. The limit of this double interdependent shifting is reached when the magnetic lines have become so crowded in the trailing-pole tips that they are almost insensible to a further shifting of the plane of commutation.

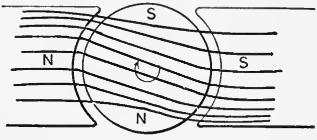


Fig. 68.

This skewing is a source of loss in the operation of a generator because it increases the magnetic reluctance in two ways, — (*a*) by saturating the iron at the horns, and thus reducing the permeability, and (*b*) by lengthening the paths, both in air and in iron, that the lines must follow.

Fig. 69 shows a curve similar to Fig. 65 taken when the generator was under load and the armature was traversed by a heavy current, the flux being distorted because of it. It is evident that the angular displacement of the neutral plane depends in magnitude upon the relative number of armature ampere turns as compared with the effective field ampere turns. The use of a strong field and a large air-gap length requires a large number of field ampere turns. Both are much used in practice with great success.

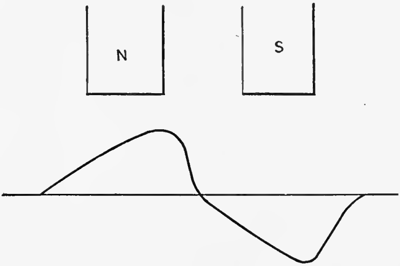


Fig. 69.

53. Demagnetizing Effect of Armature Currents. — It has been shown that it is necessary to have the commutating plane in advance of the neutral plane. The angle between them is called the angle of lag or lead. If an axial plane be passed through the armature, making with the neutral plane an angle equal to the angle of lag or lead, but on the opposite side of the neutral plane from the commutating plane, then the angular space between this plane and the commutating plane is called the *double angle of lag* or *lead.* The armature conductors, which create a magnetism that tends to skew the lines of the field magnets as shown in the last article, are called the *cross turns.*

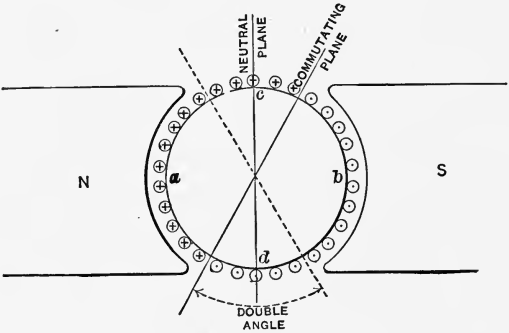


Fig. 70.

They lie outside the double angle of lead. Those armature conductors which lie within the double angle of lead are called the *back turns*, because, when carrying a current, their magnetic tendency is to send lines in a direction exactly opposite to the lines of the field magnets. They neutralize in a certain measure the action of the field turns. This action is clearer shown in Fig. 70, which is a cross-section of a bipolar drum armature. At *a* there is a north pole due to the back turns which lie in the double angle, and at *b* there is the corresponding south pole. The effect of these poles is to neutralize some of the useful magnetic lines flowing from N to S. At *c* there is a south pole due to the remaining or cross armature turns and at *d* is the corresponding north pole. These poles skew the lines flowing from N to S. Compensation for back turns is easily calculated, since the number of back turns times the current in them at any load multiplied by the coefficient of magnetic leakage at that load (§ 47) gives the number of additional field ampere turns necessary at that load for compensation.

54. Sparking. — As shown in § 51, sparking can be avoided by giving the brushes a lead sufficient to bring the coils they short circuit into fields sufficiently strong to reverse the currents in them. Sparking in the operation of machines is generally due to the misplacement of the brushes, though sometimes it is due to irregularities of the commutator surface. A high bar passing from under a brush will leave the latter suspended in air a moment, which will break the whole current through the brush and cause a bad spark or arc.

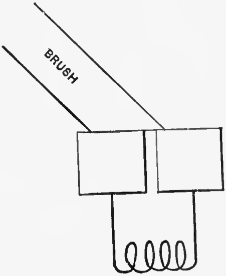


Fig. 71.

A machine may also suffer melting of the commutator bars without any visible sparking. Suppose a coil of low resistance to be short circuited by a copper brush as in Fig. 71. When the brush is chiefly on one bar, and over-laps the other very slightly, then a very considerable part of the resistance in the circuit is the transition resistance at the small contact. Under an *E.M.F.* of self-induction a current of sufficient magnitude may flow to produce enough heat in the transition resistance to melt the surface of the commutator bar. The *E.M.F.* may then disappear before the brush leaves the bar, and there will be no spark visible.

Sparking may be due to excessive electromotive force between the commutator segments undergoing commutation due to the self-induction of the coil and to mutual induction between it and other coils undergoing commutation at the same time. To be able to determine the value of this induced *E.M.F.* one must know both the self and mutual inductances, and the time rate of suppression of the current in the coil. Parshall and Hobart state that in practice one may assume that a coil of a single turn when traversed by one ampere produces and links with itself 20 *c.g.s.* lines per inch net length of armature lamination. From this datum one can calculate the values of the self-inductance and mutual inductance.

A coil which is undergoing commutation must have its current changed from a maximum value in one direction to zero and from zero to a maximum value in the other direction during the time that the two segments at its ends are connected through the brush. This time is evidently dependent upon the peripheral speed of the commutator and upon the width of the brush. It is equal to the time that it takes a point of the insulation between the segments to pass over the breadth of the brush; that is, the time in seconds is equal to the breadth of the brush in inches divided by the peripheral velocity of the commutator in inches per second. The reciprocal of this time gives the number of commutations per second, or what is termed the frequency of commutation. The frequencies found in practice lie between 200 and 500 per second. While all the current which traverses the coil is suppressed in one-half the time taken for commutation, the manner of its variation is unknown. Parshall and Hobart assume that the current strength falls sinusoidally. An assumption of a uniform decrease with the time yields results quite in accord with practice. The value of the induced voltage then will be equal to the product of the value of the commutated current and the sum of the mutual and self-inductance divided by one-half the time occupied in completing commutation. This value should not exceed 6 volts.

55. **Prevention of Sparking.** — The limit of the capacity of a machine may be excessive sparking instead of excessive heating, and therefore the suppression of sparking by proper design of the machine is of utmost importance.

Sparking may be prevented: —

a. By shifting the brushes till the short-circuited coil is just under the fringe of the pole piece. This counteracts the effects of self-induction as explained in § 51. The reversal of the direction of flux in any but the short-circuited coils is to be avoided, since a loss of useful *E.M.F.* would then occur.

b. By having a stiff field, that is, a field so strong as to suffer very little skewing because of the armature cross turns. There is then no lag. In practice, air-gap magnetic densities vary from 2500 to 7500 lines per square centimeter. The higher densities are to be found in the larger machines. There is a general tendency to increase the density.

c. By nearly saturating the teeth of the armature core. When the core teeth are nearly saturated, an increase of load increases the reluctance very markedly, and the demagnetizing effect of the back turns is restrained on increase of load, because of the greater reluctance of the circuit. This minimizes the shift of the commutating plane from no load to full load, and is a device invariably employed on railway generators and other machines that have to stand severe changes of load without change of position of brushes.

d. By using brushes of carbon, brass gauze, etc. In machines of over 100 volts, carbon brushes are commonly used. Besides their good wearing qualities, their resistance prevents the flow of a large current in the short-circuited coil in commutation, and thus a misplacement of the brushes will not result in so violent a spark. In very low-potential machines, as has already been said, carbon brushes are impracticable, because their resistance causes a too great fall of potential. So in these machines copper strip brushes are employed when possible. When too much sparking occurs with plain copper brushes, a brush of somewhat greater resistance is employed, such as copper gauze, brass, brass gauze, etc., according to the requirements of the case.

e. By slotting the pole pieces longitudinally. This increases the reluctance offered to the lines due to armature reactions, and so tends to prevent sparking.

f. By properly shaping the pole pieces. The distribution of flux should be such that a coil enters a weak field first, and so gradually comes to the strongest part. If the lines of force are allowed to crowd into the trailing-pole tips, this gradual transition is impossible. If the horns are farther from the armature surface than the body of the pole face, then the air gap and consequently the reluctance at the horns is increased, and the lines are compelled to distribute themselves more symmetrically. A place suitable for commutation is then more readily found. One may also resort to the shaping of the pole pieces by champfering the corners, or by making the pole faces with a circle of greater radius than the armature.

The Sprague Electric Company, in its split-pole type of the Lundell generator, avoids the distortion of the field under full load, due to cross magnetizing turns, by making use of a specially designed pole piece. Fig. 72 represents a cross-section of this generator, and shows the construction of the pole piece. The magnetic flux which enters the pole piece, divides between the two paths *a* and *b*. Owing, however, to the greater span covered by the shoe belonging to the part marked *b*, the magnetic reluctance of that part is much smaller than that of the part marked *a*. As a result, the flux does not divide itself equally between the two paths. The part of the pole piece marked *b*, under increasing excitation becomes saturated before the part marked *a*. At normal excitation, the flux density at *b* is above 16,000 lines per square centimeter, while the flux density in *a* is but about 10,000 lines per square centimeter. In other words, *b* is pretty well saturated, while *a* has not been brought to a magnetization as high as the knee of the magnetization curve. This saturation of half of the pole piece is effective in preventing a skewing of the field by the cross turns. This is shown in Figs. 73 and 74, where Fig. 73 represents the development of a 50 kilo-watt Lundell generator, and Fig. 74 shows the distribution of flux along the line *xy* of Fig. 73. The dotted line represents the distribution at no load, and the heavy line the distribution at full load. This small distorting effect of the cross turns permits the employment of a small air gap without serious sparking.

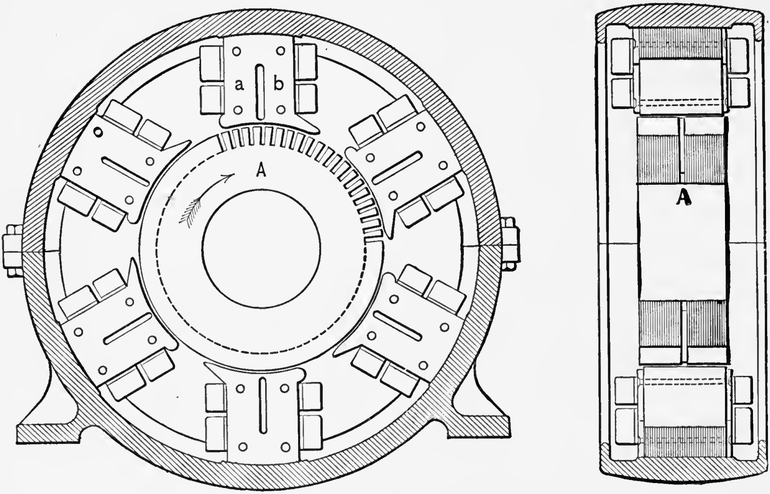


Fig. 72.

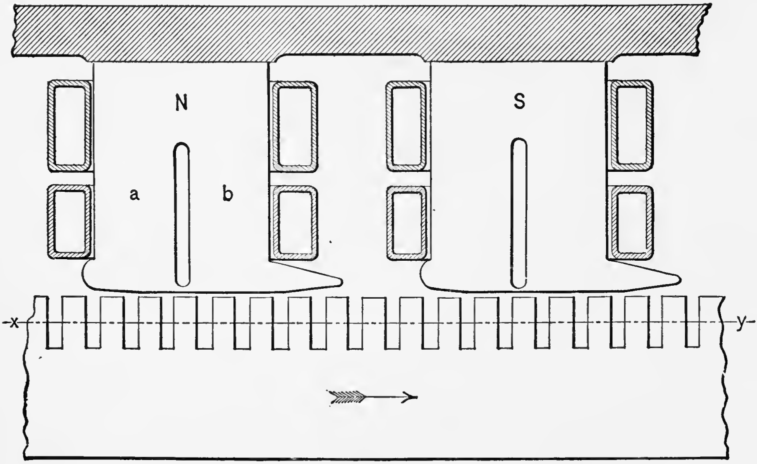


Fig. 73.

Ryan compensates for the magnetizing effects of the armature winding by surrounding the armature with a stationary winding, which passes through perforations in the pole faces. These stationary windings carry the whole current of the machine. This method prevents all sparking due to the distortion of the field, but it does not prevent the sparking which is due to self-induction and mutual induction of the armature coils. The latter sparking is prevented to a certain extent by inserting a lug between the pole horns, which is magnetized by a few series turns.

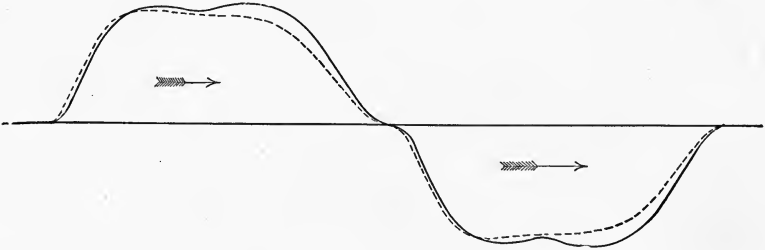


Fig. 74.

56. Energy Losses in Operation. — Besides the energy expended in exciting the field coils, there are losses of energy in the armature and connections, as follows: —

a. The bearing friction and the windage. This loss is generally considered independent of load, but it is questionable whether the friction does not increase somewhat under loads. This loss is from 15 per cent to 40 per cent of the total loss.

b. The hysteresis loss in the iron of the core due to the continued reversal of the direction of magnetism therein. According to Steinmetz's Law, the hysteresis loss in watts,

$$h = 10^7 V \mathfrak{B}_{max}^{1.6} \eta n,$$

where V is the volume of iron in cubic centimeters, $\mathcal{B}$ the flux density, n the number of magnetic reversals per second, and η a constant depending in value upon the character of the iron. A table of values is given on page 29. The value of $\mathcal{B}$ varies at different loads and at different places, as was shown by Goldsborough, so this loss cannot be said to be proportional to the speed or any power of the voltage. The hysteresis loss is from 15 per cent to 40 per cent of the total losses.

c. Eddy currents in the iron and the copper conductors. These might be expected to vary as the square of the speed, but they do not for the same reason as in *b*. Because of the laminated structure of the core, and the slight angular breadth of the conductors, this eddy loss is of small magnitude, from 2 per cent to 10 per cent of the losses. It may amount to 50 per cent of the losses in the case of smooth-core armatures. Eddy currents in the pole faces, which may be due to any variation in the reluctance encountered by the lines passing through the poles, are reduced by an increase of air-gap length. They are greatest with armature cores having slots with large openings at the top, and least with armatures whose inductors are threaded through inclosed channels in the core.

d. The armature resistance loss. This equals I^2R, where I is the total current of the machine, and R the resistance of the armature measured between points rubbed by the brushes which are drawing the current I. This is exclusive of the transition resistance at the brushes. In 500 K. W. machines the I^2R loss is about 2 per cent of the total output. In 5 K. W. machines about 4 per cent, and in smaller machines much greater.

e. The friction of the brushes against the commutator.

This loss varies about as the speed, and its importance is generally underestimated. Carbon brushes press upon the commutator with a force of from 1 to 12 pounds per square inch of contact. Railway motors and similar machines have the larger value, while central-station generators have the smaller. The coefficient of friction between carbon and copper varies from 0.28 to 0.32.

f. The resistance of the brushes and the transition resistance of the brush contacts. The first loss varies as the square of the current, and is of considerable magnitude in low-potential machines. The transition resistance seems to vary inversely as the current, thereby always causing a constant drop of voltage amounting to from 1 to 1.5 volts per transition.

The heat produced by losses *b*, *c*, and *d*, being in the armature itself, must be dissipated by the conduction, convection, and radiation. Experience shows that from 2 to 2¼ watts can be radiated from every square inch of armature surface without causing a dangerous rise of temperature in the armature core. It is found that about 500 circular mils per ampere in the armature conductors brings the loss *d* to such a point that, added to the losses *c* and *b*, they together give about 2 watts per square inch of armature surface; hence this value of 500 circular mils per ampere is the mean of what is usually adhered to in winding armatures of commercial machines.

CHAPTER VI.

EFFICIENCY OF OPERATION.

57. **Efficiency.** — The following definition and discussion of efficiency is taken from the report of the committee on standardization of the American Institute of Electrical Engineers: —

The "efficiency" of an apparatus is the ratio of its net power output to its gross power input.

Electric power should be measured at the terminals of the apparatus.

Mechanical power in machines should be measured at the pulley, gearing, coupling, etc., thus excluding the loss of power in said pulley, gearing, or coupling, but including the bearing friction and windage. The magnitude of bearing friction and windage may be considered as independent of the load. The loss of power in the belt, and the increase of bearing friction due to belt tension, should be excluded. Where, however, a machine is mounted upon the shaft of a prime mover, in such a manner that it cannot be separated therefrom, the frictional losses in bearings and in windage which ought, by definition, to be included in determining the efficiency, should be excluded, owing to the practical impossibility of determining them satisfactorily. The brush friction, however, should be included.

Where a machine has auxiliary apparatus, such as an exciter, the power lost in the auxiliary apparatus should not be charged to the machine, but to the plant consisting of machine and auxiliary apparatus taken together. The plant efficiency in such cases should be distinguished from the machine efficiency.

The efficiency may be determined by measuring all the losses individually, and adding their sum to the output to derive the input, or subtracting their sum from the input to derive the output. All losses should be measured at, or reduced to, the temperature assumed in continuous operation, or in operation under conditions specified.

58. **Coefficient of Conversion.** — This has sometimes been called the efficiency of conversion, but because of the definition of the last paragraph it is better not to use the word efficiency. The coefficient of conversion β is the ratio of the total electrical energy developed in the armature winding to the total mechanical energy expended.

$$\beta = \frac{I_t E_t}{P},$$

where P is the power expended in watts, I_t the armature current in amperes, and E_t the *E.M.F.* in volts, developed in the armature. β is always less than unity, because of the friction and windage of the armature, because of the eddy currents in the core and conductors, and because of the hysteresis of the core.

59. **Economic Coefficient.** — (η) This coefficient is equal to the ratio of the useful electrical energy to the total electrical energy developed in the armature circuit. It is always less than unity because of the necessary loss of energy in the exciting coils and in the armature coils. In the case of a series dynamo, if we let

E_t = $E.M.F.$ generated in volts, and

E = Terminal pressure in volts, then the economic coefficient for a current of I amperes is

$$\eta = \frac{IE}{IE_t} = \frac{E}{E_t}.$$

For shunt dynamos,

$$\eta = \frac{IE}{(I + I_f)E_t}.$$

Where I is the current in the outside circuit, I_f the current in the field coils, E the pressure at the terminals of the machine, and E_t the total pressure generated.

The efficiency of a machine ϵ is evidently the product of β and η.

For a series machine, $I = I_t$ and

$$\epsilon = \beta\eta = \frac{I_t E_t}{P} \times \frac{E}{E_t} = \frac{IE}{P}.$$

For a shunt machine, $I + I_f = I_t$, and

$$\epsilon = \beta\eta = \frac{I_t E_t}{P} \times \frac{IE}{(I + I_f)E_t} = \frac{IE}{P}.$$

Hence the product of β and η for either machine is the same, and corresponds to the definition of efficiency.

60. Separately Excited Dynamos. — At a constant speed and constant exciting current a nearly constant total pressure (E_t) is generated; and it is almost equal to the pressure at the terminals at no load — that is, on open circuit. This follows from the equation for the average pressure,

$$E_{av} = \frac{VS\phi p}{60.10^8} \quad (\S\ 33)$$

where $\frac{V}{60}$ is the number of revolutions per second, S the number of inductors, ϕ the flux per pair of poles, and p the number of pairs of poles. If the speed be varied, the pressure will vary proportionally if no load is on the machine. If, however, a current be taken off, then the demagnetizing effects of the armature currents become evident in a change of the value of ϕ, and there will be a falling off of pressure. The amount of this deviation is dependent upon the composition and saturation of the magnetic circuit.

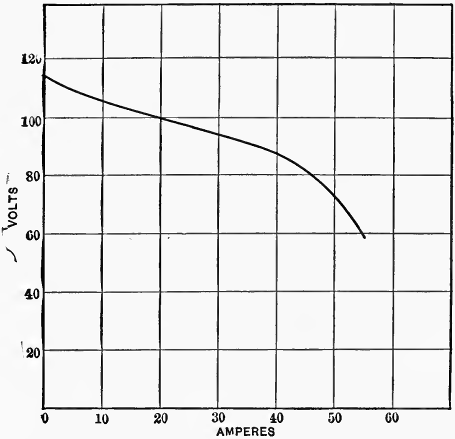


Fig. 75.

This effect is clearly seen in the curve in Fig. 75, where the armature currents are measured in the X direction, and the pressure in the Y direction, the conditions of speed and exciting current remaining constant.

Let E_t = the total volts produced,
E = the volts at the terminals of the machine,
R_a = the resistance of the armature,
R = the resistance of the external circuit, and
I = the current under these conditions.

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Then for a separately excited machine,

$$E_t = I(R + R_a),$$

$$E = IR, \text{ and}$$

$$\eta = \frac{EI}{E_t I} = \frac{I^2 R}{I^2 (R + R_a)} = \frac{R}{R + R_a},$$

and

$$E = \frac{R}{R + R_a} E_t.$$

In determining the efficiency of a separately excited machine the energy lost in the exciting coils must be charged against the coefficient of conversion.

The operation of any dynamo can best be studied by inspection of a curve which shows the relation existing between the current generated or supplied by the machine, and the voltage under which it operated. Such curves are called *Characteristic Curves*, and they are generally plotted with currents for abscissæ and volts for ordinates. The characteristic curve for a separately excited dynamo is that shown in Fig. 75.

61. Magnetos. — A separately excited dynamo whose field is maintained by a *permanent* magnet, instead of an *electric* magnet, is called a magneto. These machines from their similarity, both theoretically and practically, should be mentioned together. Magnetos are, however, generally alternating current machines with slip rings instead of commutators. They are used in very great numbers in telephone subscribers' sets, and in many electrical businesses for testing out the continuity of concealed conductors, and in some cases for determining defective insulation. To the armature is affixed a pinion, meshing with a gear turned by hand. The alternating current produced is passed through the circuit whose continuity it is desired to determine, and then passes through a polarized bell which is caused to ring These machines are manufactured so as to ring through an external resistance of as high as 50,000 ohms without undue effort at the handle. The cut Fig. 76 shows a commercial belt-driven magneto.

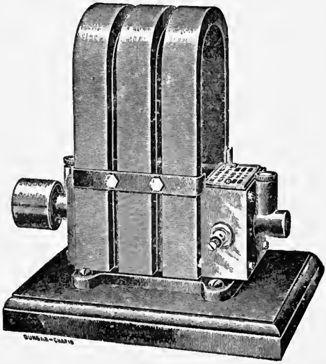
Fig. 76.

62. Series Dynamos.—Letting E, E_t, R, R_a, and I have the same significance as before, represent by R_f the resistance of the field winding, and by R_b the resistance of the brushes and transition contacts. Then

$$E = IR,$$
$$E_t = I(R + R_f + R_a + R_b),$$

whence it follows

$$\eta = \frac{EI}{E_t I} = \frac{I^2 R}{I^2(R + R_a + R_b + R_f)} = \frac{R}{R + R_a + R_b + R_f}.$$

The value of η increases as R_a, R_b, and R_f approach zero. R_b is liable to be of greater importance than is imagined. In low-tension machines all the resistances are small, and care must be taken that R_b does not unduly increase the denominator of the expression for η; in other words, copper brushes should be used on low-voltage machines.

The value of η varies as R, but the load varies inversely as R; hence η is a maximum when the load is a minimum, and $\eta = 1$ when $R = \infty$, or there is no load. Fig. 77 is a curve showing relation between η and load.

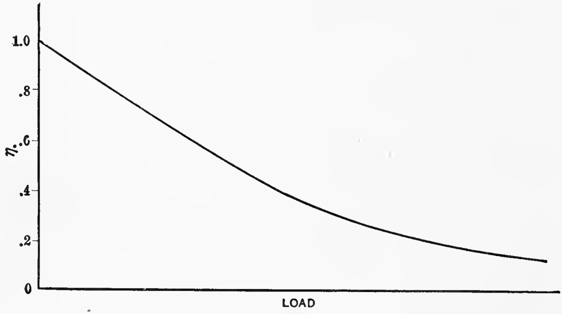

Fig. 77.

63. Characteristic Curve of a Series Machine. — Fig. 78 shows the curves of a series dynamo. The curve of total volts E_t is very similar to the magnetization of a magnetic circuit made up of iron chiefly. It falls below such a curve (a) because saturation causes increased magnetic leakage, and hence the value of ϕ in the equation $E_{av} = \dfrac{VS\phi p}{60\ 10^8}$ is not proportional to the total flux, and (b) because of the demagnetizing and cross magnetizing effects of the armature currents. The curve E_t starts above zero because of the residual magnetism in the cores of the field magnets. If operated under constant load, a

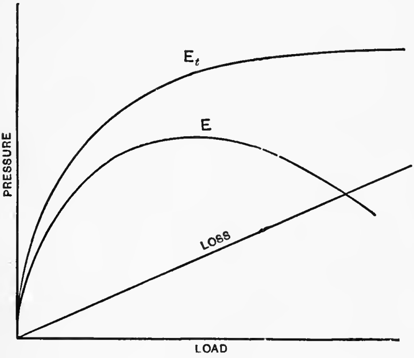

Fig. 78.

series dynamo will give E_t directly proportional to the speed.

The straight line represents the loss or drop of potential due to the resistances of the machine, R_a, R_b, and R_f. Since drop of potential is proportional to the resistance, this is a straight line, and must pass through the origin. This loss line can be established by a point found by assuming the lost volts E_l and solving for the current I from the equation $I\ (R_a + R_b + R_f) = E_l$. For example, if the resistances $R_a + R_l + R_f$ be assumed as 0.2 ohm, then 10 volts would be lost in them only when 50 amperes were flowing through them. A line drawn through the origin, and a point on the characteristic curve diagram whose coördinates were 10 volts and 50 amperes, would at every point give the volts lost in sending the corresponding number of amperes.

The curve E showing the *E.M.F.* at the terminals of the machine as a function of the current output is found by subtracting the ordinates of the loss line from those of E_t and using the differences as the ordinates of E. In practice E_t cannot be directly found; but the terminal volts and the current can be measured, thus giving the curve E, and from a knowledge of the loss line the curve E_t can be derived.

The operation of some special forms of series machines will be discussed in the chapter on arc-lighting machines.

64. Power Lines. — Where volts and amperes are used as ordinates and abscissæ, lines can be drawn connecting points of constant product of the two, representing watts or power. Fig. 79 shows such lines drawn for one, two, and three kilowatts. If E be the external characteristic of a dynamo, then the curves make it apparent that the machine cannot generate 3 K.W., but that for most values under 3 K.W. there will be two loads under which the generator can run and yield the same voltage.

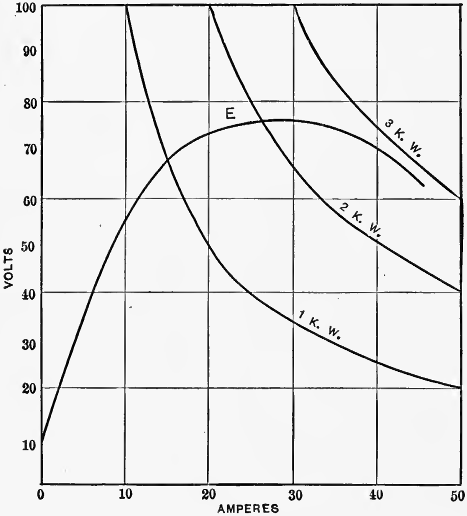

Fig. 79.

65. Shunt Dynamos. — In shunt-wound machines the current in the armature is the sum of the current in the field coils and of that in the external circuit, or $I_a = I_f + I$. For sake of simplicity we will assume $I_a = I$. Practically this introduces but a small error under ordinary conditions of load.

$$\eta = \frac{IE}{IE_t + I_f E} = \frac{I^2 R}{I^2 (R + R_a) + I_f^2 R_f} = \frac{\frac{E^2}{R}}{\frac{E^2}{R} + \frac{E^2 R_a}{R^2} + \frac{E^2}{R_f}}$$

$$= \frac{\frac{1}{R}}{\frac{1}{R} + \frac{R_a}{R^2} + \frac{1}{R_f}} = \frac{1}{1 + \frac{R_a}{R} + \frac{R}{R_f}}.$$

To determine what value of R will enable a given machine to operate with a maximum economic coefficient —

place the differential coefficient of η, in respect to R considered as a variable, equal to 0 and solve for R

$$\frac{d\eta}{dR} = \frac{1}{R_f} - \frac{R_a}{R^2} = 0 \quad \therefore \quad R = \sqrt{R_a R_f}.$$

The external resistance must be a mean proportional between R_a and R_f, and the maximum economic coefficient is

$$\eta = \frac{1}{1 + 2\sqrt{\frac{R_a}{R_f}}}.$$

66. Characteristic Curve of a Shunt Dynamo. — In Fig. 80 the curve E is plotted from experimental results obtained while the machine is running at various loads. To get satisfactory results, one should begin with an infinite resistance in the external circuit, which is then reduced step by step. In some small machines it can be reduced to zero without an extreme elevation of temperature due to excessive currents. As a rule, only the upper and lower values of E, corresponding to currents between 0 and a definite maximum value, can

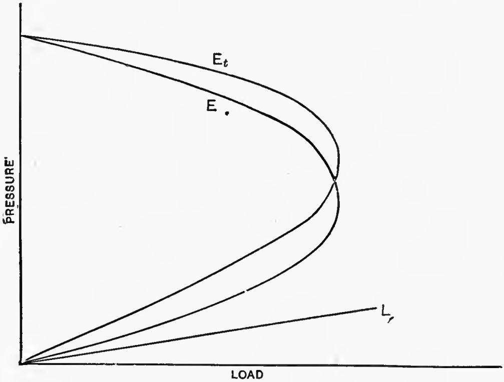

Fig. 80.

be obtained. The loss line L is obtained by calculation as before in the case of the series machine. The curve showing the relation between external current and total volts, E_t, is obtained by adding the ordinates of L to those of E. The drop in E is at first due chiefly to the drop resulting from armature resistance. As the current increases, the effects of armature reaction and saturation of the magnetic circuit become evident. At the same time E is affected by a decrease of the shunt-field current due to the fall of potential at the terminals of the field circuit. This soon becomes the predominating cause of drop, and to such an extent that the curve turns back toward the origin. When zero resistance is in the external circuit, of course no current flows through the field, and the few volts then produced are due to residual magnetism. It must be remembered that while E is a double-valued function of I it is a single-valued function of R.

The voltage of a shunt machine generally increases more rapidly than the speed. An increase of speed not only increases primarily the number of volts generated, but also increases the armature flux ϕ because of increased excitation. The condition of the magnetic circuit as regards saturation determines whether this secondary influence shall be great or small.

CHAPTER VII.

CONSTANT POTENTIAL DYNAMOS.

67. Constant Potential Supply. — The method of supplying, at any point of usage, current at a constant potential irrespective of the load which is there or elsewhere, is used in the distribution of electrical energy for purposes of incandescent electric lighting, for consumption in constant pressure motors, and for trolley-car propulsion. The great sensitiveness of the candle power of incandescent lamps to a change in voltage, the candle power varying as the fourth power or more of the voltage, requires that the pressure in lines used for lighting must not vary by more than 3 per cent of its rated value. In street-car work, where the load suffers tremendous variations, constant potential supply is equally as imperative for satisfactory operation.

68. Methods of Obtaining Constant Potential. — For accomplishing this result many devices have been tried, the more important of which are : —

a Automatic variation of the resistance in the field circuit of shunt machines.

b Automatic change of the position of the brushes and commutating plane.

c Automatic variation of armature speed.

d Hand regulation of a resistance in series with a shunt field coil.

e Self-regulation.

Of these the first three methods are no longer employed, and either hand regulation or self-regulation or both together are relied upon to maintain the constant voltage under varying loads.

69. Hand Regulation. — Inspection of the characteristic curves of either the shunt or the separately excited dynamo shows a drop in the voltage as the load increases. This is due to the internal resistance of the armature and the demagnetizing effect of armature reaction. In the formula for the $E.M.F.$ of a machine, $E = \frac{S \phi V p}{10^8 60}$, the only quantity that is practical to vary is ϕ. This can easily be accomplished by regulating the amount of resistance in a rheostat, which is in series with the field coils and which therefore governs the amount of current in them, as in Fig. 81.

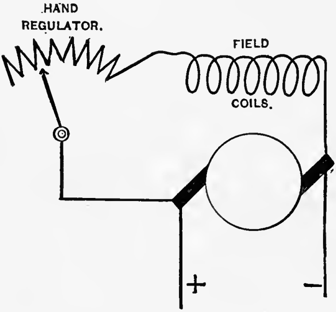

Fig. 81.

In distributing current for use among a number of consumers the current is carried to *feeding-points* which are near the locality they supply, but may be distant from the station. It is desirable to keep the pressure at these points at a constant value, irrespective of the varying loss of potential that is going on because of the resistance of the conductors leading to them. To achieve this end the

Edison system employs feeders to carry the current to the feeding-points. Each feeder is accompanied by a pilot wire imbedded in the insulation. At the feeding-point the pilot wires are attached to the feeder terminals, and at the station end are attached to a voltmeter, so that one can, in the station, regulate the pressure not at the machine terminals but at the distant distributing point.

70. Field Rheostats. — For varying the current in the shunt fields of dynamos, it is usual to employ field rheostats which are mounted on the switch-board along with indicating instruments. A form of such rheostatic regulators is the so-called Packed Card Rheostat, manufactured by the General Electric Company. This derives its name from

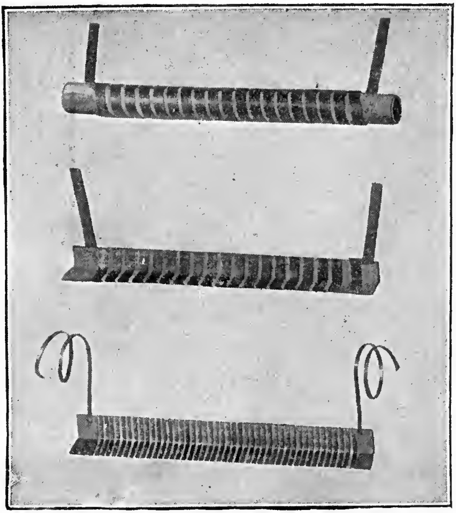

Fig. 82.

the method of constructing it. A tube of asbestos, inclosing a steel mandrel, is wound with a chosen amount of German-silver wire or ribbon. The tube is then removed from the mandrel, and pressed into the form of cards as shown in Fig. 82. These cards are then assembled, with interposed asbestos, in sufficient numbers to make up the required resistance of the rheostat. Iron plates, somewhat wider than the cards, are introduced at intervals, and thus increase the radiating surface. The whole is held together by iron end plates and bolts, as shown in Fig. 83. Contact bolts are connected with various points of the conducting part of the rheostat, and these bolts are connected through a wiping-finger with the field circuit. Fig. 84 shows a rheostat of this type built for regulating a railway generator and arranged to be placed on the back of a switch-

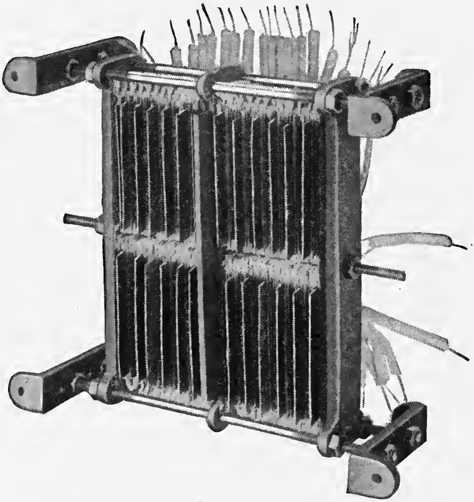

Fig. 83.

board with the regulating handle projecting in front. For the largest generators resistances made of iron grids supported in iron frames are employed. Both of these constructions are fire-proof and easily repaired in case of accident.

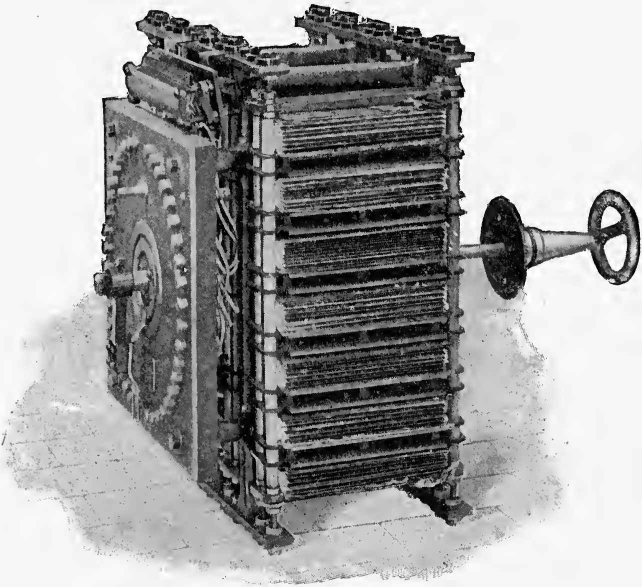

Fig. 84.

When large generators, such as are used in railroad work, have their field circuits opened, the *E.M.F.* self-induced by the disappearance of the flux in the fields is liable to reach such a magnitude as to pierce the insulation of the field coils and destroy their usefulness. To obviate this, before the field circuit is broken, the field coils are connected (Fig. 85) through a high discharge resistance, and the current in them is allowed to die out slowly. It is thus unattended with any destructive potential differences.

The Edison Electric Illuminating Company of New York City, in the case of its Duane-street generators, allows the field circuits to discharge themselves through an arc light.

Another form of field rheostat is the Carpenter Enamel Rheostat, made by the Ward Leonard Electric Company. In this rheostat the heat generated is not radiated directly from the surface of the wire, but is conducted to a supporting plate, which then becomes the radiating surface. The resistance wires are surrounded with an enamel, which attaches them to the supporting plates, insulates them therefrom, and protects them from corrosion. Owing to the increased radiating surface thus obtained, a shorter and smaller wire can be used for a given volt-ampere capacity·

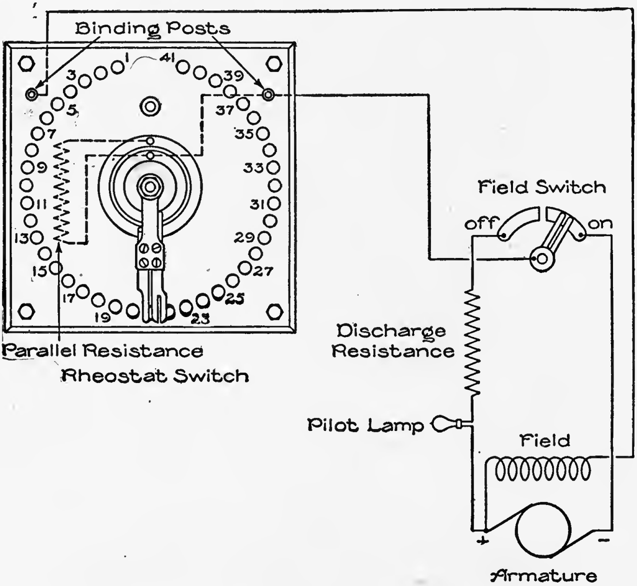

Fig. 85.

than if the wire were merely exposed to the air. No consideration of the mechanical strength of the wire enters into the design of this resistance, since it is supported and protected by the enamel. To further increase the radiating surface, the back of the plate is provided with raised annular ribs. The makers claim that this rheostat can radi-

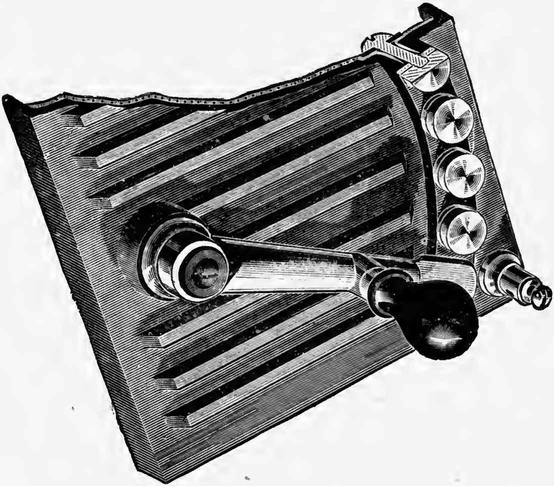

Fig. 86.

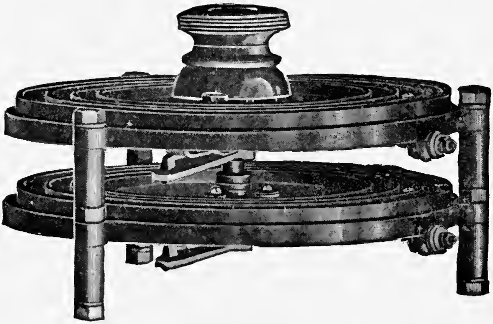

Fig. 87.

ate 5 watts for each square inch of one surface. Thus a plate 10 by 10 inches will dissipate 500 watts. The method of using iron radiating plates for purposes of dissipating large amounts of heat is to be found in the rheostats of many manufacturers. Wirt (Fig. 88) incloses resistance wire or ribbon in radiating plates, insulating them from each other by means of mica. Other firms employ sand as an insulating material.

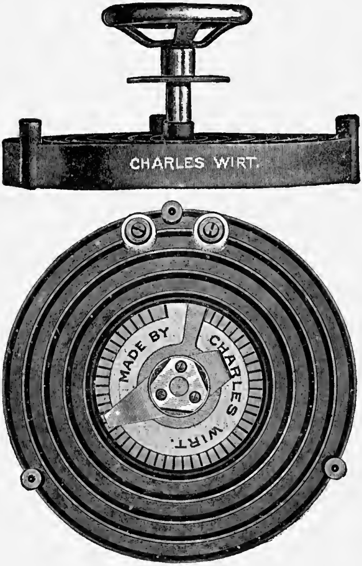

Fig. 88.

71. Self-Regulation.— By far the most elegant method of constant potential regulation is that in which the main current of the machine is utilized in maintaining constant the magnetic flux ϕ through the armature. This is accomplished by passing all or the greater part of the current produced in the armature a few times around the field magnets, so that an increased load on the armature increases the magnetizing ampere turns of the field coils. These *series turns*, when rightly proportioned, can be made to compensate for a part, for all, or for even more than all of the drop. This device can be used in connection with any other form of excitation, as permanent magnets, separate excitation, or shunt excitation. In the last case, the dynamo is said to be *compound wound*, as described in § 45. If the machine is designed to maintain a constant pressure at some distant feeding-point, instead of at the machine terminals, the machine is said to be *over-compounded*, since the potential at the terminals will rise on increase of load. From 3 to 5 per cent over-compounding is frequent in machines used to supply lighting circuits, and 10 per cent over-compounding is usual in railway generators.

72. Economic Coefficient of a Compound Machine. — To discover the value of η in this case, let R be the resistance of the external circuit, R_s the resistance of the series turns, R_{sh} the resistance of the shunt-field, and R_a the resistance of the armature. Then assuming that the current in the armature is the same as in the external circuit, an assumption which is warranted in the case of commercial machines,

$$\eta = \frac{I^2R}{I^2R + I^2R_a + I^2R_s + I^2_{sh}R_{sh}} =$$

$$\frac{\frac{1}{R}}{\frac{1}{R} + \frac{1}{R_{sh}} + \frac{R_a}{R^2} + \frac{R_s}{R^2}} = \frac{1}{1 + \frac{R}{R_{sh}} + \frac{R_a}{R} + \frac{R_s}{R}}$$

Considering R as a variable dependent on η, and solving for a maximum of η

$$\frac{d\eta}{dR} = -\frac{1}{R_{sh}} + \frac{R_a}{R^2} + \frac{R_s}{R^2} = 0,$$

and

$$R = \sqrt{(R_a + R_s)\,R_{sh}}.$$

Hence it is seen that the maximum economic coefficient is obtained, when the external resistance is the geometric mean between the shunt-field resistance and the sum of the resistances of the series field and of the armature. Under these conditions,

$$\eta = \frac{1}{1 + \frac{\sqrt{(R_a + R_s)\,R_{sh}}}{R_f} + \frac{R_a}{\sqrt{(R_a + R_s)R_{sh}}} + \frac{R_s}{\sqrt{(R_a + R_s)\,R_{sh}}}}$$

$$= \frac{1}{1 + 2\sqrt{\frac{R_a + R_s}{R_{sh}}}}.$$

73. Efficiency of Compound Machines.—The efficiency of a generator increases with the size, being quite low on small machines, and sometimes very high on the larger dynamos. Since the distribution of the magnetic and electrical losses of a generator lies within the discretion of the designer, it is possible to so design a machine as to have its point of maximum efficiency at full load or at a smaller load, for instance, at one-fourth load. The two following cuts show the relations between efficiencies and loads on two different machines.

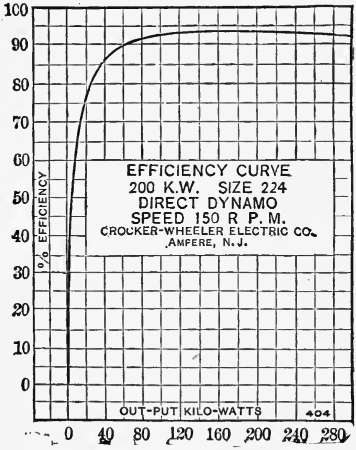

Fig. 89.

74. The Compounding Rectifier. — The gradual saturation of the fields of a generator as full load approaches causes the *E.M.F.* of even a compound-wound machine to sag at full load, or if the machine is so heavily compounded that it maintains its potential at full load, its voltage will rise abnormally at some load less than full load. To counteract this effect, the Crocker Wheeler Company employs a device which is termed a *compounding rectifier.* It consists of a suitable resistance shunted across the terminals of the series field coils. The full armature current therefore divides between this rectifying coil and the series coils. As the load increases, more current passes through each, but the coils are so designed that this increase heats the rectifier and causes its resistance to increase, while the resistance of the series coils remains practically unaltered. Thus, as the load increases, a larger proportion of the whole current passes through the series coils, and this compensates for the sag in voltage that would otherwise have existed.

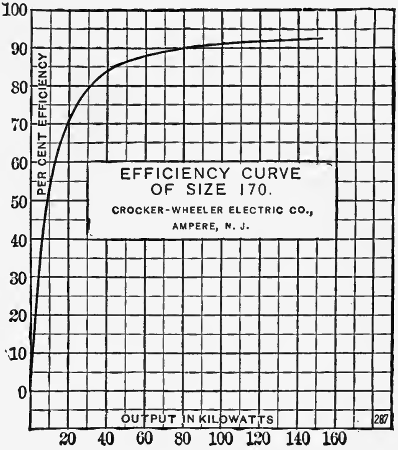

Fig. 90.

70. Theory of Self-Regulation. — To determine the number of turns of wire necessary to be used in the series regulating coils which are wound on the field magnets of a compound machine,

Let n = number of shunt turns.
n' = number of series turns.
B = number of back turns.

$X =$ number of cross turns.

$R_{a+s} =$ the resistance of the armature plus that of the series coil.

$I_{sh} =$ current in the shunt coils.

$I =$ current in the armature and also in the series coils, since they are practically the same.

$E_t =$ total pressure developed.

$E =$ pressure at terminals.

$\lambda =$ the coefficient of magnetic leakage.

$\mathcal{R} =$ the reluctance of magnetic circuit when armature is idle. Then

$$\mathcal{R}\frac{\sqrt{XI^2 + nI^2_{sh}}}{nI_{sh}} = \text{reluctance with current } I \text{ in armature.}$$

Let ϕ, ϕ', ϕ'', = flux in the armature under different conditions of working.

When no current flows in the armature,

$$\phi = \frac{4\pi n I_{sh}}{10\mathcal{R}\lambda} = 1.25\frac{nI_{sh}}{\mathcal{R}\lambda}.$$

When the current I flows in the armature,

$$\phi' = \frac{1.25}{\mathcal{R}\lambda\dfrac{\sqrt{XI^2 + nI^2_{sh}}}{nI_{sh}}}(nI_{sh} + n'I - BI) = \frac{1.25}{\mathcal{R}\lambda}a[nI_{sh} + n'I - BI]$$

where $\dfrac{1}{a} = \dfrac{\sqrt{XI^2 + nI^2_{sh}}}{nI_{sh}}$, hence a represents the ratio of the reluctance at no load to the reluctance with the load I. The latter value is the greater because of the skewing effect of the cross turns. a, therefore, is less than 1.

The flux in the armature which is due to the shunt coils only, when a current I flows in the armature circuit, is

$$\phi'' = \frac{1.25}{\mathcal{R}\lambda}anI_{sh}.$$

Thus under load the amature flux due to the shunt coils is decreased in the ratio,

$$\phi'' : \phi :: a : 1.$$

The series turns must make up this loss, and also compensate for the loss due to the back turns and for the electrical losses due to the resistances of the armature and the series coils.

Now, $E_t = \frac{VS\phi p}{10^8\, 60}$, and $E'_t = \frac{VS\phi' p}{10^8\, 60}$,

and
$$E = E'_t - IR_{a+s}$$
$$= \frac{1.25\, VSpa}{\mathfrak{R}\lambda \times 10^8 \times 60} [nI_{sh} + n'I - BI] - IR_{a+s}.$$

For convenience let

$$k = \frac{1.25\, VSp}{\mathfrak{R}\lambda \times 10^8 \times 60} \text{ then } E = kanI_{sh} + [ka\,(n' - B) - R_{a+s}]\, I.$$

The first term of the right-hand member can be written $knI_{sh} - k\,(1 - a)\, nI_{sh}$, in which the expression knI_{sh} represents the total voltage developed by the machine at no load, which is therefore the terminal voltage at that load, or in other words is the voltage for which the machine is to be compounded. The equation for the terminal voltage at the load I therefore becomes

$$E = knI_{sh} - k\,(1 - a)\, nI_{sh} + [ka\,(n' - B) - R_{a+s}]\, I.$$

Evidently, if E is to equal knI_{sh} at any and every load,

$$-\,k\,(1 - a)\, nI_{sh} + [ka\,(n' - B) - R_{a+s}]\, I = 0,$$

whence

$$n' = \frac{1 - a}{a} \frac{nI_{sh}}{I} + B + \frac{R_{a+s}}{ka}.$$

Remembering that $\frac{1}{k} = \frac{nI_{sh}}{E}$ and also that the percentage of electrical energy loss in the field $p = \frac{I_{sh}}{I} 100$,

$$n' = \frac{1 - a}{100\, a} pn + B + \frac{nI_{sh} R_{a+s}}{aE}.$$

In this value for n' the first term gives the number of series turns required to overcome the skewing due to the cross turns; the second term gives the series turns necessary to compensate for the armature back turns; and the third term shows the number of series turns to balance the loss due to the resistances of the armature and the series coils.

The difficulty of applying this formula lies in finding a suitable value for a. This differs in different machines, having according to Jackson a value of from .75 to .85 at full load. It is of course dependent on the load, and has a value of unity for no load.

76. Views of the American Institute of Electrical Engineers.

—The following statements concerning the regulation of direct current apparatus are taken from the report of the Standardization committee of the Institute: —

The regulation of an apparatus intended for the generation of constant potential, constant current, constant speed, etc., is to be measured by the maximum variation of potential, current, speed, etc., occurring within the range from full load to no load under such constant conditions of operation as give the required full-load values, the condition of full load being considered in all cases as the normal condition of operation.

The regulation of an apparatus intended for the generation of a potential, current, speed, etc., varying in a definite manner between full load and no load, is to be measured by the maximum variation of potential, current, speed, etc., from the satisfied condition, under such constant conditions of operation as give the required full-load values.

If the manner in which the variation in potential, current, speed, etc., between full load and no load is not specified, it should be assumed to be a simple linear relation; i. e., undergoing uniform variation between full load and no load.

The regulation of an apparatus may, therefore, differ according to its qualification for use. Thus the regulation of a compound-wound generator specified as a constant-potential generator will be different from that it possesses when specified as an over-compounded generator.

The regulation is given in percentage of the full-load value of potential, current, speed, etc.; and the apparatus should be steadily operated during the test under the same conditions as at full load.

The regulation of generators is to be determined at constant speed.

The regulation of a generator unit, consisting of a generator united with a prime mover, should be determined at constant conditions of the prime mover; i. e., constant steam pressure, head, etc. It would include the inherent speed variations of the prime mover. For this reason the regulation of a generator unit is to be distinguished from the regulation of either the prime mover or of the generator contained in it, when taken separately.

In commutating machines as direct current generators and motors, the regulation is to be determined under the following conditions:

a. At constant excitation in separately excited fields,

b. With constant resistance in shunt-field circuits, and

c. With constant resistance shunting series fields; i.e., the field adjustment should remain constant, and should be so chosen as to give the required full-load voltage at full-load current.

In constant potential machines the regulation is the ratio of the maximum difference of terminal voltage from the rated full-load value (occurring within the range from full-load to open circuit), to the full-load terminal voltage.

In constant current machines the regulation is the ratio of the maximum difference of current from the rated full-load value (occurring within the range from full load to short circuit), to the full-load current.

In over-compounded machines, the regulation is the ratio of the maximum difference in voltage from a straight line connecting the no-load and full-load values of terminal voltage as function of the current, to the full-load terminal voltage.

77. Direct Driven Light Generators. — The tendency of modern engineering practice is to install lighting generators which are directly connected with the steam engines which drive them. Owing to the inherent speed of engines being smaller than that of generators, direct connected armatures are designed to run at a lower speed than belt-driven ones. Economical construction demands that they be of the multipolar type. They require less floor space per kilowatt than the belt-driven machines; and this is a question of considerable importance in many installations.

They have a higher efficiency of operation consequent upon the elimination of losses in belting and counter-shafting. They also permit of operation of isolated plants in residences and other places where the noise resulting from belt-driven machinery would not be tolerated.

In order that standard generators may be easily connected with engines of any make, and *vice versa*, committees from the American Societies of Electrical Engineers and of Mechanical Engineers have recommended the adoption of the following standard sizes, speeds, and armature shaft fits :—

Sizes in K. W. Capacity .		5	7.5	10	15	20	25	35
Speeds in Rev. per Minute		450	425	400	375	350	325	310
Armature Fit in Inches .		3	3	3½	3½	4	4	4½
Sizes in K. W. Capacity .	50	75	100	125	150	200	250	300
Speeds in Rev. per Min. .	290	275	250	235	220	200	190	180
Armature Fit in Inches .	5	6	7	7½	8	9	10	11

Fig. 91 shows a machine made by the Westinghouse Electric Manufacturing Company in standard sizes of 100, 150, 200, 500, and 675 K. W., at 125 volts. The field frame is circular and divided in a vertical plane. The pole pieces are of laminated sheet steel, cast into the frame. Projecting from the field frame are brackets, which hold and carry the brush-holder mechanism. This consists of a ring concentric with the axis of the armature. Upon its rim is a gear, which engages with a worm operated by a hand-wheel. The simultaneous shifting of the brush can be accomplished by the turning of the hand-wheel. The slotted armature disks are made of sheet steel, and are held together by cast-iron end plates. The disks and end plates are mounted upon a cast-iron spider, which also carries the commutator. The spider is fitted so as to be pressed upon the engine shaft and keyed to it. The conductors are bars of copper, which are forged into shape on cast-iron formers wound and insulated with mica and fullerboard.

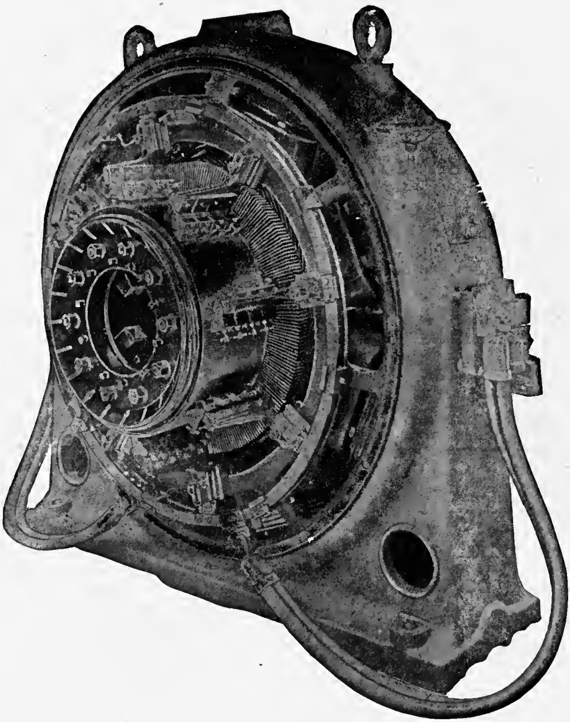

Fig. 91.

Figs. 92 and 93 represent a front and rear view of a

General Electric Company's Form L generator. The frame, of a circular form, is divided in a horizontal plane, and is made of soft cast iron. To it are bolted pole pieces

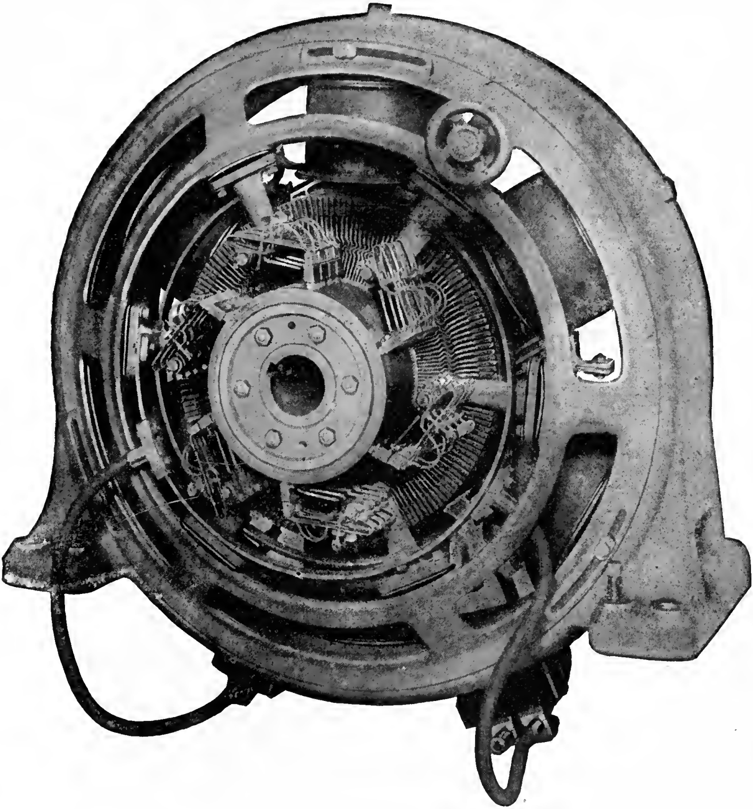

Fig. 92.

which are made of soft cast steel. A skeleton, circular, disk-like brush-holder yoke is fastened to the frame by means of three slots and bolts, and is capable of sufficient angular rotation to permit of the proper adjustment of the brushes. The movement is accomplished by means of a hand-wheel and pinion. The armature spider is so constructed that it receives the commutator as well as the

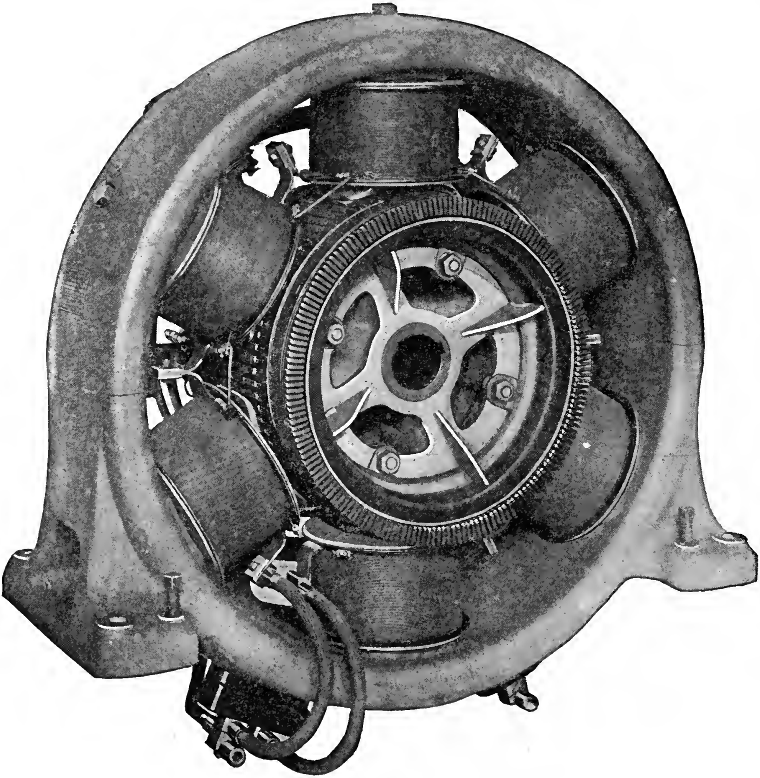

Fig. 93.

disks and the armature windings. It is open so as to offer no obstruction to the free and thorough circulation of air through it, which permits of a perfect ventilation. The windings are of copper bars, and the end connections are supported by flanges which protect them from mechanical injury. The commutator shell is pressed upon the armature spider.

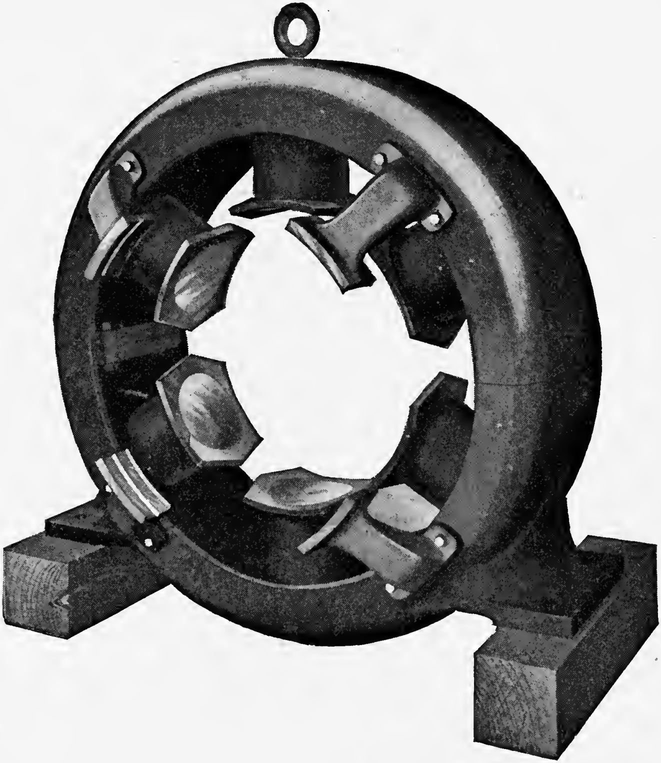

Fig. 94.

The Crocker Wheeler Electric Company's direct-connected and belt-driven generators differ from others which have been described, chiefly because of the shape of the field-magnet frame and the method of armature winding. The field frame shown in Fig. 94 is circular in form, and is divided in a horizontal plane. These frames are of cast iron, and have short internal flanges on each side, which mechanically strengthen the frame, and offer considerable protection from mechanical injury to the field coils. The round poles are of cast steel, cast-welded into the frame. They are provided with removable cast-iron shoes, which are clamped in place after the field coils have been put on. The armatures, instead of being bar-wound, are wound with solid copper wire of large sizes, which are triple cotton covered. The conductors are threaded through tubes which are placed one upon the other, and which are made of micanite cloth and press-board rolled up on a form and glued together. The brush holders and brush rigging were shown in Figs. 48 and 49.

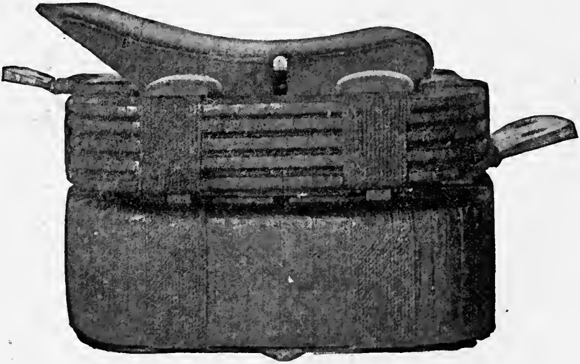

Fig. 95.

The Sprague Electric Company manufactures two types of Lundell generators, both for direct connection and for belt connection. They are, namely, the split-pole type, which employs the principle laid down in paragraph 55 for compensating for armature reaction, and the single-coil type, which takes its name from the peculiar shape of the field frame and poles, which permits of the use of but a single field coil. Both frames are of the circular type,

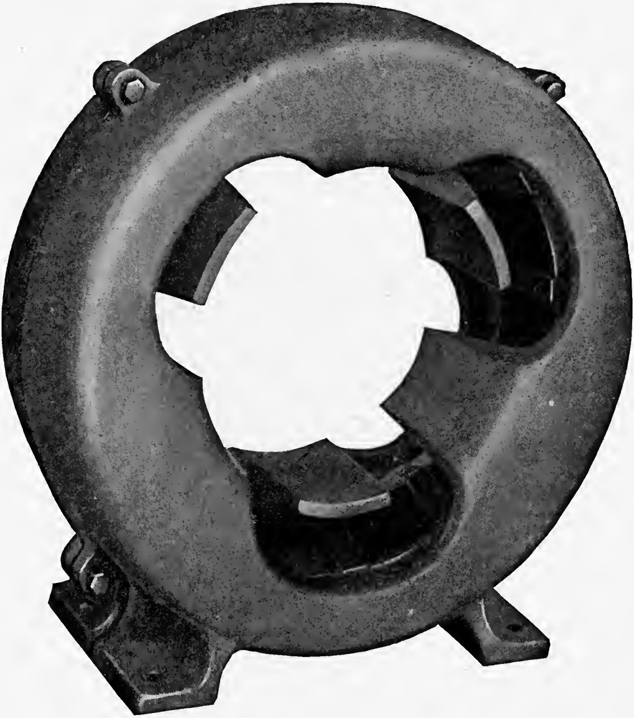

Fig. 96.

the split-pole field being divided in a horizontal plane, and the single-coil type being divided in a vertical plane which is perpendicular to the axis of the armature. A split pole, with its windings, is shown in Fig. 95. The compound coil is placed nearer the shoe than the shunt coil, and both are kept in place by lugs, as shown in the figure. Fig. 96 shows a 6-pole, single-coil type field-magnet frame with its coil inclosed in the frame. The brush holders which are employed on both types of machine are illustrated in Fig. 97, the brushes being of

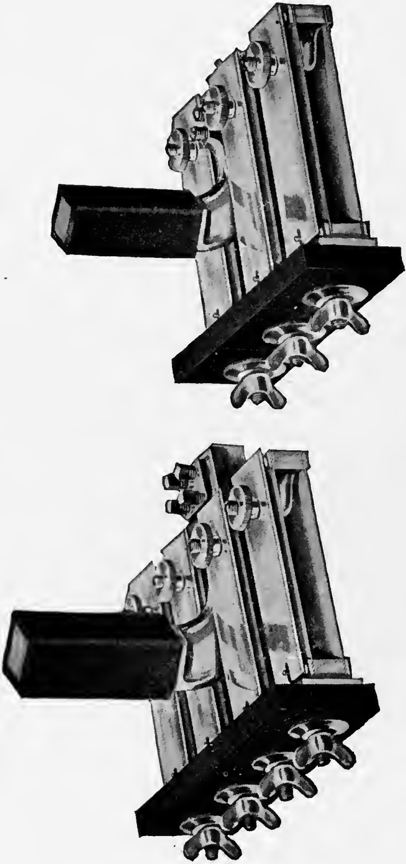

Fig. 97.

carbon used radially, and being perforated to receive a bolt for clamping them to the holders.

The Bullock Electric Manufacturing Company's direct connected generator, Fig. 98, has an external appearance similar to that of the generators of other companies. It is different from them, however, in having peculiarly constructed poles. These poles are made up of laminated steel stampings, which are much thinner than are ordinarily used, and which have the peculiar shape shown in Fig. 99. In assembling these stampings to form the pole, every alternate one is reversed from the position which is

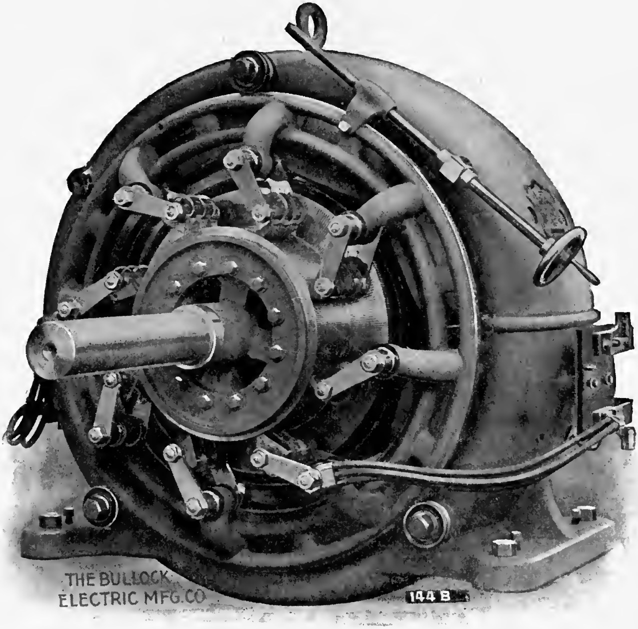

Fig. 98.

indicated in the figure. The method of assembling is shown in Fig. 100. After assembling, it will be seen that the face of the pole for a short depth contains but one-half as much iron as the main body of the pole. This results, under normal excitation, in a saturated pole face. It has the same effect in preventing distortion of the field under the influence of armature reaction, as saturation of the teeth of the armature core. The teeth can, therefore, be operated at a smaller magnetic flux density. The hysteresis losses in the teeth can accordingly be made smaller. The thinness of the stampings, and the ideally perfect lamination of the pole face, permit the use of a smaller ratio of tooth width to slot width, without the excessive eddy current loss in the pole face which would occur in ordinary machines. The possibility of using narrow teeth results in a reduction of the inductances of the armature coils. This facilitates effective commutation.

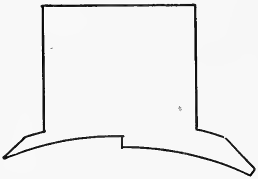

Fig. 99.

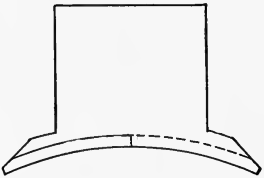

Fig. 100.

CHAPTER VIII.

CONSTANT CURRENT DYNAMOS.

78. Direct Current Arc Lighting Generators. — For lighting by arc lights where considerable energy is expended at the points of illumination, and where these points are separated from each other by considerable distances, it is sometimes economical and desirable to connect the lamps in series and use a constant current. A single line then completes a circuit of all the lamps (Fig. 101). The line can be made of much smaller wire than in the case of a constant pressure circuit, for on a constant current circuit as the load increases the power or energy transmitted is increased by raising the potential, the current remaining unaltered; while in a constant pressure circuit an increase of load is met by an increase of current, and the wires of the line have to be of sufficient size to safely carry the maximum. The size of wire necessary is dictated, not by the energy transmitted, but by the current flowing, hence a wire large enough to supply just one lamp of a constant pressure circuit can supply all the lamps of a constant current circuit.

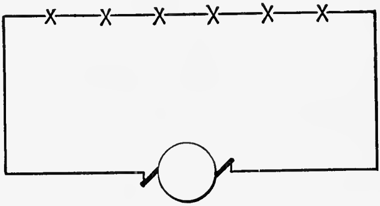

Fig. 101.

The more general forms of arc lamps have what is termed a spherical candle-power of 800, 1200, or 2000. Lamps used in search-lights and in light-houses often exceed this in candle-power, and may consume many more amperes. The arc lamp of 800 candle-power takes a current of 4.5 amperes, that of 1200 candle-power 6.6 to 6.8 amperes, and that of 2000 candle-power 9.6 to 9.8 amperes.

An ordinary arc lamp, as it is trimmed and adjusted for general use, requires between 45 and 50 volts to force its rated current through it. A generator supplying a circuit of say 2000 candle-power lamps with n such lamps in the circuit must be capable of generating a constant current of 9.8 amperes. It must be able to regulate its pressure between the limits of 50 and $50n$ volts. This is necessary in order that it may operate all the lamps or any part of the whole number.

The current of an arc-light machine must not exceed nor fall below its normal value, no matter how suddenly the load is varied; for the slightest change, even for a very brief instant of time, affects the quality of the light at the lamps. It is obvious that some mechanical device could be applied to an ordinary shunt-wound generator to cause it to give constant current, either by changing the position of the brushes or by varying the ampere turns of the field coils. However, any such device would be slow of operation, and a sudden short circuit would cause a destructive current to flow before the regulator completed its action. It is, therefore, necessary to rely on the armature reactions for regulation, since they vary simultaneously with the current. All successful constant current machines are constructed on this principle. The machine is designed with a field of very great magnetizing power, the armature reactions are very great, and thus the total flux effective in producing *E.M.F.* is reduced. A slight increase of current in the armature materially increases the armature reactions. The effective flux is thus reduced, and the pressure falls until the current returns to its normal value. Thus the machine is completely and instantly self-regulating. Since the field magnetization is kept constant and the machine produces constant current the field coils are series wound on all arc-light generators, and the cores of the field magnets are worked at a very high magnetic density, since the magnets are then more insensible to slight changes in the magnetizing force. In commercial machines the densities in the field cores are from 17,000 to 18,000 lines per square centimeter for wrought iron or steel, and from 9000 to 11,000 lines for cast iron.

In the armature high magnetic density is also required to prevent a sudden rise of voltage when the circuit is broken. With no current in the armature, the total magneto-motive force of the field magnets would be effective in producing *E.M.F.*, and a destructive rise of pressure would result, since the total *M.M.F.* of the field magnets is much greater than the normal effective *M.M.F.* But a high magnetic density in the armature core leaves the latter incapable of receiving such an increase of flux, and therefore destructive voltages are avoided. In practice the armature core is designed to have a density of from 15,000 to 20,000 lines per square centimeter at its minimum cross-section.

A consideration of the foregoing theory of regulation shows that the following conditions should obtain more or less completely in a successful constant current generator:

(*a*) since the current is small, there must be a great number of armature turns; (*b*) the magnetic field of the machine must be much distorted; (*c*) the path of the lines of force of the field coils must be long and of small area, so the *M.M.F.* cannot be readily changed; (*d*) the path of the lines of force due to armature magnetization must be short and of great area, so the *M.M.F.* of the armature will change with the slightest change of current; and (*e*) the pole piece must be worked at a high density.

Evidently extreme difficulty is found in so designing the different parts of the machine as to give proper consideration to each of the conditions and yet produce a machine that will regulate for constant current at all loads. This leads to the introduction of automatic mechanical devices for aiding in the regulation. These devices must not be considered as being the sole regulators, for in every case they are secondary to the natural self-regulating tendency of the armature. In general they regulate for the gradual and greater changes of load, while the armature reactions take care of the smaller and more sudden fluctuations.

There are two general systems of regulating arc dynamos. The first method is to cause the machine to develop an *E.M.F.* in excess of that required for the load, and to then collect an *E.M.F.* just sufficient for the load in hand. This is done by shifting the brushes from the neutral plane (§50). In a closed-coil armature this causes a counter pressure to be developed in those conductors lying between the neutral and the commutating planes. This reduces the pressure to the desired amount. In an open-coil armature the brushes, when in the maximum position, connect to the circuit those coils of the armature which at that instant have the maximum *E.M.F.* generated in them. By shifting the brushes either way coils can be connected to the circuit which have some *E.M.F.* less than the total *E.M.F.* generated in them, and the amount of shifting regulates the pressure on the line.

The second method of arc-light dynamo regulation is to vary the magnetizing force in the field magnets just enough to put the required pressure on the line. Since the magnetizing force is dependent on the ampere turns of the field coils, it can be varied either by cutting out or short circuiting some of the turns or by changing the current in them by means of a variable resistance which is shunted across the field terminals. In practice both these methods have been used.

Whether regulation is effected by changing the position of the brushes, or by changing the field excitation, sparking will occur at the points of collection of the current if means are not provided to avoid it. Non-sparking collection could be obtained if the field were perfectly uniform all around the armature. In general this condition is impracticable, since it requires almost the whole armature to be covered by the pole faces, and it requires the density in the gap beneath them to be uniform. Considerations of magnetic leakage and armature reaction render almost impossible the satisfying of these conditions. Another and more practical method is to employ for collection at one terminal of the machine two brushes connected in parallel. These are moved in opposite directions, thus giving the effect of a single brush of varying circumferential contact, whose center can always be kept in the neutral plane. This prevents bad sparking. The device is used quite successfully in practice. There is, however, some question as to the advisability of resorting to it.

9. The Brush Machine. — Fig. 102 shows a standard 160-light Brush arc generator, made by the General Electric Company. The armature revolves between the opposed pole faces of two sets of field magnets. Like poles are opposed to each other. The flux, therefore, takes a path out of the opposing pole faces into the arma-

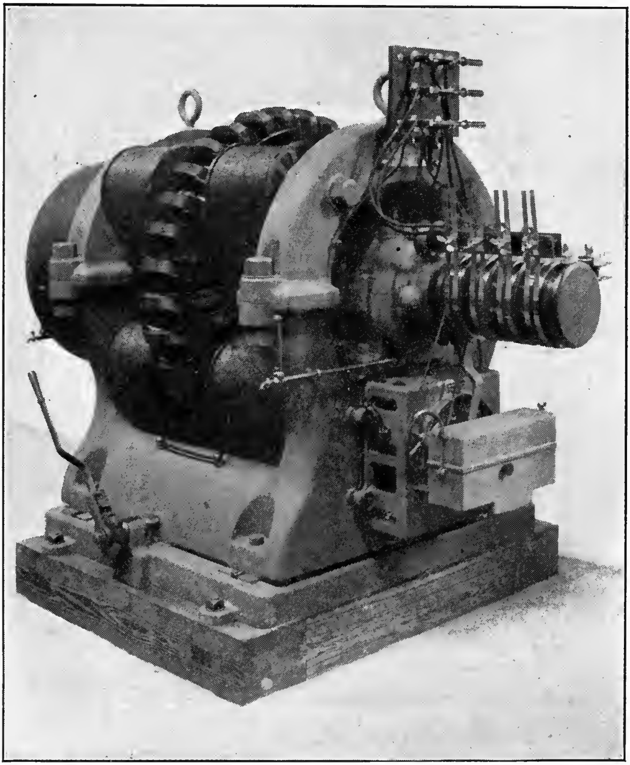

Fig. 102.

ture core, and then circumferentially through the core and out into the next pair of opposing pole faces.

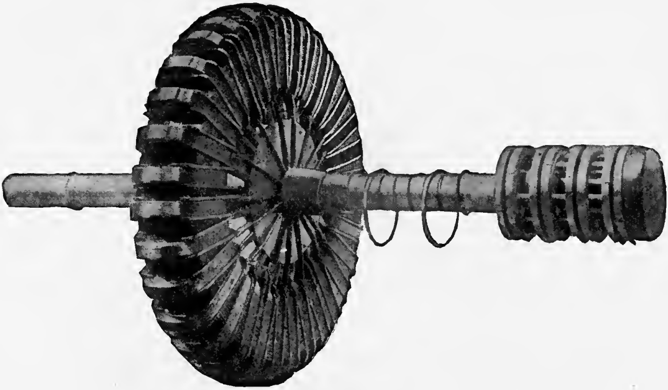

Fig. 103.

The armature, Fig. 103, consists of a number of coils or bobbins placed on a ring core of greater radial depth than breadth, and the pole faces cover the sides instead of the circumference. The bobbins are protected by an insulating box, shown in Figs. 104 and 105, but are not surrounded by any masses of metal. This fact, coupled with the fact that the armature is of such a shape as to cause great air

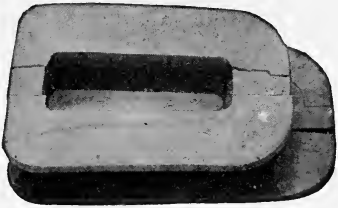

Fig. 104.

disturbance, insures exceptional ventilation of the armature, and tends to prevent the "roasting out" of the coils when subject to an overload. This machine is of relatively slow speed, the larger sizes running at only 500 *R.P.M.*

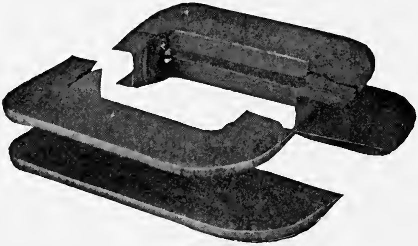

Fig. 105.

At a given instant of time, the different coils on the moving armature have *E.M.F.*'s of widely different magnitudes induced in them. The commutator, Fig. 106, is so designed that it connects the coils of highest *E.M.F.* in series with each other to the external circuit, and connects the coils of medium *E.M.F.* in multiple with each

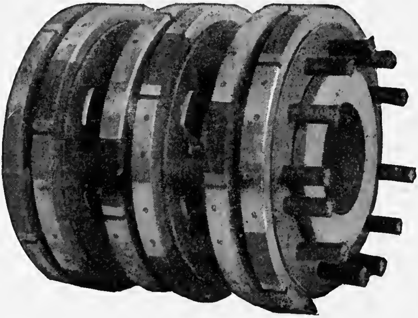

Fig. 106.

other to the external circuit, while those of smallest *E.M.F.* are cut out entirely from the circuit.

The bearings are self-lubricated by means of rings. Since the poles are on the sides of the armature, side play in the bearings must be prevented. To this end the commutator end of the shaft is turned with six thrust collars, as seen in Fig. 107, which are engaged by corresponding annular recesses in the brasses.

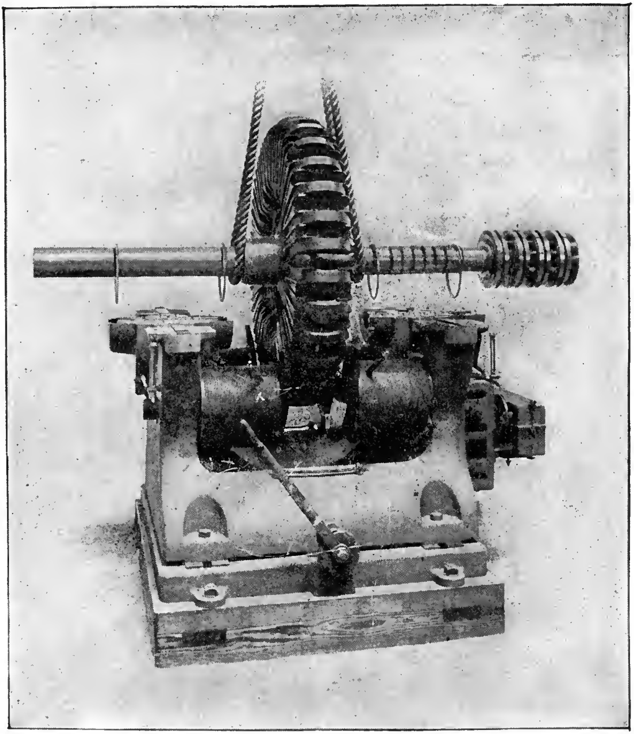

Fig. 107.

Regulation on these machines is effected by a variable resistance in shunt with the field coils; and as the field current is changed the position of the brushes is also changed, not to collect current at a lower voltage as described in § 78, but to obtain sparkless collection. These two operations are performed by a regulator (Fig. 108), which is attached directly to the frame of the machine. The mechanism consists of a rotary oil-pump driven by a belt from the armature shaft, a balance valve of the piston type, and a rotary piston in a short cylinder, which is directly connected to an arm sweeping the contacts of the field-shunt rheostat. The valve is operated by a lever

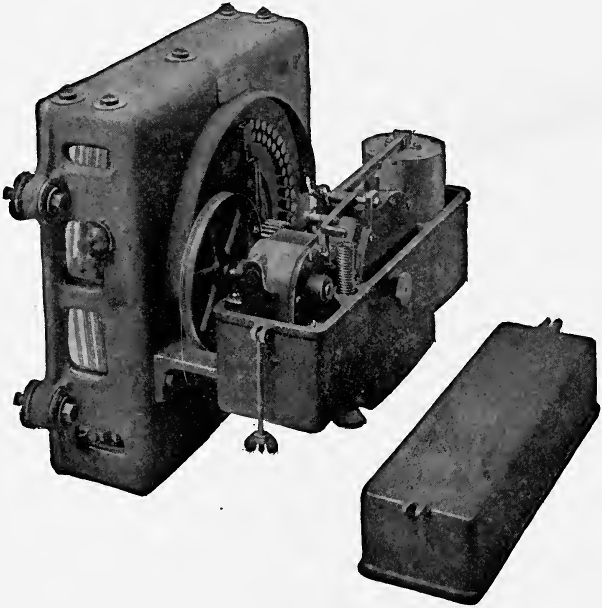

Fig. 108.

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actuated by a controlling electro-magnet which is energized by the whole generator current. At normal current the valve is centrally placed, and the oil from the pump flows around the overlapping ports into the reservoir without effect (See Fig. 109). If the current rises above the normal, the armature of the controlling magnet is attracted, the balance valve moves up, and oil enters the cylinder, moving the rotary piston in a clockwise direction. The shaft of this piston moves the arm of the rheostat, cutting out resistance and thus lowering the field exciting current. At the same time a pinion on the shaft, seen in Fig. 110, actuates a rocker arm which moves the brush holders to a position such that the collection by the brushes will be sparkless. When the current returns to normal the adjusting spring, seen in Fig. 111, returns the lever and balance valve to the central position. If the current falls

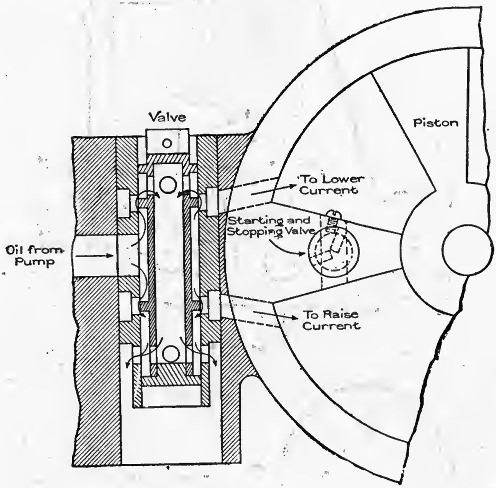

Fig. 109.

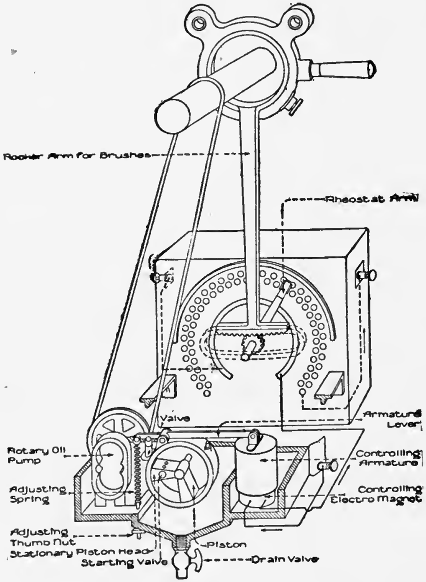

Fig. 110.

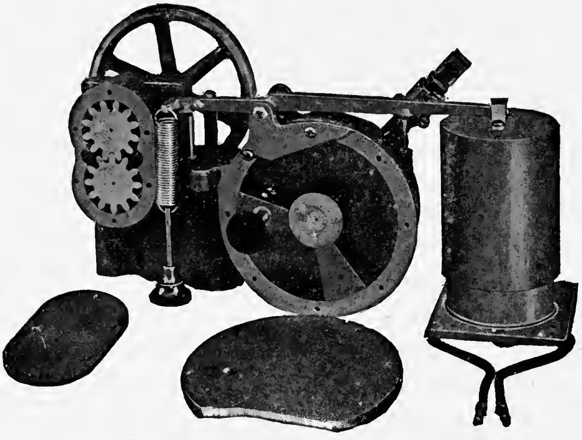

Fig. 111.

below the normal, these operations are reversed. The tension of the adjusting spring can be regulated from the outside of the dust-proof case by a hard rubber knob. From the nature of the case the parts are always well lubricated.

It is claimed for this regulator that it can bring the current back to normal from a dead short-circuit in from 3½ to 4 seconds.

80. The Westinghouse Arc-Light Machine. — Fig. 112 shows a 75-light direct current arc-lighting generator, made by the Westinghouse Electric and Manufacturing Company. It is of rigid construction, the bearing supports being cast integral with the frame. For facilitating transportation and repairs the yoke parts in the middle on a horizontal plane. The bearings are of the self-oiling, self-aligning type described in § 41. The armature shown in Fig. 113 is of the open-coil type, which gives a unidirectional but not absolutely continuous current. The slight pulsations of the current thus set up, while not affecting the steady mean value of the current, cause a slight constant vibration in the mechanism of the lamps that helps overcome any tendency to stick or a failure to feed the carbons. A unique feature of this armature consists in its having two separate sets of windings on the same core, each set having its own commutator. The coils and commutators are so arranged that while a set of coils of one winding is being cut into or out of the curcuit a set of the other winding is supplying current to the line. It is claimed for this method of connecting open-coil armatures, that it yields a more satisfactory current, and obviates the vicious sparking at the commutator found in other types of open-coil machines. The armature is made of laminated steel sheets punched with T-shaped teeth between the winding slots. The armature coils are wound on

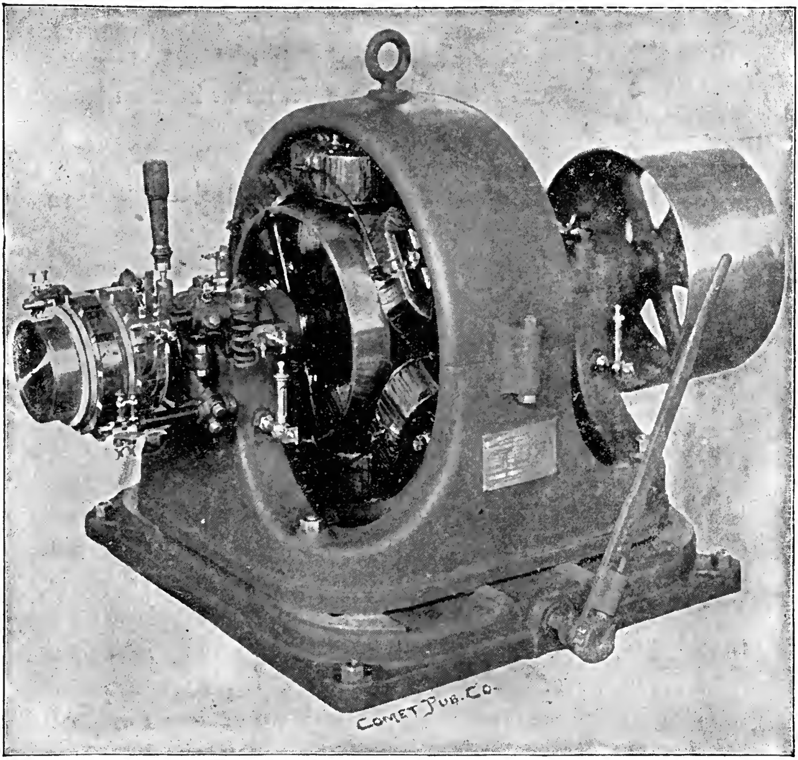

Fig. 112.

molds, and insulated and mounted on the armature as shown in Fig. 114. They are held in place by wooden wedges forced into the loops left at the ends of the armature. This construction admits of removing one coil for repairs without disturbing any of the other coils.

This machine differs from the general type of arc-lighting machines in that it is separately excited, a small auxiliary machine generating current for the field coils at 100 volts. This obviates the possibility of danger from a too high pressure resulting from an open circuit.

Regulation is obtained by careful design, so that the armature reactions cause the voltage to vary in just the proper proportions, as described in § 78. The exciting field current is regulated to give the proper excitation by a series rheostat. By this means the line current can be raised or lowered slightly if desired, without affecting the self-regulation.

Fig. 115 shows the double commutator of this machine. The segments are easily removed and replaced in case they wear or burn out.

Fig. 113.

81. The Wood Arc Dynamo. — Fig. 116 shows a Wood constant current dynamo for lighting 125 2000 c.p. lamps. This machine claims an efficiency of 90 per cent on full load. The bearings are self-oiling, and may be removed for repairs or inspection without removing the armature. The armature has large radiating surface and shallow winding, and its temperature does not rise more than 40° C. above the temperature of the room. This armature is of the closed-coil type, requiring a commutator of many segments with but a small potential between any two adjacent

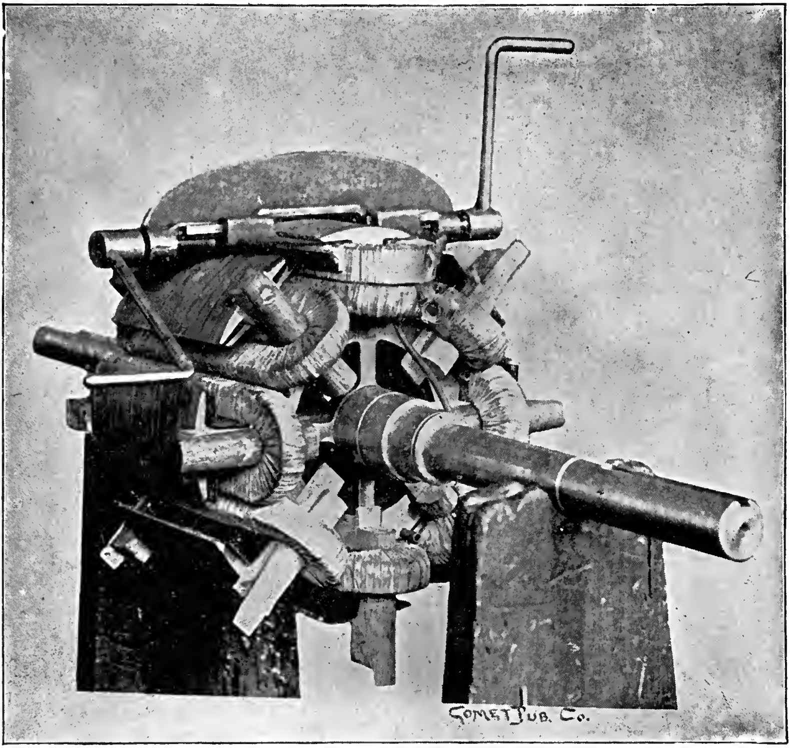

Fig. 114.

ones. This fact, and the use of two brushes in parallel, as explained in §78, obviates all sparking.

This machine operates by generating full pressure at all times, and by automatically setting the brushes to take off just such potential as is necessary. This allows of regulation without making use of rheostats, separate exciters, wall controllers, motors, or relays. The regulating mechanism is set in operation by a sensitive and rather powerful electro-magnet excited by the main armature current. This attracts a lever which is restrained by an adjustable coiled spring. A variation in the current strength causes this lever to throw into train one or the other of two oppositely revolving fiber friction cones, which, acting through gears and levers, shifts the brushes the re-

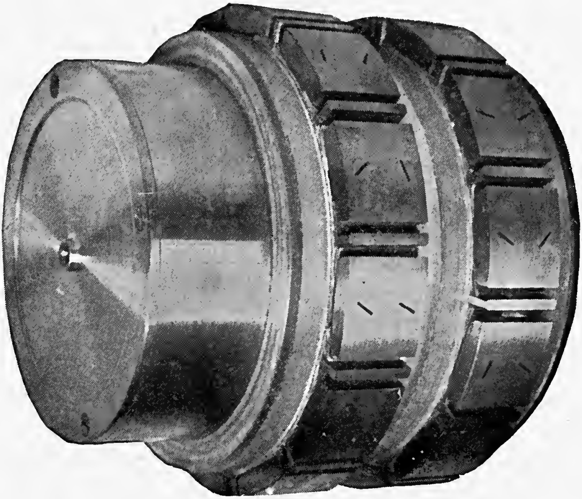

Fig. 115.

quisite amount, and also varies their angular contact or collecting extent. All the delicate parts of this mechanism are inclosed in the pillar supporting the commutator end of the armature shaft, and are thereby protected from injury, dust, and grit. The wearing surfaces of this regulator are all large and the speed is slow, so that wear is reduced to a minimum. Without any change of adjustments this regulator will operate when run either way, which is an advantage when two or more dynamos are run from one engine, and economy of space is essential, or in case of accident to a prime mover.

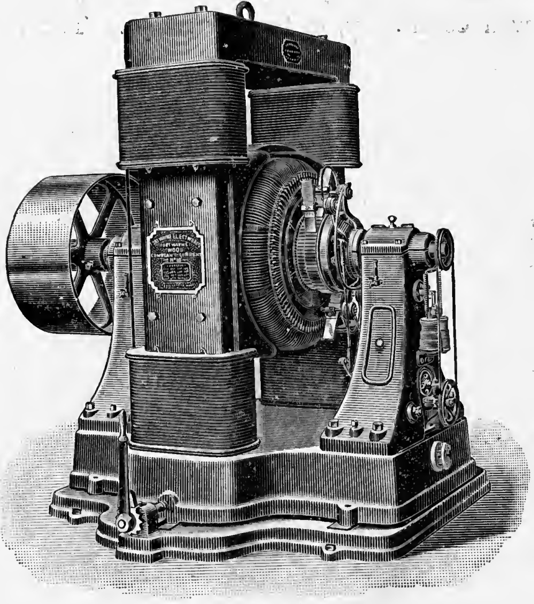

Fig. 116.

82. The Excelsior Arc Dynamo. — This machine, Fig. 117, is a closed-coil ring armature generator, having pole faces that cover both the sides and the circumference of the armature. The interesting feature of this machine is the method of regulation. The proper potential is supplied to the line by using both methods of control in conjunction; that is, sections of the field windings are cut in or out of circuit, and at the same time the position of the brushes is shifted. The proper motion of the field regulator arm and of the brush holder is obtained by means of a small motor whose field is "sneaked" from the main magnets of the machine. This motor is operated by a device shown in Fig. 118. The whole device is inserted in series with one of the mains from the generator. The right-hand lever is of insulating material, with the contact blocks *a* and *b* properly placed upon it. The left-hand lever is of conducting material, and is capable of being attracted by the electro-magnet which is excited by the main current. The magnet and spring are so adjusted that when the normal current is flowing, both *a* and *b* are in contact with the left lever, and the current flows in the

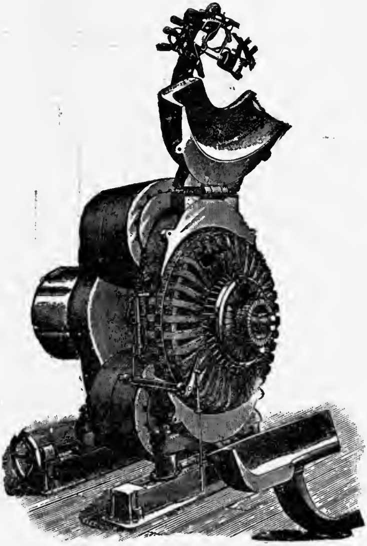

Fig. 117.

three shunt paths, R, R_1, and R_2. There will be no current in the armature of the regulating motor, since the potential at brush x is equal to the potential at brush y. If now the line current becomes too strong the magnet attracts the left lever to it and the contact at a is broken.

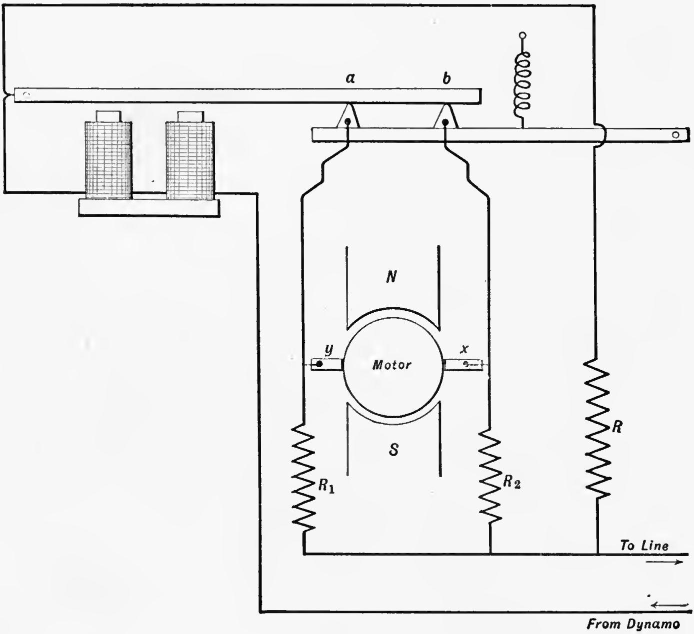

Fig. 118.

Immediately the current flowing through b divides at the brush x, part going through R_2 and part through the motor armature and R_1. The motor will then revolve in a given direction, and by simple mechanical devices will cut out sections of the field windings, and will shift the brushes until the normal current is flowing, when contact is again made at *a* and the controlling motor stops. If the line current drops below normal, the spring pulls the lever away from the magnet and the contact at *b* is broken. Part of the current then flows from *y* to *x* through the motor armature. It therefore revolves in a direction opposite to that which it had before. The brushes on the dynamo are shifted back again, and more sections of field winding are put into circuit.

In practice the levers and the magnet are mounted on the wall or the switch-board, while the regulating motor is mounted on the dynamo frame.

When the current is broken at *a* or *b*, there is no serious sparking, since there are always two circuits in shunt with the break. The whole current of the dynamo does not exceed ten amperes; and the resistances R, R_1, and R_2 are so proportioned that only a small portion of that flows through *a* or *b*.

83. The Ball Arc Generator.—Fig. 119 shows a double armature, automatic regulating constant current generator, made by the Ball Electric Company. Two independent circuits, each automatically controlled, can be operated from the one machine, since it has two distinct armatures, commutators, and regulators. The advantage claimed for this arrangement is that the pressure has to be but half as high as if the two circuits were united and fed by a single armature. Yet if it be undesirable to bring the ends of two circuits into the power-house, they can be connected in series, and fed by the two armatures also connected in series, and then the voltage per armature will be half that of a single armature machine giving like results.

The armatures are of the closed-coil ring type. The air

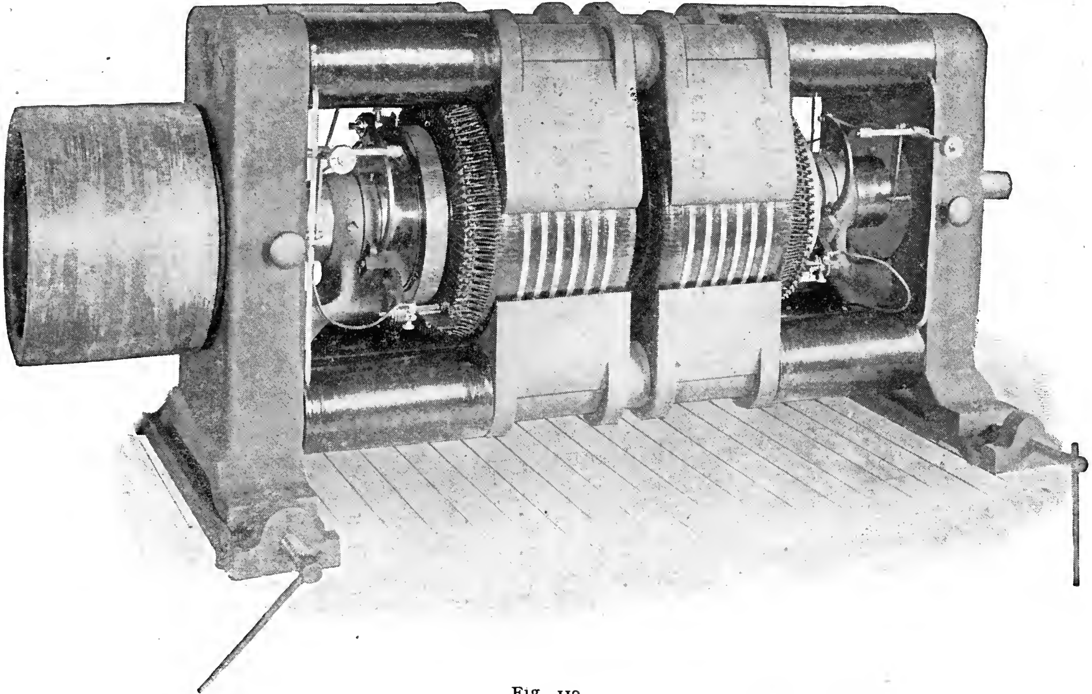

Fig. 119.

gap between pole faces and armature is short in length and great in area, requiring a minimum of magnetic excitation. The commutator is built up of a great number of segments, the potential between any two adjacent segments not exceeding fifteen volts. This assures sparkless commutation.

This generator is regulated by shifting the brushes until pressure of a suitable magnitude is collected.

A magnetic body placed in a magnetic field will tend to rotate until the longest axis is parallel to the magnetic lines of force. This principle is applied to the Ball regulator as follows: A magnetic portion of the brush carrier is made a part of the magnetic circuit, and is placed in a recess of the dynamo frame. It tends to assume an axial position with a force varying as the flux through it. As the line current increases the flux increases, and the brush holder, which is mounted on ball bearings, rotates, shifting the brushes the required amount. The impulse to regulate is applied directly to the brush holder, instead of being communicated to it by by a more or less complex mechanism. The magnetic tendency to shift the brush holder is opposed by gravity.

84. The Thomson-Houston Dynamo. — The Thomson-Houston arc generator is of a type entirely different from the other machines here described, not only in appearance, but also in method of armature winding and of regulation. A view of this machine is given in Fig. 120. Each field coil has for its core an iron tube, flanged exteriorly at each end to form a recess for the windings, and fitted at the armature end with a concave iron piece that surrounds part of the armature. This tube, with the flanges and the cup-shaped end, is cast in one piece. The farthermost flange of each field core is bolted to a number of wrought-iron connecting-rods which hold the magnets in place, protect the field windings, and take the place of the yoke of other machines in completing the magnetic circuit. The magnets are mounted on a frame, including legs and bearing supports for the armature shaft.

The armatures of the older machines of this type are spheroidal in shape, while the more recent ones have ring armatures which are more readily repaired or rewound. The winding of either form of armature is peculiar in that only three coils are employed, set with an angular displacement from one another of 120 degrees. In the ring armature no difficulty is found in properly winding these coils; but in the old spherical armature the following device was employed to secure the windings, and give each of them the same average distance from the pole face. A hollow spheroidal iron core was keyed on the shaft. The core had three rows of externally projecting wooden pins. Between these pins the coils were wound, half of coil *A* being wound first, then at 120 degrees distance half of coil *B* was wound, covering parts of coil *A*. Then at 120 degrees from both *A* and *B* all of coil *C* was wound. Over this, but in its proper angular position, the other half of coil *B* was wound, and finally the rest of coil *A* was put in place. By this arrangement the average distance of each coil from the pole face or from the iron core was the same. In either type of armature the inner ends of the three coils are joined to each other, and are not attached to any other conductor, an arrangement unique in direct current dynamos. The outside ends are connected to the segments of a three-bar commutator, from which the current is collected by four copper brushes connected in multiple.

Regulation is obtained by shifting the brushes in the following manner. Fig. 121 shows the two possible relations between brushes and commutator that may exist at any instant. Both brushes of each set may rest on one commutator bar, or the brushes of one set may span the

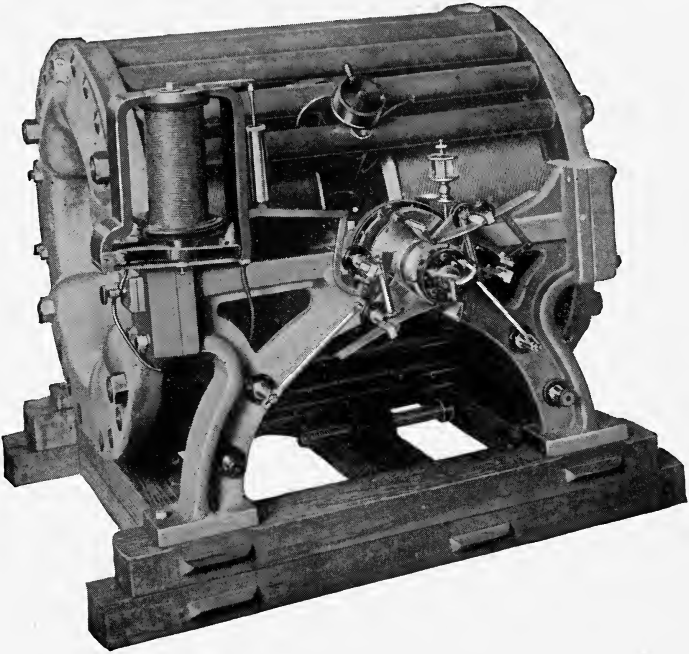

Fig. 120.

break between two of the bars. These conditions are repeated three times at each brush for each revolution. If the dotted line shows the position where the maximum *E.M.F.* is generated in the coils, then in Fig. 121*a* the two most active coils are connected in series with the outside circuit, while the coil near the position of least activity is out of circuit. In Fig. 121*b* the two less active coils are in multiple with themselves and in series with the most active coil and the external circuit. In practice the

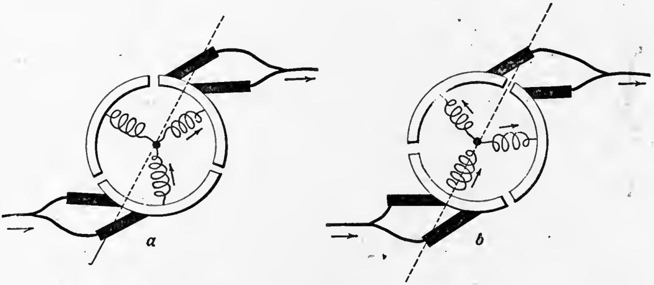

Fig. 121.

brushes of a set are 60 degrees apart, leaving 120 degrees between the leading brush of one set and the following brush of the other set; and since 120 degrees is the angular measure of the length of a commutator bar, there is no coil out of circuit at normal load, two being always in parallel and in series with a third. If the current rise above the normal the leading brushes move a small angle forward, while the following brushes recede through three times that angle. This will shorten the time that a single coil gives its whole *E.M.F.* to the circuit, and will place it more quickly in parallel with a comparatively inactive coil. But such a movement will reduce the angular distance between the nearest brushes of the opposite sets to less than 120 degrees, hence the machine will be short circuited six times per revolution, since one brush of each set will touch one segment of the commutator at the same time. If the current in the line falls below normal, then the brushes close together, and the time that a coil is in series is lengthened, and the time that it is in parallel with an inactive one is lessened.

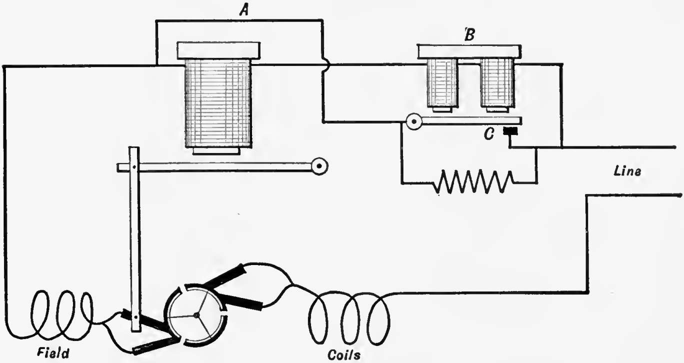

Fig. 122.

The arrangement for moving the brushes is shown in Fig. 122. The leading brushes are shifted forward on an increase of current merely to help avoid sparking. The brushes are moved by levers actuated by a series magnet *A*. This magnet is normally short circuited by the by-pass circuit. On an undue rise of current this circuit is broken by the series magnet *B*. *A* then becomes more powerful, and the levers separate the brushes. While the machine is in operation the circuit-breaker *C* is constantly vibrating, and brushes adjusting to suit the load. A high carbon resistance is shunted across *C* to prevent sparking at that point.

As might be expected, with but three parts to the commutator and collection made with small regard to the neutral point, the sparking of this machine is such as to speedily ruin the commutator and the brushes, if means are not taken to suppress it. A rotary blower is mounted on the shaft, and is arranged to give intermittent puffs of air, which at the right moment blow out the spark. The insulation between the segments is air, considerable gap being left between them, and through these gaps the sparks are blown.

85. Western Electric Arc Dynamo. — Fig. 123 represents this machine, which is regulated by means of shifting the brushes. The brush and rocker are connected by means of a link and a ball and socket joint with a long screw. This screw is held in position by a nut. When the current is normal, both the nut and screw revolve at the same rate, and consequently there is no end movement of the screw. The brush, therefore, remains stationary. An electro-magnet, energized by a coil which is in series with the main circuit, attracts an armature whose movement towards the magnet is opposed by the action of a spring which is susceptible of regulation. When the current has too high a value, the electro-magnet attracts its armature more strongly than ordinarily. The latter moves toward the magnet, and by its movement catches a stop on the revolving nut, and thereby prevents the revolution of the nut until the resulting longitudinal movement of the screw has shifted the brushes sufficiently to bring the current to its normal value. If the current be too weak, the spring which is attached to the magnet armature overpowers the electro-magnetic attraction. The resulting movement of the armature stops the rotation of the screw and permits the rotation of the nut. This results in a longitudinal movement of the screw and a shifting of the brushes in the opposite direction. The stopping and starting of the nut and screw is accomplished through the medium of small triggers controlled by the armature of the series magnet. The triggers are fastened to a gear rotated from the main shaft by a belt. They engage with stops on the nut and screw respectively.

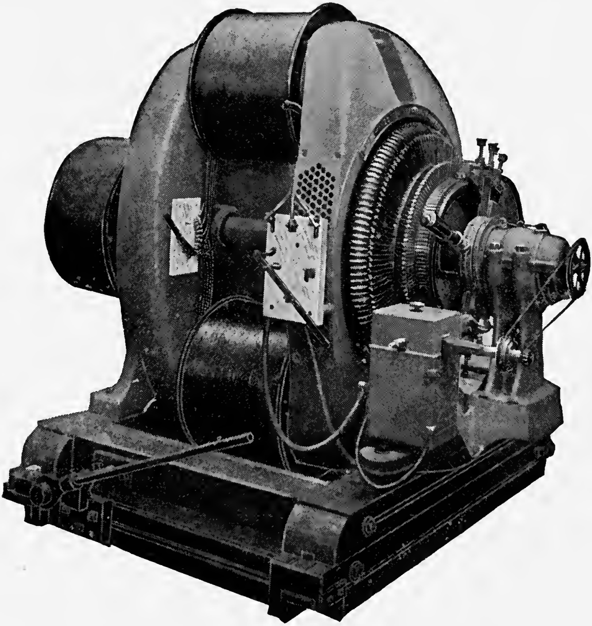

Fig. 123.

Fig. 124 gives a sectional view of the regulator, and the

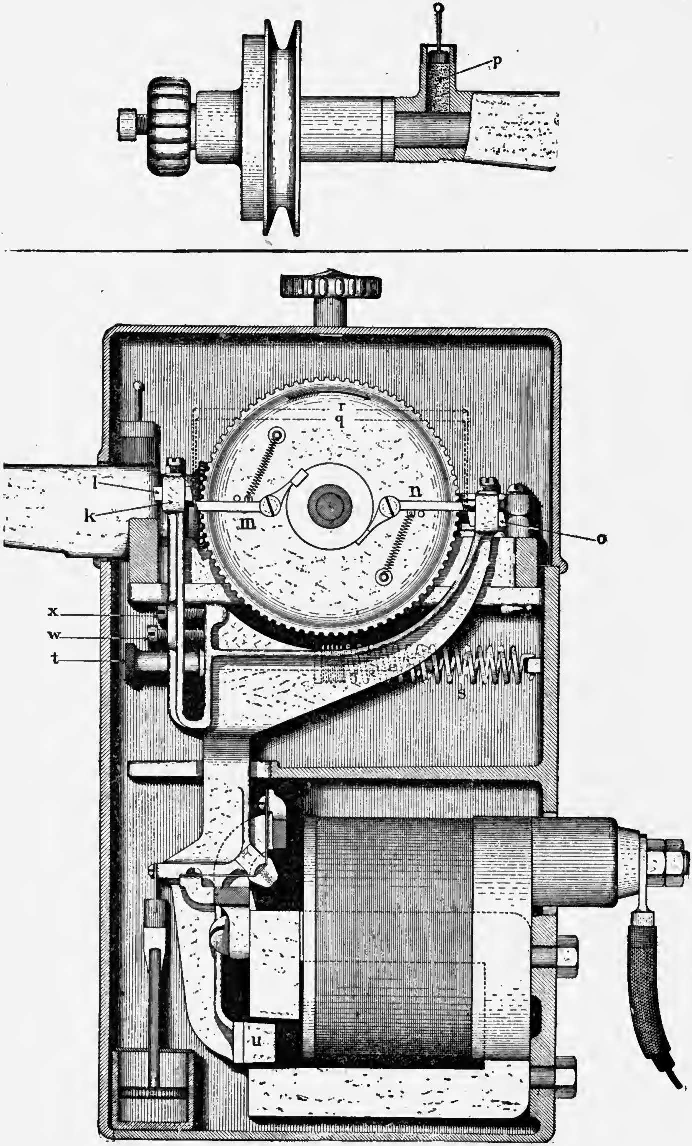

Fig. 124.

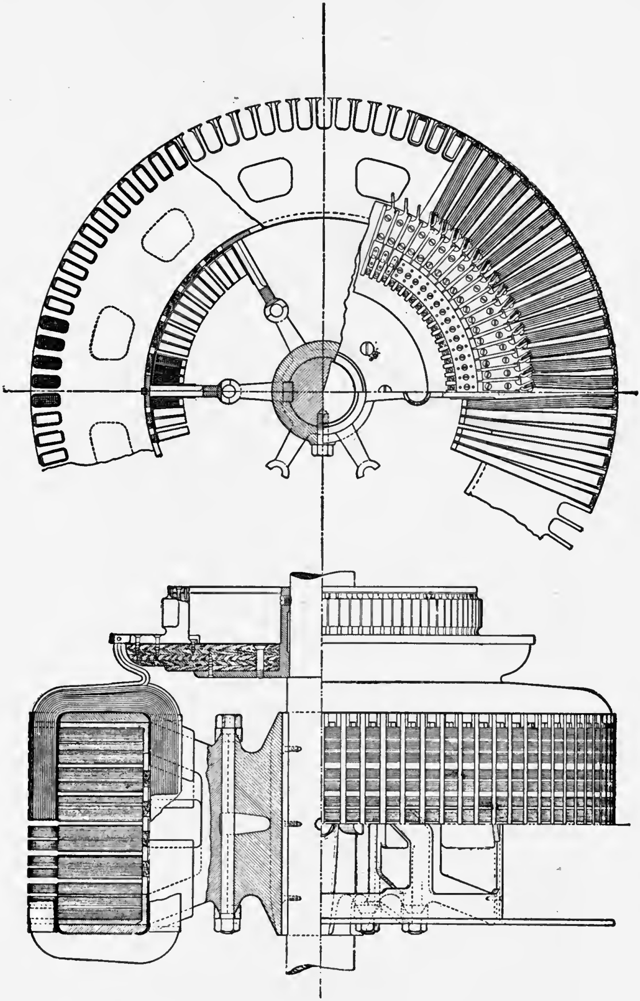

Fig. 125.

trigger which engages with the screw is shown at *n*, and the one which engages with the nut is shown at *m*.

Fig. 125 represents the details of the armature construction. The latter is ring wound with a large number of turns in each section.

CHAPTER IX.

MOTORS.

86. Principle of the Motor.—Any direct current dynamo will act as a motor if supplied with current from some external source. This source may be a constant *E.M.F.* system, a constant current system, or any other system. The rotation of the armature is a direct consequence of the conditions laid down in § 20. It is evident that if the negative and positive terminals of a dynamo be connected with the corresponding terminals of some external source of supply, the direction of flow in the armature will be reversed. Irrespective of the multipolarity of the field or of the method of armature winding, the electro-dynamic actions between the field and all the currents in the inductors will conspire to produce rotation in one direction.

87. Direction of Rotation.—To determine the direction of movement of an inductor carrying a current of known direction in a magnetic field of known direction, one may employ a modification of Fleming's rule. Thus in a dynamo the thumb and two first fingers of the right hand determine the direction of induced *E.M.F.* as shown in Fig. 126. But in a motor the thumb and two first fingers of the *left* hand can be made to determine the direction of motion as shown in Fig. 127.

If in a dynamo the direction of the field flux be not altered, and if the armature be supplied with a current flowing in the same direction as when the machine was operated as a dynamo, the direction of rotation will be reversed. Thus, if the positive brush of a dynamo be connected to the positive terminal of an external source of supply, and if the negative brush be connected to the negative terminal, then the direction of current flow in the armature will be reversed. The direction of rotation of the armature, in series-wound machines, since the field flux has its direction also changed, will be reversed. In shunt-wound, separately excited, and magneto machines, since these do not have their fields reversed, the direction of rotation will be *unaltered.* Compound-wound machines will have the *same* or *reversed* direction of rotation, depending upon whether the magnetizing effect of the shunt coils is stronger or weaker than that of the series coils. In a compound generator the actions of the shunt coils and the series coils are cumulative, i. e., in the same direction ; but when used as a motor the actions are differential, i. e., opposed to each other. Motors are also wound so as to have cumulatively acting series coils.

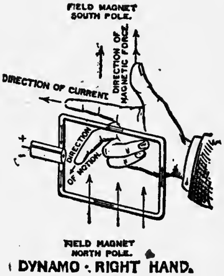

Fig. 126.

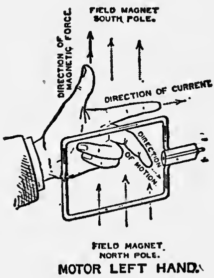

Fig. 127.

88. Speed Conditions. — If an electric motor be supplied with electrical energy, it will vary its rate of rotation until it has attained such a speed as will produce an equality between the input of energy and the output of energy. The latter appears both as useful work and as losses. In the case of a motor, speed acts toward electrical energy like temperature in the case of heat energy. Temperature always rises until the heat energy which is produced is equal to the heat energy which is disposed of by conduction, convection, and radiation.

The electrical energy which is communicated to a motor is transformed, *a*, into useful mechanical energy, which is taken from the armature shaft either by a belt or by direct connection; *b*, into friction at the bearings and at the brushes; *c*, into windage; *d*, into foucault and eddy currents; and finally *e*, into ohmic heat energy in the motor's electrical circuits. The energy required per unit of time to overcome friction, windage, hysteresis, and foucault and eddy currents increases as the speed of rotation increases. Nearly all practical loads put upon a motor — machinery in one form or another — require an increase of power for an increase of speed. Therefore, if a given amount of electrical power be communicated to a motor under load, the armature will assume some speed of rotation, so that a balance between the input and the output of energy is maintained.

89. Counter *E.M.F.* — If the variation of losses and useful energy with the speed were the only conditions governing the speed, then there would result in practice variations of speed through enormous ranges. But there is another condition affecting the speed. The armature, by varying its speed, not only governs the rate of expenditure of energy, but also governs the amount of electrical energy received.

The armature of a motor revolving in a field under the influence of supplied electrical energy differs in no respect from the same armature revolving in a field under the influence of supplied mechanical energy. There is an *E.M.F.* generated in it which is determined by the speed and quantity of flux. For the same speed and the same flux there would be generated the same *E.M.F.* in the case of a motor as in the case of a dynamo. The direction of this *E.M.F.* is, however, such as to tend to send a current in a direction opposite to that of the current flowing under the influence of the external supply of *E.M.F.*, according to § 87. Therefore this pressure which is induced in the armature of a motor is called *counter electro-motive force*. The current which will flow through the inductors of an armature is therefore equal to the difference between the supply *E.M.F.* and the counter *E.M.F.* divided by the resistance of the armature, or

$$I_a = \frac{E_s - E_c}{R_a}.$$

For example, an unloaded 1 K.W. shunt motor having an armature resistance of 1 ohm, when connected to a constant source of potential supply of 100 volts, would not take a current of 100 amperes as dictated by Ohm's law, unless its armature were clamped so as to prevent rotation. If unclamped, its armature would assume such a speed that it would have induced in it a counter *E.M.F.* of say 97.5 volts. The current then flowing in the armature would be

$$\frac{100 - 97.5}{1} = 2.5 \text{ amperes.}$$

The power represented by this current, viz., 2.5 × 100 watts, would all be expended in overcoming the losses of the machine.

90. Armature Reactions. — Since in a motor, for a given direction of rotation and flux, the current in the armature flows in a direction contrary to that which it would have as a dynamo, therefore the effect of the motor armature cross turns is to skew the field against the direction of rotation, as in Fig. 128. Tnis increases the magnetic density in the leading pole tip, and decreases it in the trailing tip. This necessitates, for sparkless operation, a *backward lead*, or a *lag*, of the brushes. If the brushes were in the same place as when the machine was operated as a generator, the direction of armature current having been reversed, then the demagnetizing or back turns of the generator would become magnetizing turns for the motor; but with the brushes shifted to a position of lag, then the motor has also demagnetizing or back turns.

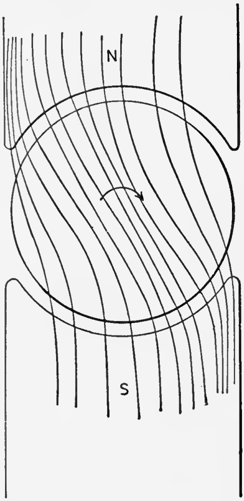

Fig. 128.

91. Efficiency. — In a compound-wound motor connected to a constant pressure supply,

Let R_{sh} = resistance of shunt field coils,
R_{a+s} = resistance of armature plus that of the series field coils,
V = number of revolutions per minute,
T = torque given off at the pulley in pound feet,
E = supply voltage,
I_n = no-load armature current in amperes, and
I = armature current when torque T is yielded.

$$\text{The efficiency} = \frac{\text{useful power output}}{\text{electrical power input}},$$

hence,

$$\epsilon = \frac{2\,\pi VT\,\frac{746}{33000}}{EI + \dfrac{E^2}{R_{sh}}}.$$

The useful power can be expressed as the difference between the power input and the losses. Now at no load, when there is no useful power output, the following relations exist :

$$EI_n + \frac{E^2}{R_{sh}} = \text{power input},$$

and

$$I_n^2 R_{a+s} = P' = \text{power in the armature and series coils.}$$

Assuming the friction, the windage, the foucault current, and the hysteresis losses to be constant and the same as at no load, we have for their value a constant loss = the no-load power input − the variable loss.

Hence,

$$\text{The constant loss} = P_f = EI_n + P_{sh} - P',$$

where

$$P_{sh} = \text{loss in shunt coils} = \frac{E^2}{R_{sh}}.$$

The efficiency under load will therefore be

$$\epsilon = \frac{EI - P_f - I^2 R_{a+s}}{EI + P_{sh}}.$$

In a shunt motor R_{a+s} represents the armature resistance only ; hence,

$$\epsilon = \frac{EI - P_f - I^2 R_a}{EI + P_{sh}}.$$

In a series motor $P_{sh} = 0$; hence,

$$\epsilon = \frac{EI - P_f - I^2 R_{a+s}}{EI}.$$

In the first of these three expressions for efficiency, solving for that value of I which will give a maximum efficiency, we have

$$\frac{d\epsilon}{dI}=\frac{(EI+P_{sh})(E-2\,IR_{a+s})-(EI-P_f-I^2R_{a+s})E}{EI+P_{sh}}=0,$$

whence

$$I=\pm\sqrt{\frac{P_f+P_{sh}}{R_{a+s}}+\frac{P_{sh}^{\,2}}{E^2}}-\frac{P_{sh}}{E}.$$

Fig. 129 gives a set of curves indicating the performance of a motor whose fixed losses are large. Fig. 130

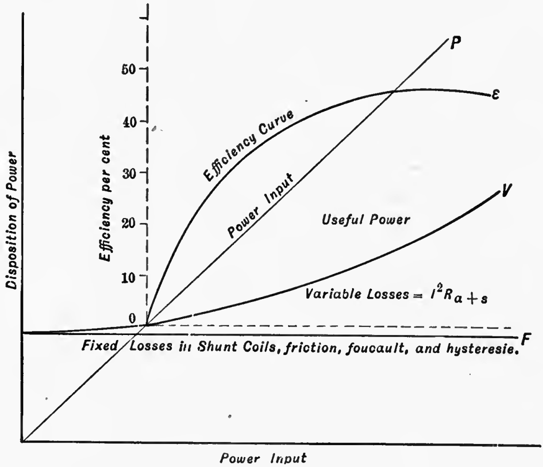

Fig. 129.

gives a set of curves for an exactly similar machine save that the fixed losses are smaller. They might be considered as taken from the same machine as the first, but with journals better oiled, and hence with less friction loss. The difference in the efficiency curves is noticeable.

Abscissæ in all cases represent power input. The ordinate of P at any given load shows the power input at that load. The constant ordinate of F represents the power consumed by the fixed losses, which is constant for all loads. The ordinates of V, measured from F, follow the law I^2R_{a+s}, and represent the variable loss at various loads. Therefore the total loss for any load is represented by the total ordinate of V at that load. The difference between the power input and the losses gives the useful power, which is represented by the difference of the ordinates of P and V. The values of the ratio $\frac{\text{useful power}}{\text{power input}}$ for each load are plotted in the efficiency curve. Comparing the curves of the two machines, it is seen that to get a high efficiency at full load the variable loss must be kept small, while to obtain a good efficiency at small loads, the fixed

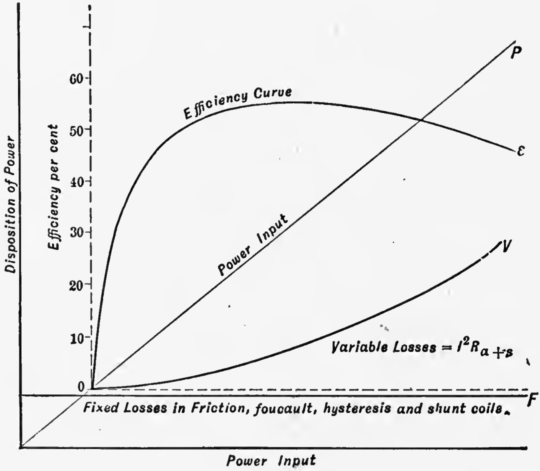

Fig. 130.

losses must be made small. The shape of the efficiency curve can be controlled by a proper adjustment of the relation which exists between the fixed and the variable losses.

92. Starting Rheostats. — When the armature of a motor is at rest there is no counter *E.M.F.;* and at the instant of closing the circuit a destructive current would flow if a resistance were not first inserted in the circuit, except in the case of very small motors whose armatures have small moments of inertia. As the speed increases the resistance can be lessened without allowing too severe a current to flow, and when full speed is obtained the resistance must all be cut out to avoid loss. In order that counter *E.M.F.* may be generated from the start, the shunt field circuit must first of all be closed. These ends are obtained by the use of a *starting-box or rheostat,* the wiring of the ordinary type of which is shown in Fig. 131. Its main feature is a contact arm pivoted at its center, and revolving through almost 180°, making various contacts. This arm is connected to one terminal of the supply as shown. As it is slowly turned on, one end of it first makes a connection which completes the shunt field circuit. Then the other end makes a contact which closes the armature and series coils through the maximum resistance of the starting-box. As the speed increases, the revolving

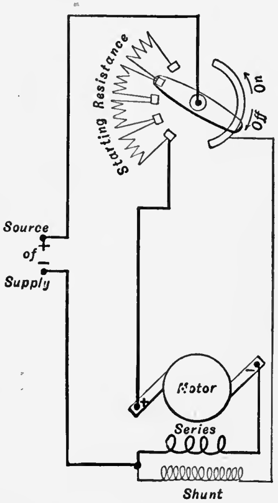

Fig. 131.

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arm is made to cut out the resistance, piece by piece, until it is finally all out of the circuit and the machine is running independent of the starting rheostat.

Fig. 132 shows such a starting-box as made by the Crocker Wheeler Company. The brass contact points and the arm are mounted on a slate slab, which serves as the top of an open-work cast-iron box which contains the resistances in the form of spiral coils of bare wire. The wire is generally either of German silver or of some one of the special iron alloy resistance materials.

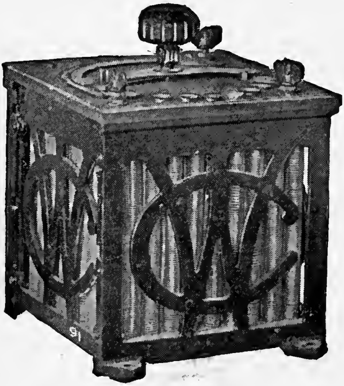

Fig. 132.

A shunt motor may have its armature coils destroyed by an excessive rush of current resulting from a dropping or ceasing altogether of the supply voltage followed by a sudden renewal after the speed of the armature has fallen. These conditions may arise through accidents to mains or because of a too heavy load on mains of insufficient cross-section. An armature may also be burned out by an excessive current due to overloading the motor. The resulting lowering of its speed is accompanied by a corresponding lowering of the counter *E.M.F.* Again, a too high supply voltage, which might result from some cross or other accident might cause a destructive rush of current. To meet these conditions, starting rheostats are often made with attachments for opening the circuit on *no voltage* or low voltage, and

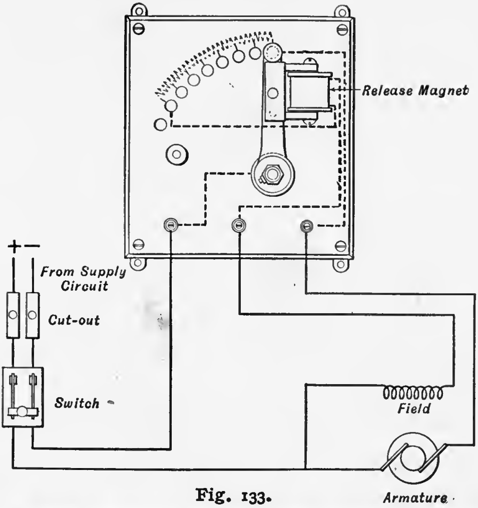

Fig. 133.

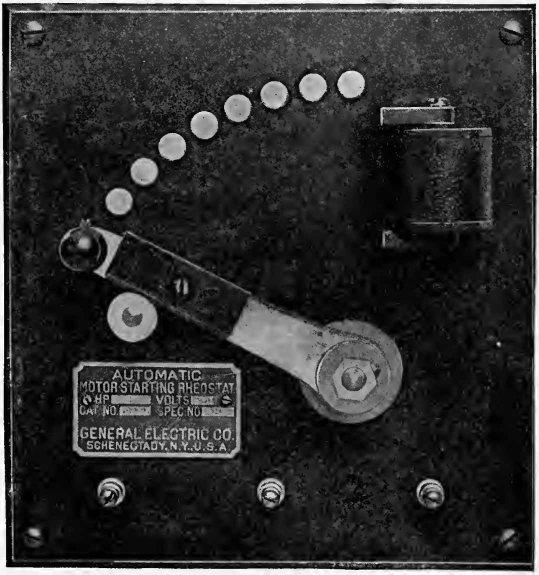

Fig. 134.

others with attachments for opening the circuit on *overload.* Some have both attachments, but it is modern practice to remove the overload attachment from the starting-box and put it on the switchboard. Fig. 133 is a diagram of the wiring of a starting rheostat for a shunt motor with automatic release and low-voltage attachment. Fig. 134 gives a front view of this same instrument. When the starting-

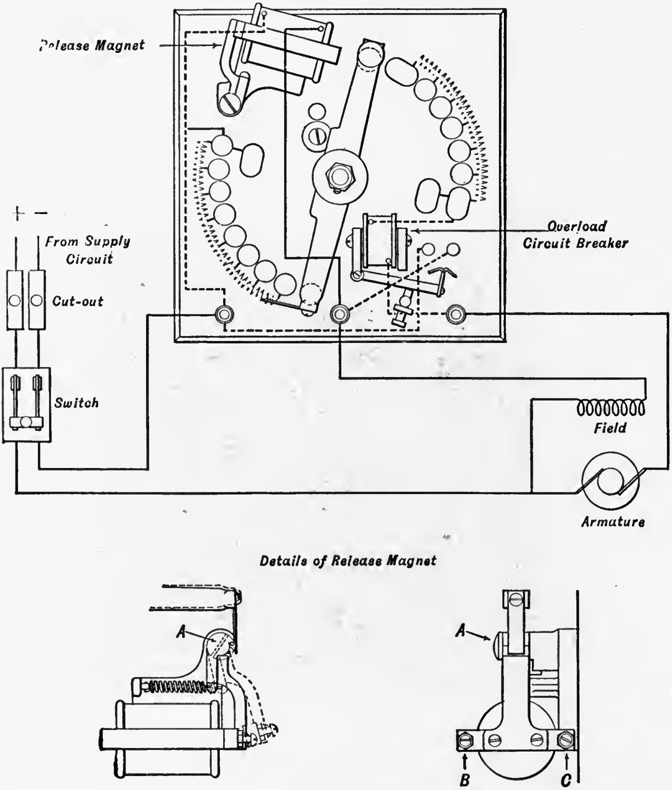

Fig. 135.

handle is placed in the "on" position, the magnet in the field circuit holds it there, although a spring tends to throw it back. If now, because of low voltage, the current in field and magnet becomes weak, the magnet is no longer able to detain the handle, and the spring throws it to the "off" position, where it stays until the motor is again turned on by an attendant.

Figs. 135 and 136 show a view and a diagram of the wiring of a rheostat with both release and overload attachments. The former is similar to the one just described, while the overload attachment consists of a magnet in the armature circuit which on overload becomes strong enough to attract to itself a pivoted iron arm supplied at its end with a device which short circuits the field current around

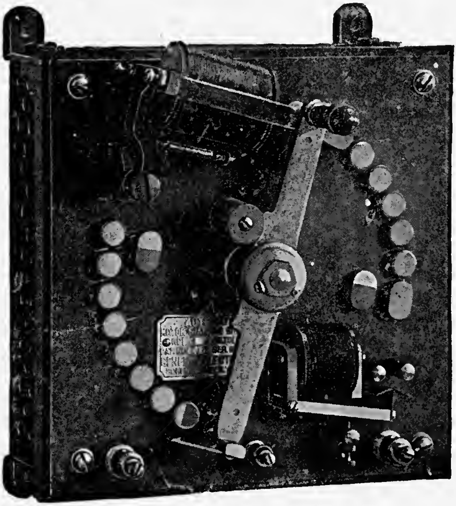

Fig. 136.

the release magnet. This causes the latter to let the starting-handle drop as in the case of low voltage.

93. Characteristic Curves of a Shunt Motor. — A shunt motor, having a small R_a and a large R_{sh}, and having the field well saturated, will give a fairly constant speed under all loads, if supplied from a constant pressure circuit. This is shown by the curves in Fig. 137, which are from a bipolar, shunt-wound, 10 horse-power, 230-volt Crocker Wheeler motor.

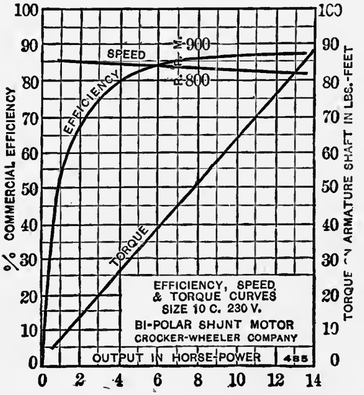

Fig. 137.

A shunt motor when started cold on no load quickly arrives at a speed which then *gradually* rises to a maximum. The gradual heating of the field coils increases their resistance. This allows less current to flow in them, and the resulting magnetic flux is less. Therefore the armature must rotate faster to generate the same counter *E.M.F.*, as explained in § 89.

94. Compound-Wound Motors. — In silk-mills and other textile factories where any slight variation in the speed affects the character of the manufactured product, compound motors give a satisfactorily constant speed. The object of the compounding coils is to weaken the flux in the armature as the load increases. If, at a given load, under the influence of shunt excitation alone, the speed would fall a certain per cent of the speed at no load, then the armature flux must be lessened by the same percentage in order to bring the speed up to its original value. In calculating the number of series turns, account must be taken of the fact of magnetic leakage, since the regulating coils are on the field magnets and not on the armature direct. Cumulatively compound-wound motors are used in order to obtain a large starting torque. The influence of the series coils is not very great after full speed has been attained.

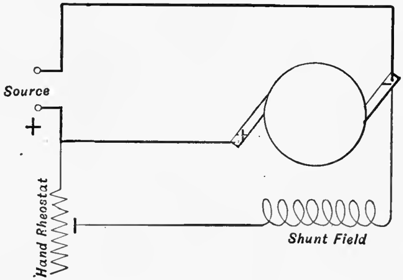

Fig. 138.

95. Hand Speed Regulation. — A rheostat placed in the field circuit of a shunt motor can be used to vary the speed of the motor at will, as in Fig. 138. An increase of the resistance will decrease the current in the field coils. As a result the armature magnetic flux will decrease and hence the speed will *increase*. If the fields be pretty well saturated, it will require a resistance of some considerable size, say twice as large as the field resistance, to cut the current down enough to materially reduce the flux and increase the speed. Motors of older make seldom had fields magnetized anywhere near saturation. Therefore they are very susceptible to the slightest change of resistance in their field circuits. If the demagnetizing armature ampere turns be large, it is possible for a motor to increase its speed under increase of load. This is due to the decrease of armature flux.

96. Speed Regulation by Series Resistances. — The speed of a motor on a constant pressure circuit can easily be varied over a wide range, from rest to full speed, by manipulating a resistance in series with it. The use of this method is not to be advised save for experimental purposes, since it is very wasteful of energy. The I^2 R loss in the regulating resistance is sometimes considerably more than the power actually used. Fig. 139 shows the wiring for this style of regulation.

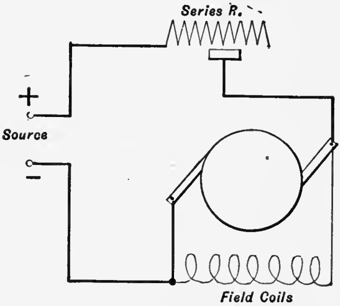

Fig. 139.

97. The Leonard System of Motor Speed Control. — This system is especially advocated for use in operating elevators, cranes, battleship turrets, and all equipments requiring a thorough control of the speed and precision of stoppage. Fig. 140 shows the arrangement of such a system. M is a motor whose field is separately excited all the time from a source of constant potential, E. G is a dynamo which generates power for the armature of motor M. The armature of the dynamo G is maintained at approximately constant speed by the prime mover S, which may be a steam engine or a motor run by power taken from the source E. The generator G is separately excited by current derived from E and controlled by the reversing rheostat C.

When it is desired to start the motor, the field of the generator is weakly excited by moving the controller so that a high resistance is in circuit with the field. This causes the dynamo to send current of low potential to the armature of the motor *M*. The latter then starts to move slowly. To accelerate the speed, more resistance is cut out of the controller. The pressure of the current supplied to the motor armature simultaneously increases and with it the motor's speed. Since the power represented by the current required to excite the field of *G* is at most but a small fraction of the useful power given out by the motor, the I^2 R loss in the resistance *C* is very much less than would be the loss in a series regulating resistance as described in the last section. It is claimed that the extra first cost of this system is offset by the decreased cost of repairs, since violent stresses and bad sparking are avoided.

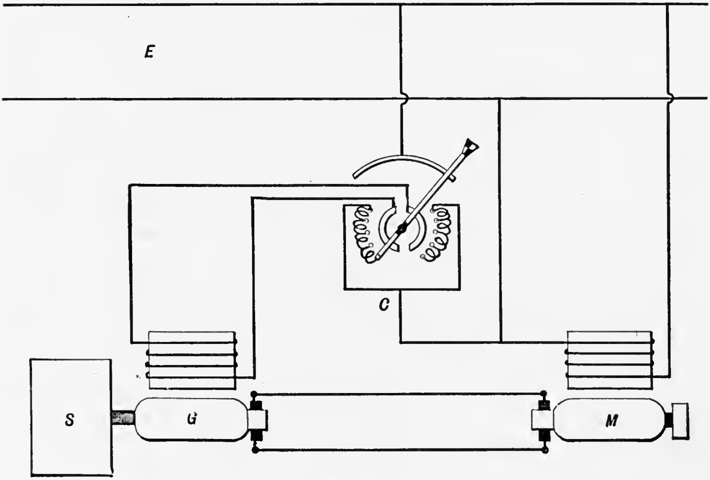

Fig. 140.

98. Slow-Speed Motors. — It is a practical advantage to have a motor connected directly to the machine it is to operate, without the intervention of belting or reducing gears. Slow speed is also of advantage where absence of jarring is desired or where many stops and starts are to be made. Slow speed can always be obtained from an electric motor; but it is generally expensive, since the natural speed of motors as well as of dynamos is high. Increase of magnetic flux and increase of armature diameter is necessary to obtain slow speed. The increase of material increases both the first cost and the losses during operation.

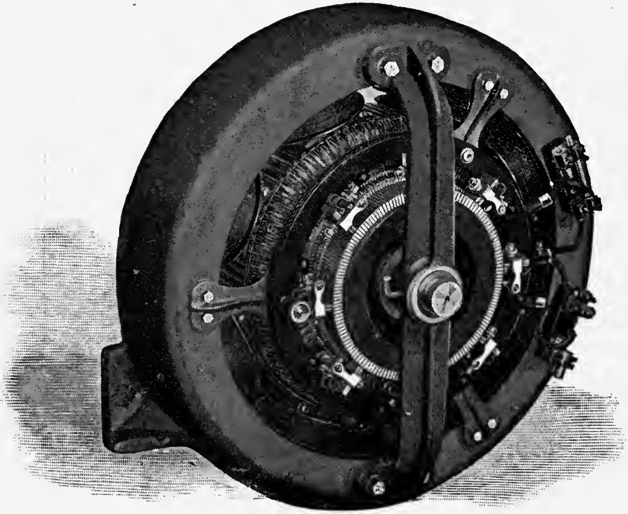

Fig. 141.

The power of a motor is its torque or turning moment multiplied by the number of revolutions; hence for the same output of work, a machine making half as many revolutions as another must have twice the turning moment. These conditions make it imperative that the materials of construction, both iron and copper, be worked at maximum magnetic and current densities respectively, in order to economize in first cost and weight. In general the efficiencies of low-speed motors do not compare favorably with those of motors having a higher speed. Fig. 141 is a cut of a Crocker Wheeler eight-pole, direct current motor for direct connection. It will furnish 2 horse-power at 100 revolutions per minute, 4 horse-power at 200 *R. P.M.*, and the quotient of its speed per minute by its full load horse-power is equal to the constant quantity 50. Its efficiency increases as the speed according to the curves shown in Fig. 142.

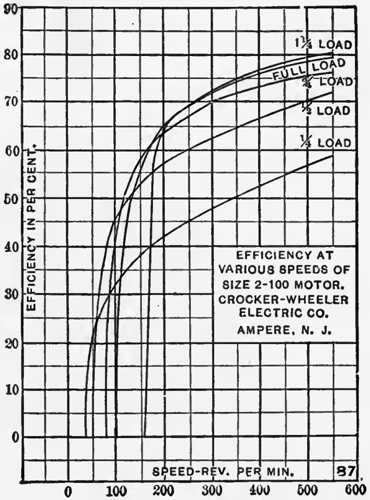

Fig. 142.

99. Brake Motors. — For cranes, elevators, and hoists, where it is necessary to hold the load after raising it, and for looms and printing-presses, where it is important to secure a sudden and accurate stop instead of a gradual slowing down, it is desirable to use motors with a brake attachment. A brake operated by hand or foot requires careful operation lest it be applied too soon and injure the machine, or too late and allow the load to fall some; hence an automatic brake is desirable.

Fig. 143 shows the construction used by the Crocker Wheeler Company. One of the pole pieces is pivoted at its base, and thus has a slight motion to or from the armature. It is normally held from the armature by a heavy coil spring, and in this position tightens the brake band. The moment that current is allowed to pass through the field coils, the poles attract each other, overcoming the resistance of the spring, and the brake band is thus loosened. The spring and band may be adjusted to allow a few revolutions before stopping, or the armature may be clamped the instant current is turned off. In the latter case, if connected to heavy machinery, shafting or gearing may be broken.

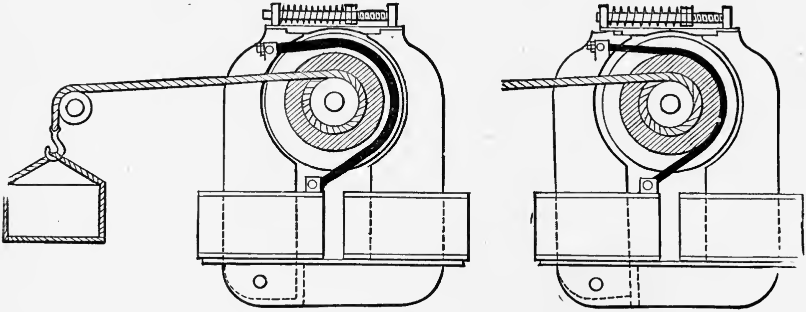

Fig. 143.

Strap brakes are cumulative in their action; the friction on the free end of the brake against the drum tightens the whole brake, thus increasing its effect. This action is only obtained when the motion of the drum is away from the fixed end. To obtain powerful brake action, therefore, on motors that run either way, as in elevator motors, a reversing brake is employed. This is operated by the movement of one pole piece as before, but the ends of the brake band are attached to a system of links and levers so that either end may become the fixed end. This construction is shown diagrammatically in Fig. 144. When the brake is applied, the friction causes the whole band to follow the drum until the sliding link attached to one or the other end of the band is held by the stud. The other, or free, end of the band, is tightened by the pull of the levers on one of the smaller straps attached to the brake band as shown. Fig. 145 shows a one horsepower Crocker Wheeler motor fitted with reversing brake.

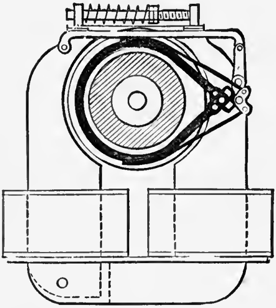

Fig. 144.

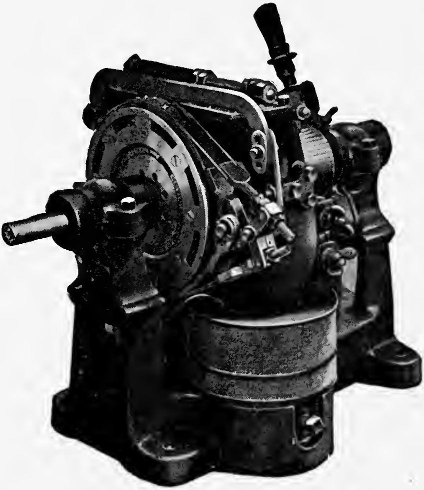
Fig. 145.

In multipolar machines it is impracticable to employ a moving piece, and in large bipolar machines it is undesirable to interrupt the magnetic circuit by a pivot joint; hence a solenoid brake is employed. This is simply a spring actuated friction brake kept normally in engagement. On current being supplied to the machine a solenoid acts to release the brake. The operation of this type is clearly seen by inspecting Fig. 146.

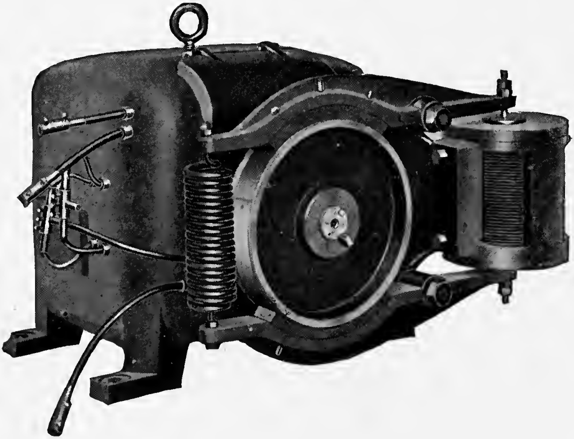

Fig. 146.

An objection to this type of automatic brake is that it consumes electrical energy all the time that the machine is in motion.

100. Recording Meters.—The recording watt-hour meter, Fig. 147, is coming into extensive use, both as a station instrument and as a measurer of the quantity of energy supplied to individual consumers. It is a very delicately adjusted compound-wound motor, having no iron in its magnetic circuit. When a current flows, the time integral of the watts or power is registered, by means of a train of wheels operated by the armature, on a dial similar to that of a gas-meter. The connections for such a meter are shown in Fig. 148. The armature is connected in series with a high resistance across the service wires; hence the current flowing in the armature is proportional to the volts of the supply. The field coils are in series with the service, giving a field strength proportional to the current, and the motor effort is proportional to the product of the two or to the watts supplied. The shunt field coils are added to compensate for the friction of the moving parts. Since a small current is always flowing in the armature, as well as in the

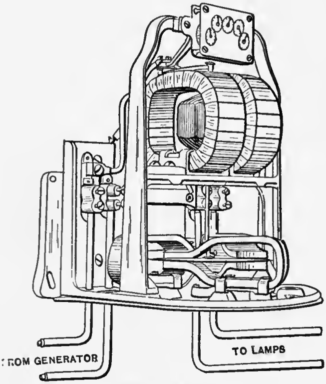

Fig. 147.

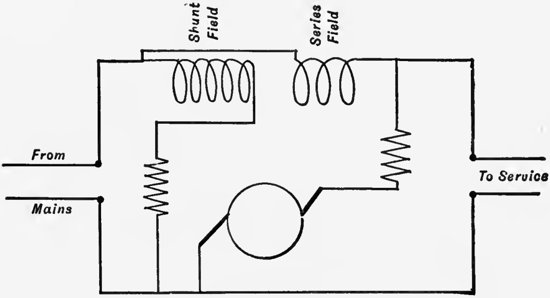

Fig. 148.

shunt field coils, the motor is always slightly excited, and by regulating the number of shunt turns the amount of this excitation is adjusted so that at no load on the service wires the armature almost, but not quite, moves. If it were not for this constant excitation, a small, though continuous, current could be drawn off the mains without operating the recording mechanism because of its friction. To control the speed a copper disk is mounted on the armature shaft and between the poles of two or more adjustable and permanent horseshoe magnets. When the armature revolves, Foucault currents are set up in this plate, and cause the proper retardation. By moving the poles of these horseshoe magnets from the center to the circumference of the disk, a variation of about 16 per cent in the speed for a given watt consumption can be effected. Advantage is taken of this fact in adjusting the instruments. The more important bearings are constructed of jewels, such as are used in watches, and the whole machine is carefully protected from dust. When the instrument is in a position where it is subject to jars or vibrations that reduce the friction of standing to such a point that the constant excitation causes the armature to revolve a little, the machine is said to "creep." The remedy is to mount on a rubber or other non-vibrating base, or to reduce the number of shunt field turns.

CHAPTER X.

SERIES MOTORS.

101. **Series Motors.** — When subjected to a heavy load on starting, that is when there is a heavy current at a very low speed, a series-wound machine is far superior to one that is shunt-wound. For work that requires good effort at widely different speeds the series motor is particularly adapted. For this reason series-wound machines are used on electric railways, for crane motors, for ammunition and other hoists, for mill motors, and in all other places where a good effort is required at a varying speeds. A series-wound machine can be used on either a constant current circuit or on a constant potential circuit; but a series motor is seldom run on a constant potential circuit unless it is directly or very solidly coupled with its load, as in the case, for instance, of a railroad motor. If connected by means of a belt, and if the belt should break off or slip off, the motor would race and damage might result. This difficulty does not present itself when series motors are used on a constant current circuit.

102. **Series Motors on Constant Potential Circuits.** — As in the case of a shunt motor, on a constant pressure circuit, the armature speed of a series motor will increase until it reaches a value where the counter *E.M.F.* cuts down the armature current to such a point that the total

electric power, (*IE*), received by the motor, is equal to the sum of the fixed losses, the variable losses, and the useful mechanical power. With a shunt-wound motor, a very small variation of speed is sufficient to compensate for a wide variation of load. A series motor tends to increase its speed on removal of the load, as in the case with shunt motors. It in this manner increases the counter *E.M.F.* The resulting decrease of current results, however, in a weakening of the field, and as a consequence additional speed is required to maintain the *E.M.F.* Thus a small change in load results in a wide change of speed in a series motor. For a series-wound mill motor, the relations which exist between speed, current, and useful torque (turning moment) are shown in Fig. 149. There is also given a curve of the efficiency of the machine including gearing. It is evident that if, while the motor is at rest, the circuit be closed, an enormous rush of current would occur, giving an enormous torque. Destructive heating and sparking would probably result. To prevent damage it is therefore necessary, in the operation of these motors, to insert a series resistance at the start which may be cut out after the speed has risen enough to give a sufficient counter *E.M.F.* In practice controllers are used as described later.

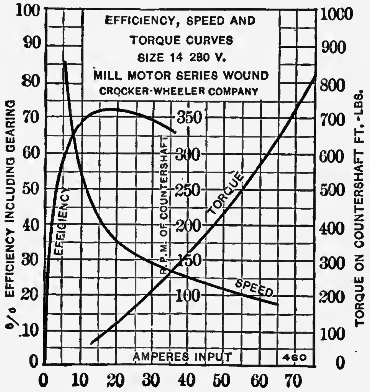

Fig. 149.

103. Railroad Motors. — Experience has shown that series motors operating on a constant potential circuit of 550 volts, furnish a very satisfactory motive power for the propulsion of trolley street-cars and electric railroad motor-cars. At the time of this writing there are nearly two million horse-power of street-car motors in service in this country. The railway motor has been developed to a high degree of perfection during recent years, and is reasonably well fitted to meet the many requirements that are found in this service. A railway motor must be mechanically strong to withstand the excessive hammering to which it will be subjected when in service. Rough tracks and bad switches are usual in trolley road beds. When satisfactorily geared to the wheel axle, the motor can be suspended by springs on one side only, the other side being of necessity mounted directly on the axle. Railway motors are also subject to abuse at the hands of the motormen. The series resistance is often cut out rapidly before the car has an opportunity to accelerate. As a result there is an enormous current and torque with little speed. This severely strains the motor and is particularly liable to disturb the armature windings. The motor must be either weatherproof of itself or incased in a weatherproof shell, because of the mud, the water and the slush through which cars must often run. Furthermore a railway motor should permit of quick, convenient, and accurate alignment of parts and adjustment of the intermediate driving mechanism.

The method of suspending the motors from the trucks is a matter of considerable importance. In practice four styles of suspension are used, viz., the side bar, the cradle, the nose, and the yoke suspensions. In every case one end of the motor frame contains bearings which run on

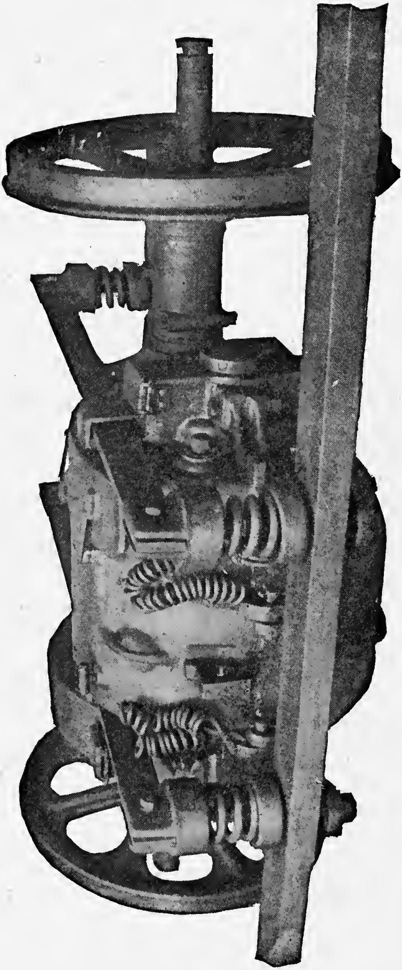

Fig. 150.

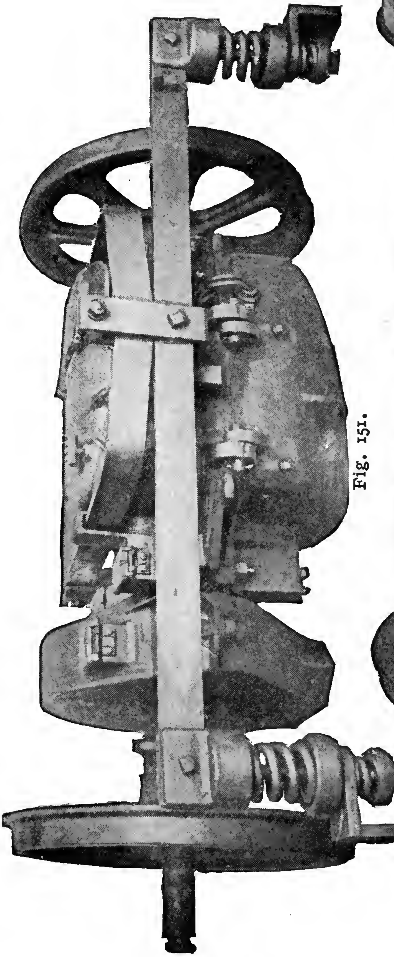

Fig. 151.

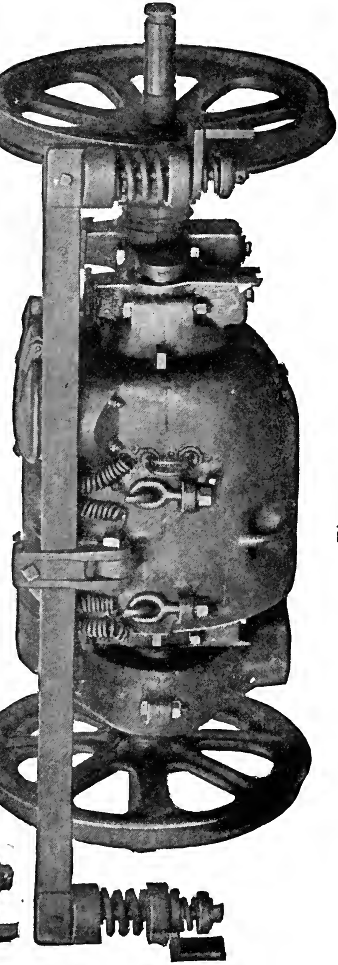

Fig. 152.

the wheel axle and keep the pitch circle of the armature shaft pinion always tangent to the pitch circle of the gear which is mounted on the axle. The side-bar suspension, shown in Fig. 150, consists of two parallel side-bars which are mounted on the truck through heavy springs, and which support the motor in the line of its center of gravity. The motor-axle bearings are thus relieved of the weight of the motor, and the latter is held without undue strains.

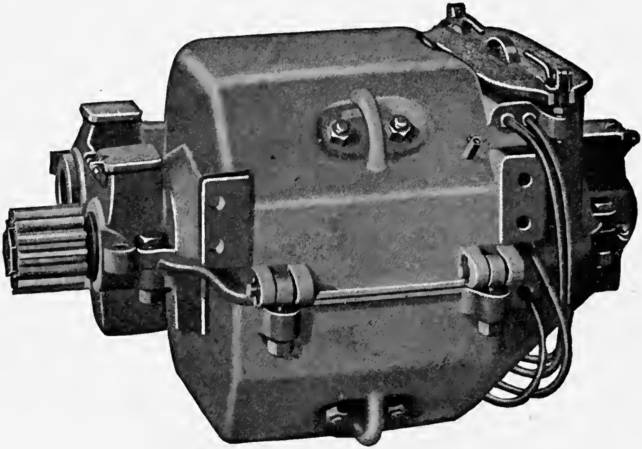

Fig. 153.

The cradle suspension, Fig. 151, is very similar to the side bar, the difference being that the two side bars are replaced by one U-shaped piece. This, at its curved end, is mounted flexibly on a part of the truck frame which in turn is mounted on the truck through springs. The nose suspension, Fig. 152, does not hold the machine at its center of gravity, but part of the weight is thrown on the motor-axle bearings. The rest is suspended from a spring-mounted member of the truck by a link, bolted to a "nose" cast in the motor frame. The yoke suspension, which is the least flexible of all, differs from the nose suspension in that the link is dispensed with and the spring-supported member of the truck is bolted rigidly to the motor frame. The cradle-suspension type is advocated by the Westinghouse Company, the yoke or nose by the General Electric Company. The size or style of truck frequently requires a particular type of suspension.

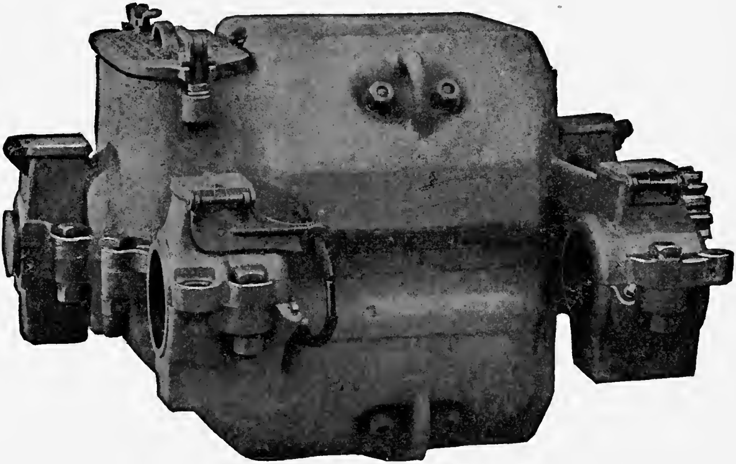

Fig. 154.

A GE-67 railway motor, made by the General Electric Company, is shown in Figs. 153 and 154. This machine will develop 38 horse-power when operated on a 500-volt circuit without heating more than 75° C. above the surrounding atmosphere after one hour's run. The magnet frame is hexagonal, with rounded corners, and is cast in two pieces from soft steel of high permeability. The parts are hinged together so that the lower part may be swung down for inspection or repairs (Fig. 155). The upper part has cast on it two lugs, shown clearly in Fig. 153, pierced with two holes each for bolting to the yoke. Nose suspension can, however, be substituted. A covered opening over the commutator permits removal of the brushes without disturbing the rest of the machine. The bearings, both for armature shaft and for axle, consist of cast-iron rings or shells, with Babbitt metal swaged into them, and are arranged for lubrication by both oil and grease. The oil is supplied to the shafts by felt wicks leading from oil-wells. The grease is fed through a slotted opening in the top of each bearing from a grease-box directly over each bearing, and means is provided for the passage of the lubricant from the bearing after it has been used. The armature bearings are 3″ × 8″ at the pinion end and $2\frac{5}{8}$″ ×

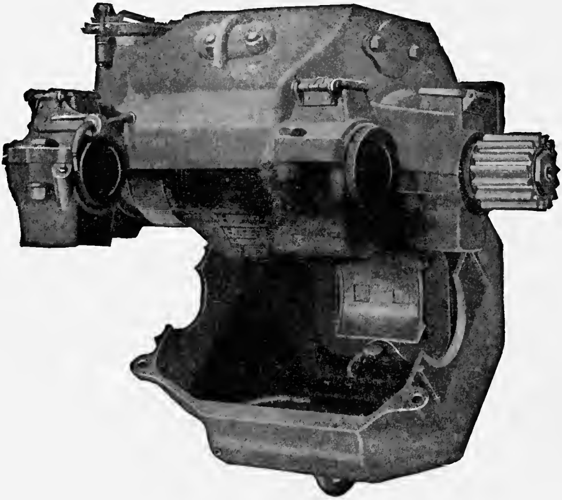

Fig. 155.

6⅛″ at the commutator end. The motor-axle bearings are each 8″ long. The pole pieces are built of soft iron laminations, riveted together, and are securely bolted into place on the magnet frame. The coils are spool wound, and are held in place by steel flanges. These magnetically imperfect constructions are rendered necessary by the severe service the machine is expected to stand.

The armature is built up of thin, soft iron laminations, japanned, and keyed to the shaft. At each end is a cast-iron head, also keyed to the shaft. The core is hollow, ventilation being effected by air which enters at the pinion end and passes out through ventilating ducts left in the laminations. The winding is of the series drum type, 111 coils being used, which are connected to a commutator of 111 segments. The number of turns to a coil depends upon the class of service the motor is to render. The coils are made up of sets of three, each set being separately insulated before being placed in the slots. The coils are firmly secured in place by tinned steel wire bands held by chips and soldered together. Where the windings cross the ends of the core, they are protected by canvas. On the pinion end, a projecting flange protects the windings from injury by careless handling. The brushes slide radially in finished ways in a brass brush holder, and are held in contact by independent pressure fingers. All the leads to the motor pass through rubber-bushed holes in the front of the magnet frame. The pinion has a taper fit on the armature shaft. It, as also the gear on the axle, is made of steel, and has teeth of 4½″ face and 3″ pitch. When mounted properly on a truck with the ordinary 33-inch wheels, there is 4½″ clearance between the bottom of the motor and the top of the rails. The shapes of the different parts of this motor are well shown in the exploded Fig. 156.

A motor for railway service, very similar in design to the one just described, is No. 49, made by the Westinghouse Electric and Manufacturing Company. This motor, shown in Fig. 157, has a weather-proof cast-steel frame, hinged to open in a horizontal plane through its center, and having a hand-hole above and one below the commutator. The upper half is cast with lugs for side-bar or cradle suspension, and also with a lug for nose suspension. The pole pieces are of laminated soft iron, are four in number, and are secured to the frame by having the latter cast around them. The lathe-wound field coils are secured on the pole pieces by brass castings, which are bolted to the frame.

The armature is of the slotted drum type, having a laminated core with three ventilation passages parallel to the shaft. The coils are wound on formers, insulated in sets of two, and then applied to the core. This armature is constructed as light and as small in diameter as is practicable, for the double reason of decreased centrifugal strain on the armature coils and decreased wear on the parts in stopping the car. When the motor is started, energy is stored in the armature and other revolving parts, as in a fly-wheel; and when the car is stopped, this energy is wasted, and causes wear and tear on the pinions and bearings. In street-car service, where stops are frequent, this loss and this wear is by no means inconsiderable. Hence the armature of a street-railway motor should not be built with a great fly-wheel capacity. The high speed of car-motor armatures makes the operating expenses for car acceleration and retardation considerable.

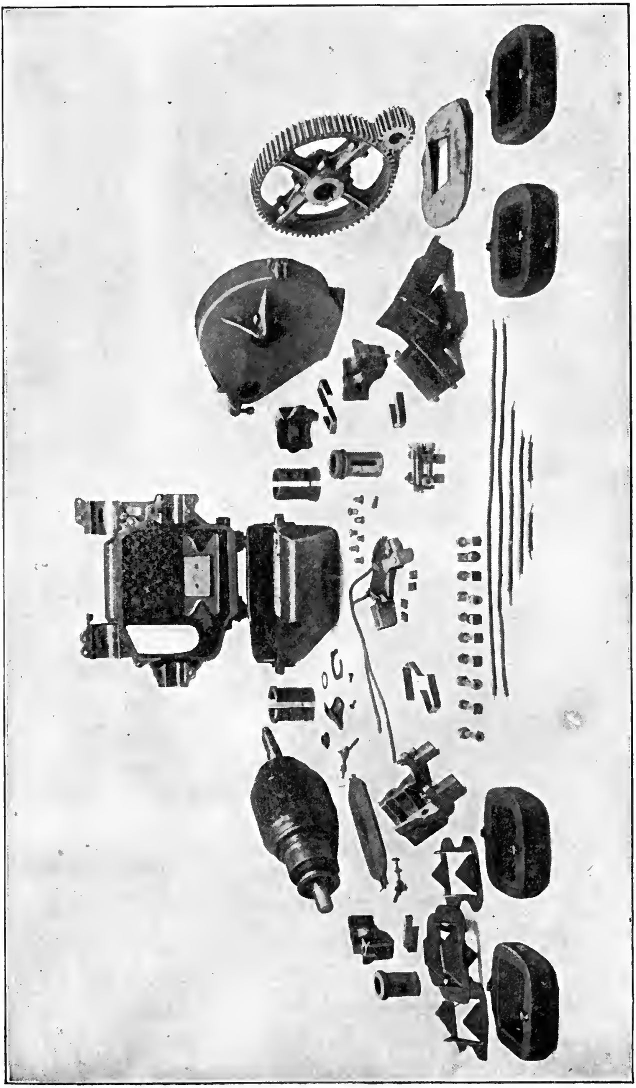

Fig. 156.

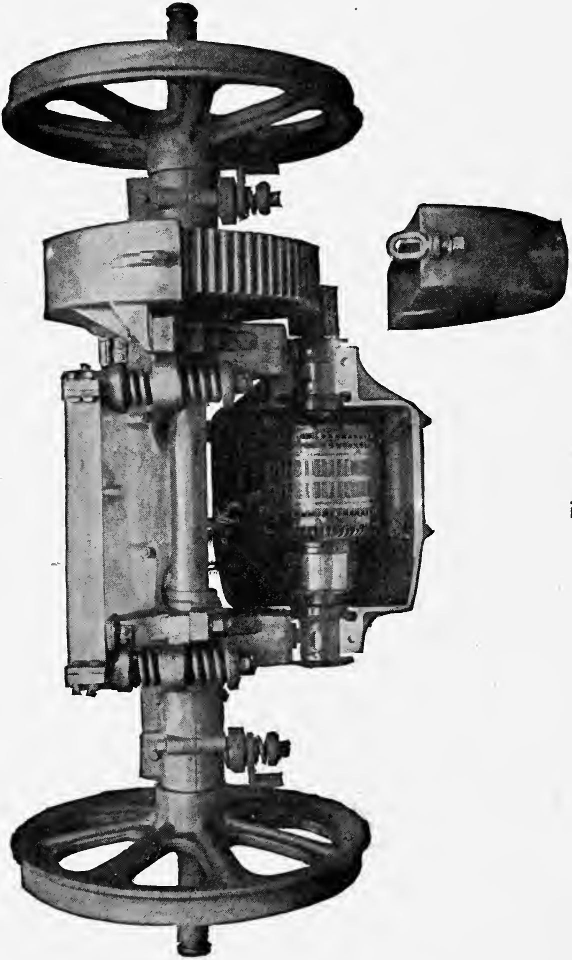

Fig. 157.

104. Controllers. — It is general practice to equip each trolley car with at least two motors, and to regulate the speed of the car in the following manner: First, the two motors and a resistance are connected in series. The resistance is then cut out step by step until the two motors are operating in series on 500 volts. Since, with all the resistance cut out, there is no unnecessary I^2R loss, this is called a running connection, and the controlling mechanism is said to be upon a *running point*. To further increase the speed, the motors are placed in parallel with a resistance in series with both. This resistance is then cut out step by step until the motors are each operating on 500 volts. This, again, constitutes a running connection. A further change is sometimes effected by placing a small

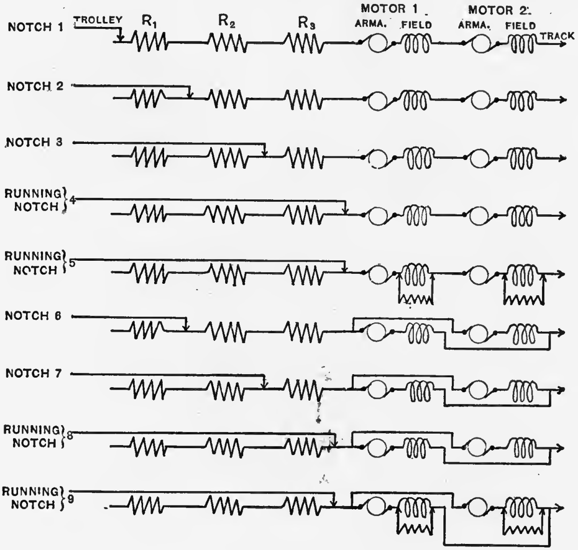

Fig. 158.

resistance in shunt with the fields when all the series resistance is out. This reduces the field flux, and causes a higher armature speed to maintain the necessary counter *E.M.F.* A car governed in this way has four running connections. On heavy cars, such as are used in elevated railway or inter-urban service, four motors are used on each car. In this case, the motors are governed in two series-parallel combinations, as if there were two separate cars governed by one controller. The connections for a two-motor car having nine speeds, a three-part series resistance, and a field-shunt resistance, are shown diagrammatically in Fig. 158.

The different connections are made by a motorman, who operates a handle on top of a *controller.* Each different combination is called a *point* or a *notch.* A pointer affixed to the controller handle indicates at what notch the car is running. Running points are indicated on the controller top by longer marks than the resistance points. A controller is almost invariably placed at each end of the car.

Fig. 159 shows the interior of a General Electric Company's k-10 series parallel controller. The wires from the trolley, from the fields, from the armature, and from the different terminals of the series and shunt resistances are brought up under the car to terminals on a connecting-board in the bottom of the controller. On this connecting-board there are also switches, one for each motor. These enable one to cut out an injured motor without interfering with the operation of the other motor or motors. From the connecting-board conductors are run to terminals, called *fingers* or *wipes.* Mounted on an insulating cylinder, which may be revolved by the controller handle, are insulated contact pieces, which at various angular positions of the cylinder make electrical connections between various wipes, and give the proper connections for the various "points" or "notches." A smaller cylinder connected to a *reversing-lever*, is situated to the right of the main cylinder. This has contact pieces which are arranged so as to enable the motorman to reverse the direction of rotation of both motors or to cut them out entirely. Interlocking devices are supplied so

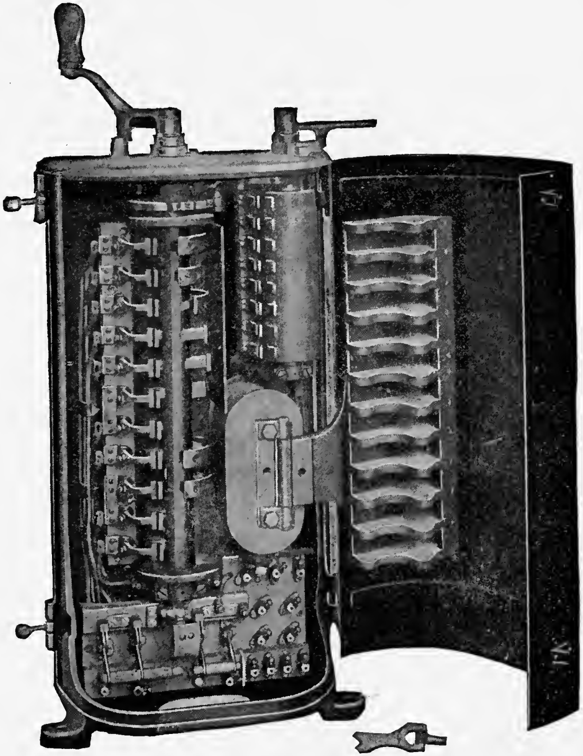

Fig. 159.

that the reversing handle cannot be moved unless the controlling handle is in such a position that connection with the trolley is broken. The controlling handle also cannot be moved, if the reversing handle is not properly set either to go forward or to go backward. The reversing handle cannot be removed from the controller, save when the smaller cylinder is in the position that cuts out both motors.

As serious arcs are liable to develop upon breaking a circuit of 500 volts, the contact pieces and wipes are separated from adjacent ones by strips of insulating material which are fastened to the inside of the controller cover, and which fold into place when the cover is closed. These are to be seen at the right of the figure. The power should never be turned off by a slow reverse movement of the controller handle, as destructive arcs are liable to occur upon a slow break. To lessen the speed of a car, the power should be completely and suddenly shut off. Before the car has slackened its speed too much the controller handle can be brought up to the proper point. The arcs, which form upon disconnection at the fingers, are pretty effectively blown out by the field of an electromagnet whose coil is above the connecting-board at the right.

105. Motors For Automobiles. — For electric automobiles the series-wound motor is invariably employed. A storage battery of 40 or 44 cells is the customary source of power for these motors. The use of these cells affords a convenient and economical means of speed control. In the case of a single motor, for the first controller notch, the cells may be connected in four-series groups of 10 or 11 each, giving about 22 volts, the four groups being connected in parallel. Other notches would correspond to other series parallel combinations, and finally the last and highest speed notch would correspond to a connection of all the cells in series. By this arrangement one cell is used just as much as any other, and they are discharged at equal rates. As the voltage supplied to the motor is varied without recourse to a series regulating resistance, there is no useless I^2R loss in starting or running at less than full speed. Often a series parallel control is employed when two motors are used. It is also common to use two 37½ volt motors connected permanently in series and controlled as one motor.

The advantage of using two motors on an automobile is that each may drive a wheel, allowing independent rotation on turning curves, while if one motor only is used some form of differential gear must be employed to allow for sharp turns. But the efficiency of one motor is in general greater than the efficiency of two motors of half the power, and the gain in efficiency by using one motor more than balances the cost and complication of a differential gear in the case of light vehicles.

The question of efficiency in these motors is of great importance, for practice has shown that it is profitable to purchase 1 per cent efficiency, even at the cost of 10 per cent increase of motor weight. This is because the ratio of the battery weight to the motor weight is such that a decrease of 1 per cent in the capacity of the battery reduces its weight more than 10 per cent of the motor weight. Since lightness is a prime object, only the very best materials can enter into the construction of a successful automobile motor. The magnetic circuit must be of material of the highest permeability. Ball bearings are not infrequently used in the shaft bearings, but their liability to wear and the consequent regrinding is an objection.

It is general practice to rate these motors at 75 volts, or $37\frac{1}{2}$ volts if two are used. Since 40 or 44 cells of battery in series can fall to 75 volts without injury, this is the lowest pressure on which the motors will be expected to run for any length of time at full speed. Hence this voltage is used as the basis for rating. For the best motors the rating is for a temperature rise of 50° or 60° C. on an indefinite run. A motor so rated will carry 100 per cent overload for half an hour, 150 per cent for ten minutes, and a momentary overload of 400 or 500 without overheating or damage to the insulation.

The battery of 40 or 44 cells is well adapted to automobile purposes. It can conveniently be made to have the required capacity, and it may be charged from any 115-volt direct current, incandescent lighting circuit with very little resistance in series and hence a small I^2R loss.

Although the voltage of these motors is somewhat low for the use of carbon brushes, the necessity of reversal of direction and the liability of sparking on over-load make their use desirable. Soft carbon brushes of low resistance can, however, be obtained, and they are to be recommended.

Fig. 160 illustrates a motor which is used on automobiles and manufactured by the Eddy Electric Manufacturing Company. It is a four-pole machine. The frame is ring shape and made of cast steel. The pole pieces, also made of cast steel, are fastened to the frame by bolts and steady pins. The armature is wound with formed coils which are cross connected, and therefore require but two sets of brushes. These brushes are made accessible by the existence of a window in the end plate. A pinion which is mounted upon the armature shaft meshes with an inside gear placed upon the wheel of the vehicle. A recess in the exterior of the magnet frame is fitted to receive some part of the frame of the vehicle. Clamps for fastening to this frame are provided to suit the character of the vehicle. The motor is intended to be operated on 75 volts, and is rated at 1.6 horse-power, at the speed of 1400 revolutions per minute. Its weight is 142 lbs., and it has an efficiency of 79½ per cent at full load. At 100 per cent over-load it has an efficiency of 76½ per cent, and at 150 per cent over-load an efficiency of 73 per cent.

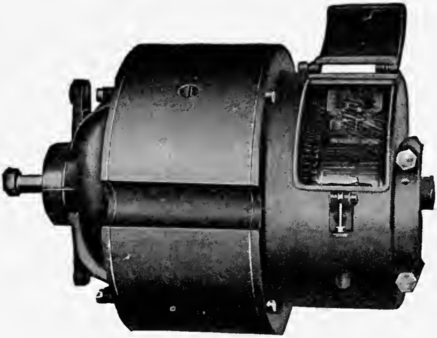

Fig. 160.

106. Mill Motors. — For many kinds of mill work requiring great torque at low speed, reversibility, and wide variation of speed, the series-wound motor is well adapted. Since mill motors are to be used in places where dust, grit, and small particles of metal are apt to be floating in the air, it is necessary, to insure good continuous operation,

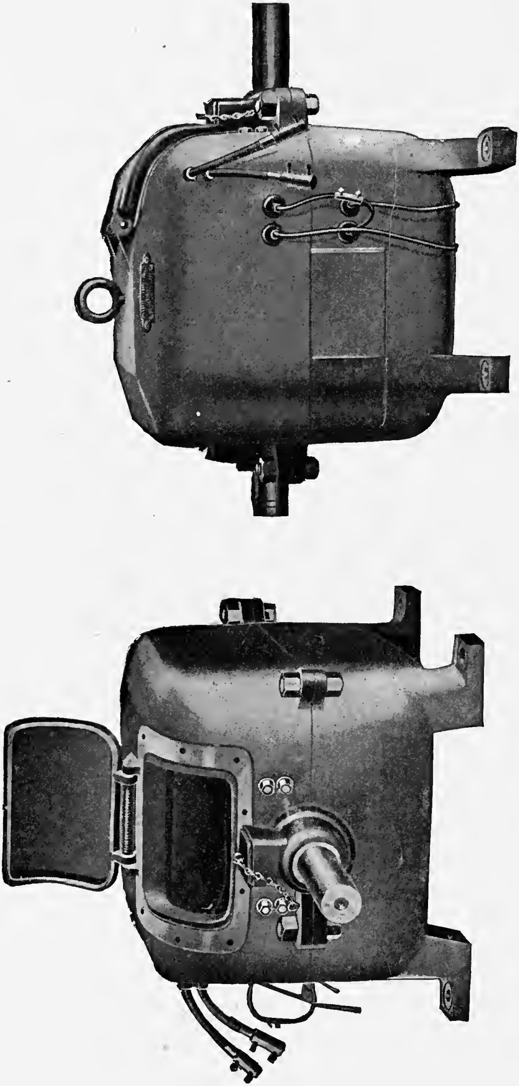

Fig. 161.

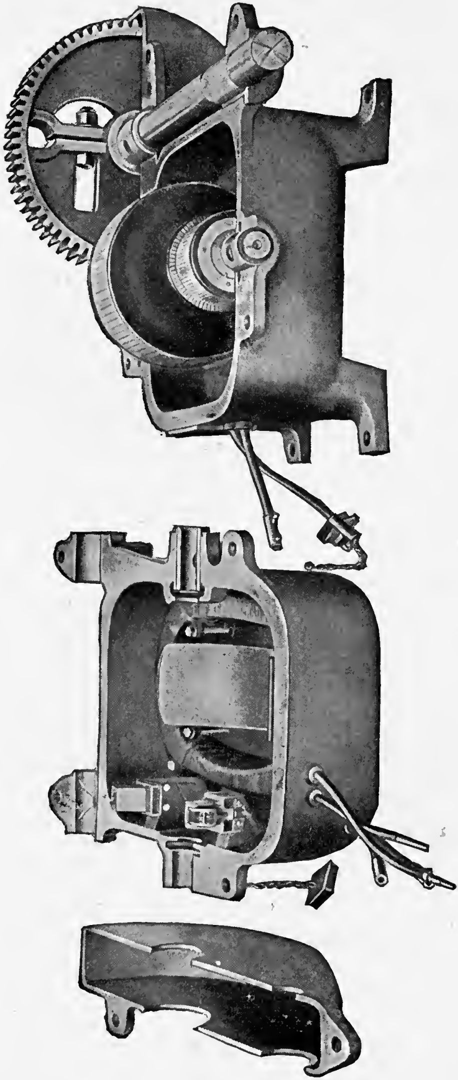

Fig. 162.

that they be inclosed after the fashion of railway motors. Mill motors differ from shunt-wound machines in that they are capable of giving a turning-power, when slowed down or started from rest, many times as great as that given at full speed.

Fig. 161 shows a Crocker Wheeler mill motor, and Fig. 162 shows the same disassembled. It is a bipolar drum armature machine, designed for about 800 *R.P.M.*, and giving without overheating an intermittent horse-power of 14 or a continuous horse-power of 5. It is rated in this way, since frequent stops and starts are expected in the use of such a motor. The hotter a motor gets during an interval of use the more it will cool off during an interval of rest. Of course an inclosed motor such as a mill motor heats up much more rapidly and severely than does an open motor where the air circulates around the fields and the armature.

Fig. 163.

Since these motors are reversible the brushes can have no lead. Sparkless running is accomplished by a long air gap. Being series wound the field increases with load and the speed is reduced correspondingly, hence commutation is readily effected.

These motors are controlled by a variable series resistance, the various connections being made in a controller, such as is shown in Fig. 163. The circuits are made by contact pieces on a cylinder coming in contact with fingers or wipers which are mounted on a board forming the back of the controller. The controller illustrated is also a *reverser.* The motor can be run in either direction by moving the controller handle to the right or to the left of the central position.

CHAPTER XI.

DYNAMOTORS, MOTOR-GENERATORS, AND BOOSTERS.

107. Dynamotors. — A dynamotor is a transforming device combining both motor and generator action in one magnetic field, with two armatures or with an armature having two separate windings. They are generally supplied with a commutator at each end, which are connected to the two windings respectively. Either winding of the armature may be used as a motor winding, and the other as the dynamo winding. These machines occupy the same position as regards direct current practice as is occupied by transformers in alternating current practice. That is, they enable one to take electrical energy from a system of supply at one voltage, and deliver it at another voltage to a circuit where it is to be utilized. They cannot, however, be constructed so as to operate with the same high efficiency as a transformer does. As the currents in the two armatures flow in opposite directions, and the machines are so designed as to have practically the same number of armature ampere turns when in operation, there is practically no armature reaction. The field, therefore, is not distorted so as to require a shifting of the brushes, nor is there sparking present as a result of a change of load. These machines are more efficient than motor generators, which will be described later, as they have but a single field. They cannot be compounded so as to yield a constant *E.M.F.* at the dynamo end. A cumulative series coil would tend to raise the *E.M.F.* at the dynamo end, but it would lower the speed of the armature as a motor by a corresponding amount.

108. The Bullock Teaser System. — Dynamotors are used extensively by the Bullock Electric Manufacturing Company in their so-called Teaser system of motor-speed control. This system is used in driving large printing-presses from supply circuits, which are at the same time used for lighting and other purposes. Large printing-presses contain very many sets of gears, and possess very large moments of inertia. These large machines require an unusually large torque on the part of the motor to start them. Sometimes it is as much as five or six times that torque which the motor is called upon to produce at full load. Now, the torque which is exerted by a motor is dependent upon the current which flows through its armature, while the speed at which this torque is applied is dependent upon the impressed electromotive force. As the current, which is required to produce the normal running torque is already of considerable strength, it is desirable that some direct current electrical transformation be employed to avoid the excessive starting current. The Teaser system accomplishes this by making use of the dynamotor. The motor winding is designed for five times the electromotive force of the dynamo winding. Its field winding is excited directly from the supply mains. The negative brush of the motor side is connected with the positive brush of the dynamo side. The two armature windings are connected in series with a regulating resistance to the supply mains. At starting, the main motor, which drives the press and which is generally a cumulatively compound-wound motor, is supplied with current from the dynamo end of the dynamotor. The voltage with which it is supplied is somewhat less than one-fifth that of the main supply, depending upon the magnitude of the resistance in series with the dynamotor. This low voltage permits of the application of a proper amount of torque at a low speed. Furthermore, the drain of current from the supply mains is but about one-fifth that which passes through the main motor. By manipulating the dynamo regulating resistance, the electromotive force supplied to the main motor is raised, and with it the speed. The highest speed of the main motor which can be attained by this arrangement is such, that, when attained, the motor's connections may be transferred to the supply mains

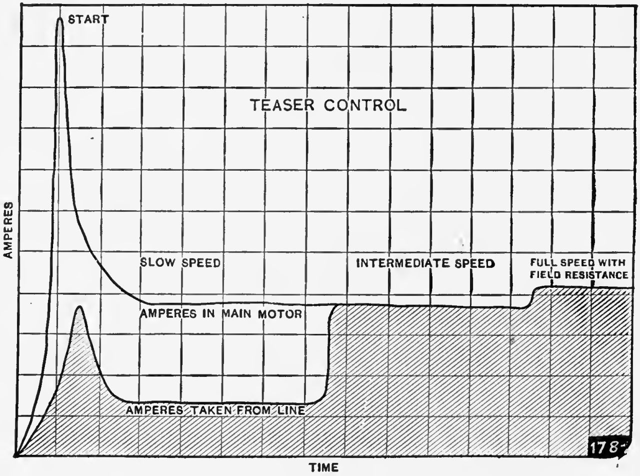

Fig. 164.

through another series regulating resistance without any excessive drain of current from those mains. The arrangement of the apparatus is shown in Fig. 165, and the amount of current which is taken by the main motor as compared with the amount of current which is drawn from the supply mains is represented in Fig. 164. Regulation of the resistances and changes of connection are accomplished through the aid of a controller. The different speeds are secured by the manipulation of a single hand-wheel on the controller, and thus the pressman has at his command a means of manipulating the press which is not complicated.

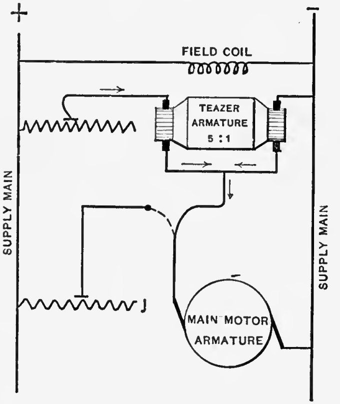

Fig. 165.

109. Dynamotors for Electro-Deposition of Metals. — In large electro-plating establishments, it is common to introduce a dynamotor, whose two armature circuits are exactly similar, and under ordinary excitation give 5 or 10 volts. The commutators, brushes, collecting devices, and leads are of necessity quite massive. The leads are generally so arranged that the two armatures may be placed in series with each other, or in multiple. The low voltage of platers makes it impracticable to have a machine self-exciting. It is common practice in cities to excite these machines from 110-volt lighting circuits, with a regulating rheostat whose resistance is of such a magnitude as to permit of the variation of the voltage of the machine over a range of 25 per cent of its full-load value. Fig. 166 shows a dynamotor constructed by the Eddy Electric Manufacturing Company for the electro-deposition of copper. Each armature winding gives 10 volts and 4,500 amperes. It is designed to be belt-driven through a large pulley at one end of the armature shaft. A small pulley upon the other end is for the purpose of receiving a belt connected with a small separate exciter. The large split clamps connected with the leads are for the reception of the terminals of the main conductors.

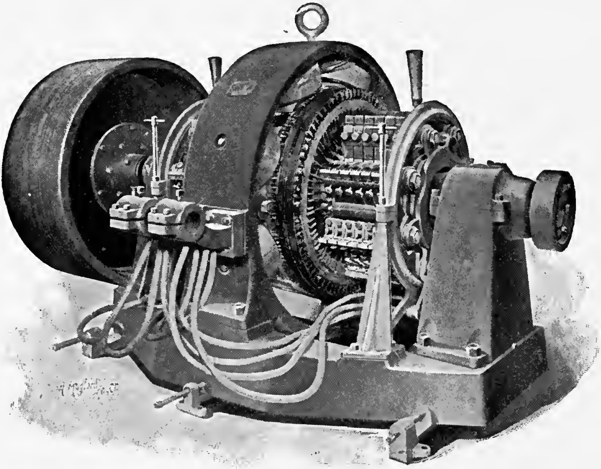

Fig. 166.

110. The Eddy Company's Rotary Equalizer. — This is a dynamotor having a single field which is excited from a 220-volt circuit, and a single armature core upon which is wound two distinct 110-volt armatures. One armature has its commutator on one end of the shaft and the other at the other end. The machine is used in connection with a 220-volt generator, to enable one to use it for supplying energy to a three-wire, 110-volt, incandescent lighting system. The principle of its action can be seen from an inspection of Fig. 167. When the system is unbalanced, that side which has the smaller load has the lesser drop, and therefore the higher difference of potential. The armature winding of the dynamotor which is connected with that side acts as a motor, runs the armature, and causes the other armature winding to act as a generator in raising the pressure of the heavier loaded side. Obviously the employment of this system can, in some cases, result in a considerable saving of copper.

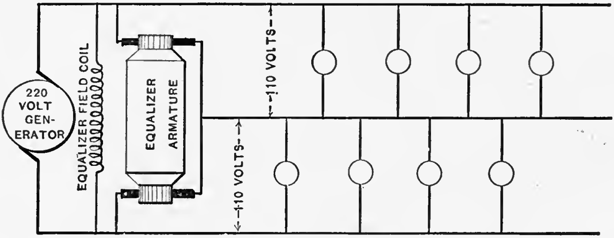

Fig. 167.

111. Other Applications of Dynamotors. — The Crocker Wheeler Company manufactures a special line of dynamotors (Fig. 168) for use in telegraphic work. The motor is designed to be supplied with electrical energy from street service mains, or from the house-lighting mains in the case of isolated plants. The generator end furnishes currents at a constant potential, which is different in the case of different machines. These machines are designed to take the place of batteries of a large number of gravity cells such as were used, in large quantities, a few years ago. The cost of operation of a dynamotor for this service is about one-fifth of what it is in the case of the gravity cells. The space which the machine occupies is but $\frac{1}{3000}$ that of the cells. They are to be preferred to batteries also on the ground of cleanliness. Their reliability, when supplied by electric energy from large city service mains is equal to that of the cells. The same cannot be said in the case of small towns. The telephone companies are also rapidly adopting the dynamotor for the purpose of charging storage cells. With some forms, the charging of the cells can go on continuously, they being at the same

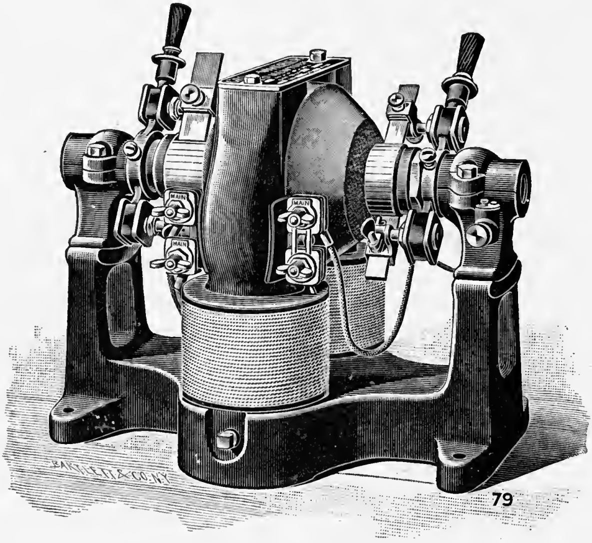

Fig. 168.

time used for telephone purposes. Dynamotors also furnish a convenient and satisfactory means of heating surgeons' electro-cauteries. Cautery knives take from 3 to 8 amperes at 5 volts, while dome cauteries take from 15 to 20 amperes at the same voltage.

112. Motor-Generators. — A motor generator is a transforming device consisting of two machines, a motor and generator, mechanically connected together. They have the advantage over dynamotors in that the voltage of the dynamo armature can be made to assume almost any value within limits by means of a resistance placed in series with its field-winding and capable of variation. They can furthermore, besides being separately excited, be shunt wound or compound wound. They are used quite extensively in the Ward-Leonard system of motor speed control, which was described in paragraph 97. They are also used for charging storage batteries. In this case

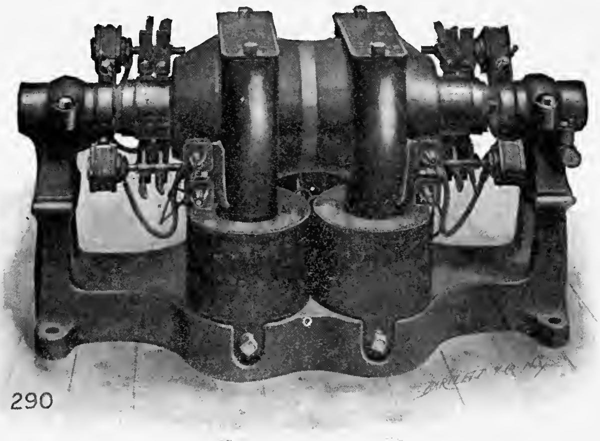

Fig. 169.

they are almost always shunt wound. They are also used in electro-plating establishments. In this case they are separately excited, as the voltage generally employed in such places is too small to give satisfactory self-excitation. For general laboratory work on tests which require large current at a low voltage or a small current at a high voltage, motor generators are of inestimable value.

113. **Boosters.**—A booster is a machine inserted in series in a circuit to change its voltage, and may be driven either by an electric motor, or otherwise. In the former case it is a motor-booster. This machine is used very extensively on Edison three-wire incandescent lighting systems which supply current at a constant potential. Feeders which run to feeding-points at a great distance, if supplied by current from the same bus bars as shorter feeders, will have too small a difference of potential at the feeding-points to give satisfactory service. A booster with its field and armature windings in series inserted in series in the feeder will add *E.M.F.* to the feeder which in magnitude is proportional to the current flowing in the feeder, that is, as the current increases the field excitation will increase and with it the *E.M.F.* produced by the armature. The machine may, therefore, be so designed as to just compensate for any drop which is due to the resistance of the feeders and to the current flowing through them. As all the current of the feeder must pass through the booster armature, the collecting devices must be massive and must be designed to carry these heavy currents. The rating of a booster is of course determined by the voltage which it produces, and the total current which passes through it and the feeders. Boosters are also used in the central stations of trolley companies to

raise the voltage which is supplied to the feeders connected with distant sections of the line. They are also being introduced in office buildings in connection with electric elevator service. When the elevator motors are supplied from the same generators as the lights and fans in an office building they give to the generators what is called a *lumpy* load. The excessive currents demanded by the elevator motors on starting produce wide fluctuations of voltage in the mains. A booster inserted in these mains may be made to add *E.M.F.* to the mains on these occasions.

CHAPTER XII.

MANAGEMENT OF MACHINES.

114. Connections for Combined Output of Dynamos. — In general a dynamo is much more efficient when operated at its full load than when operated at one-half or one-quarter load. It is usual to install in central stations, which, as a rule, have to supply different quantities of electrical energy at different times of the day, a number of smaller units rather than one unit large enough to supply the total energy. By this means any load can be handled by a machine or a number of machines all operating at about their maximum of efficiency. It is well, therefore, to consider the methods of combining two or more machines on one load. The simplest and most usual method of connecting dynamos is that employed in incandescent light generating stations. Here a number of constant pressure machines are arranged as in Fig. 170, to act in parallel on one pair of bus bars. The figure shows shunt machines with hand regulators. The various external circuits are connected in parallel to the bus bars. This practice is frequently modified by separating those machines which supply the circuits that deliver at the more distant points from those that operate the shorter circuits. This is because the maintaining of a constant and uniform pressure at all distributing points requires a higher pressure on the station ends of the longer mains than on the shorter. When a machine

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is to be thrown into circuit on to bus bars already in operation, it is first brought up to speed, the field magnetization is then adjusted till the machine gives the same pressure as exists between the bus bars, and the main switch is then closed, which puts the machine in circuit. The proper pressure at which to throw in the new machine may be roughly determined by comparing the relative brightness of its pilot lamp with that of the lamps operating on the circuit.

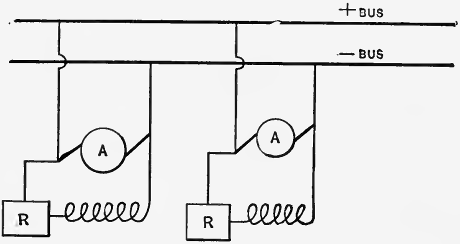

Fig. 170.

A more exact way is to compare the readings of a volt-meter across the terminals of the machine with one across the bus bars. The most convenient way is to use a "cutting-in galvanometer." Of these there are two forms, the zero galvanometer and the differential galvanometer. The zero galvanometer, shown with connections in Fig. 171, has a single coil of high resistance. When the pressure of the machine is not exactly that of the bus bars a current will flow one way or the other, and

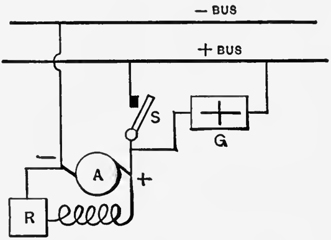

Fig. 171.

the needle will be correspondingly deflected. When there is no deflection, the machine may be thrown into circuit. This instrument is simple and cheap, but it requires that one terminal of the machine be permanently connected to a bus, which is not always desirable. The differential galvanometer, Fig. 172, has two high resistance coils, one in shunt across the bus bars, and one in shunt across the machine terminals.

When equal pressures are impressed on each of the coils, they, by their differential action, hold the needle in equilibrium, but when one coil is subject to more pressure than the other a deflection occurs. This instrument is more costly and more complex than the last, but it has the advantage that a two-pole switch may be used to cut in or out the machine.

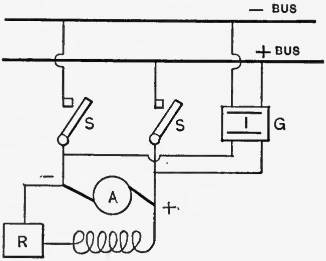

Fig. 172.

When shunt machines are connected in parallel, it is expected that they will all be kept at the same pressure. If they are not, no serious damage is likely to occur, since the lower pressure machine merely fails to take its full share of the load. If the pressure of one machine falls so low that it is overpowered and run as a motor, still no damage will result, save perhaps the blowing of a fuse, since the direction of rotation for a shunt machine is the same whether it be run as a dynamo or as a motor. If it be desired to regulate a number of machines together by one regulator, it may be accomplished by bringing the positive ends of the field coils to one side of the regulator and connecting the other side to the negative bus.

Shunt machines may be operated in series by connecting the positive brush of one machine to the negative brush of the next, and connecting the extreme outside brushes with the line wires. When this is done each machine can be regulated separately to generate any portion of the pressure. If it be desired to regulate all the machines thus connected uniformly and as a unit, the field coils of all the machines may be put in series with one regulating rheostat, and shunted across the extreme brushes of the set. In the Edison three-wire system two 115-volt direct-connected shunt machines are mounted on one engine shaft. The dynamos are connected in series as described above, the neutral wire being connected to the united brushes, as in Fig. 173.

Series-wound dynamos may be operated in series without any difficulty, though it is not customary to do so. Series generators are used almost exclusively on constant current (arc light) circuits, and it is usual to have as many machines as there are external circuits, each machine being of capacity enough to operate that circuit alone. A new form of Brush generator supplies several series circuits from its terminals, and regulates for all of them. If it be attempted to operate series dynamos in parallel, the following difficulty occurs: If the machines start with a proper distribution of load among them and one does not generate just its full pressure, then this one does not continue to take its full share of the load; and, since it is series wound, a decrease in load is followed by a decrease in pressure.

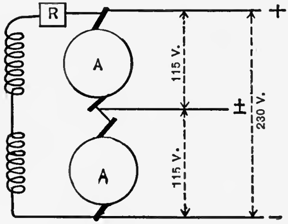

Fig. 173.

The conditions become always more uneven until the machine is overpowered and it turns into a motor. Since the direction of rotation of a series-wound motor is opposite to its direction when run as a dynamo, serious results may occur. The only remedy for this trouble is to arrange the field coils so that the magnetization in any one machine will remain the same as in the other machines, even though its pressure falls below that of the others. To accomplish this the series fields must all be placed in parallel. This may be done by means of an *equalizer*, which is a wire of small resistance connected across one set of brushes, and by placing the fields in parallel, as shown in Fig. 174. Two series dynamos may be run in parallel without an equalizer by resorting to *mutual excitation*, that is, by letting the current of one armature excite the field of the other. In this case if the pressure of one machine falls and its load therefore decreases, the magnetization of the other is reduced, compelling the first to maintain its share of the load. Series dynamos are never operated in parallel in practice, but this discussion is introduced because of its application to compound-wound dynamos.

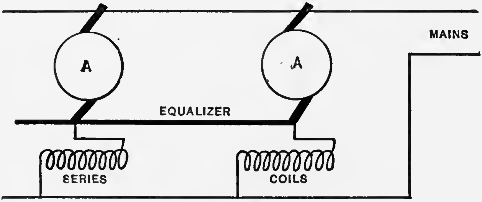

Fig. 174.

The use of compound generators for constant pressure circuits is very common. Since these have series coils they cannot be run in parallel without special arrangements. It is usual to fit the series coils with an equalizer, as in Fig. 175. The desired end might be accomplished in the case of two machines by making the series coils mutually exciting.

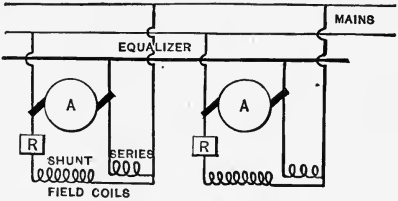

Fig. 175.

115. Connections of Motors for Combined Output. — Any number of shunt motors may be placed in parallel across mains of a constant pressure, and their operation will be satisfactory whether each has a separate load or whether they be connected through proper ratios to one shaft. Shunt motors will operate in series on a constant pressure circuit when positively connected together; but if connected to the same shaft by belts, and one belt slips or comes off, that motor will race, and rob its mates of their proper portion of the voltage. This arrangement is not common.

Series motors will operate satisfactorily on constant pressure circuits: but when two or more such machines, that are arranged in parallel on a constant pressure circuit, are connected to one shaft an equalizing connection is sometimes used. Series motors in series on constant pressure mains will operate satisfactorily, dividing up the total voltage between them according to the load each is carrying. If it be desired to make them share a load equally they must be geared together so that each rotates at the speed corresponding to its share of the voltage. Series motors only are used on constant current circuits. Any number of these may be placed in series on such a circuit individually or connected to a common shaft. A series motor on a constant current circuit may be overloaded until it stops without harm, since a constant current flows at any speed.

Compound-wound motors are coming into quite general use, and they are invariably operated on constant pressure circuits, and each machine has its own load.

In ordinary electric railroad practice, as has been stated, there are two series-wound motors to a car, operating either in series or parallel, according to the position of the controller handle, on a constant pressure of 500 volts. Each of these motors is geared to a separate pair of driving-wheels. Since under ordinary conditions the rate of rotation of the two motors is the same, the *E.M.F.* supplied to each is the same when they are in series, and since the current is common they divide the work evenly. When in parallel the pressure on each is 500 volts, and since the rotations are the same the currents will be the same and the load will be divided evenly. It often occurs that the back platform of a car is so loaded that the front drivers slip when the power is applied at starting. This occurs when the motors are in series and the current is common to the two. But the higher rate of rotation of the front motor causes it to generate a greater counter *E.M.F.*, thus lowering the pressure acting on the rear motor. Thus more electric energy is consumed in the front motor, and the surplus of work turns into heat from the friction between the slipping wheels and rails. When the car gains such a velocity that the front wheels bite the rails, the work is again evenly distributed between the two motors. It should be remembered that this occurs only when the motors are in series.

116. Care and Operation of Machines. — In what follows on the operation of motors and dynamos, it is assumed that the machine is properly designed and of sufficient capacity for the work it is called upon to perform. For satisfactory operation, the machine must be connected with an appropriate circuit and one of the voltage or amperage for which the machine was designed. Further it is assumed that the mere mechanical details have been looked to, such as proper foundation, proper alignment with shafting, and good lubrication. Only electrical trouble will be treated.

If trouble be detected, a machine should be at once stopped to prevent further trouble. In central generating stations, one of the most positive rules is not to shut down while any possible means is left to keep running. In such plants there are always one or two units held in reserve, and one of these may be started and substituted for a machine developing a fault so that the latter may be shut down and its fault remedied.

Sparking at the brushes is the most general trouble, and it has more causes than any other. The brushes must make good contact with the commutator, they must be true, and have good contact surface. The commutator must be clean. Any collection of carbonized oil is sure to cause sparking. A very thin layer of good oil, free from dust, is advantageous. On a bipolar machine the brushes must be diametrically opposite, on a four pole exactly 90° apart, etc. This condition must be attained while the machine is at rest, either by actual measurement or by counting the commutator bars between each brush. If the brushes of one set are "staggered" they may cover too much armature circumference and cause sparking.

The brushes must be set at the proper point. This is accomplished while the machine is in operation under its required load. The rocker arm, which carries all the brush holders, is moved carefully back and forth until the point of minimum sparking is found. Sometimes there is quite an arc of movement in which sparking is not observed. The brushes should then be set at the center of this arc, since heating occurs when the brushes are off the proper commutating point, even if sparks be not seen.

Sparking may be due to fault in the commutator. A *high-bar*, a *low-bar*, or *flat*, projecting mica, rough or grooved surface, eccentricity, or any condition of surface which causes the brushes to vibrate and lose contact with the commutator will surely cause sparking. If sparking be allowed to go without correction, it will pit the commutator and aggravate these conditions. If the irregularity of surface be slight, it may be cut down by sandpaper (never emery) held in a block cut to fit the commutator. If the surface be very bad, it must be cut down by a machine. A small armature may be swung in a lathe ; but a large one must be left in its own bearings, and a tool held against the commutator by some special device. A perfectly true commutator may act eccentrically toward the brushes because of wear in the shaft bearings. New bearings will remedy this fault.

If a coil of the armature be short-circuited, periodic sparking may result. The coil is liable to burn out if the machine is not immediately stopped. The short circuit may occur from breakdown of the insulation within the armature, in which case rewinding is necessary ; or it may be caused by metal chips or the like at or near the commutator, in which case the cause can be easily removed.

When a coil is broken very violent sparking occurs, since half the armature current is broken every time the commutator bar connected to the broken coil passes from under a brush. Such a break may occur within the armature, requiring rewinding; but it is more likely to occur where the coil end is attached to the commutator bar lug. If the break be at this place, the wire needs but to be screwed or soldered to the lug and the machine is repaired.

If the field of a motor is too weak, sufficient counter *E.M.F.* is not generated, and excessive current flows and causes sparking. The weakening of the fields may occur from a short circuit in the field coils or two or more grounds between the field coils and the pole piece, or by a broken field circuit (shunt coils) which reduces the magnetism to almost zero. In any case, unless the trouble is to be found external to the coils, rewinding is necessary.

Heating of machines is another frequent source of trouble. The limit of temperature that may be allowed in the bearings depends on the flashing-point of the lubricant used, but a well designed and lubricated bearing ought always to run cooler than the commutator or armature. The limit of temperature that may be allowed in the armature depends on the "baking"-point of insulation used, and also on the melting-point of the solder used if the coil ends are soldered to the commutator lugs. A good general rule is this: If you can hold your hand on any part of the machine for more than a few seconds, that part is not dangerously hot. Of course metal feels warmer than insulating cotton for the same temperature, and allowance should be made for this. If a burning smell or smoke comes from a machine, the safe temperature limit has been far exceeded, and the machine should be shut down at once. This indicates a serious trouble — a short circut or a hot bearing probably.

If the trouble arises from the bearings the ordinary mechanical precautions of cleaning, aligning, lubricating, etc., will generally cure it. Never use water to cool hot bearings. If water gets into the windings of either the field or the armature, short circuits will occur and ruin the machine. It must not be assumed that because one part of a machine is hot the trouble lies with that part. Heat is quickly conducted all over a machine; and when heat is detected in one place the machine should be felt all over, the hottest part probably being the part at fault. The brushes of a machine should not be set too tight, for, besides reducing the efficiency greatly, they cause much heat from friction. The commutator should not be more than 5° C. hotter than the armature.

Machines that operate on constant pressure circuits are liable to overheat because of too much current flowing through some parts of them. This may result from overloads, in which case the remedy is obvious, or because of short circuits in the machines, in which case rewinding is generally necessary. In the case of constant potential generators a short circuit of the mains will produce a sudden and severe overload, which can only be remedied by tracing out the lines and removing the short circuit.

When a machine makes an unwarranted amount of noise it usually indicates the need of attention. Carbon brushes chatter and spark sometimes when the commutator is sticky, the action being something like a bow on a violin string. Cleaning the commutator will cure this. Humming and vibration result when the revolving parts are not revolved about their center of gravity. This may be because of faulty construction or warping after completion. If the fault be with the pulley, it may be turned out or counterweighted. If the shaft be sprung it may be straightened or a new one used. If the armature core or windings be out of balance, there is not much help for it. Slower speed will reduce the noise from this cause.

Noise may occur from the armature rubbing or striking against the pole faces. This is a serious matter, and if not immediately attended to results in the destruction of the armature. It is caused generally by wear in the shaft bearings, in which case new brasses will remedy the trouble. Sometimes it results from a sprung shaft, in which case the shaft must be either straightened or replaced. A rattle produced by loose collars, bolts, nuts, or connections would indicate that these parts needed setting up or adjusting.

If a motor revolves too slowly, it may be because of an overload of mechanical work, because of excessive friction in the machine, or because of the armature rubbing against the pole face. A variation in the pressure supplied to a motor causes a variation in speed. If the field magnetism be too weak the motor will revolve too fast when not loaded, and too slow when under full load, and will take excessive current. A weak field may be caused by a short circuit which cuts out some or all of the field turns, or by a broken field circuit. If the load be removed from a series motor on a constant current circuit it will race badly unless its field coils are shunted. Practically such a motor should not be used in any position where it may be suddenly relieved of its load, as by the slipping of a belt. A shunt motor, whose fields are not excited, will run either forward or backward when a current is allowed to flow in the armature, according to the relative magnitudes and directions of the residual magnetism and the armature reactions. Ordinarily, however, if a motor runs backward, it may be assumed that the connections are wrong. Usually changing the connections to the brush holders, so that the brushes change their signs without changing any other connections, will make the motor change its direction of rotation. A series motor also may be made to change its direction by changing the direction of current flow in either field coils or armature, but not in both.

On starting up, a self-exciting dynamo is supposed to build up its voltage to normal, having at first no excitation save that of residual magnetism. After standing some time, or in proximity to other dynamos, or after being hammered, the magnet frame may have lost all its residual magnetism. In this case the machine does not build up when revolved. By passing a current from another machine through the field coils the dynamo will generate as a separately excited one. Then the exciting current may be thrown off and the self-excitation thrown on, when the machine will build up satisfactorily. If the residual magnetism becomes changed in direction, or the separately exciting current be passed in the wrong direction, then what little voltage may be generated will, when connected for self-excitation, send the current in such a direction as to tend to demagnetize the field, and building up will be impossible. A shunt machine builds up better the less the outside load, since at no load the terminal voltage is the greatest and the most likely to send a magnetizing current in the field coils. A series machine builds up better when the outside load is increased. Such a machine may even be momentarily short circuited to make it build up. For a given voltage resulting from residual magnetism, the current in the field coils is greater the less the resistance in the circuit. If the connections to one of the field coils in a bipolar machine be reversed, causing two poles of the same polarity, the machine will of course fail to generate. This condition may be detected by the use of a compass needle. Small machines sometimes generate at starting a few volts, showing proper connections and the presence of some residual magnetism, but refuse to build up beyond this point. It is sometimes convenient to materially increase the speed of such a machine, whereupon it will build up rapidly, and the speed may then be reduced to normal, and the dynamo will continue to generate at its normal pressure.

CHAPTER XIII.

THE DESIGN OF MACHINES.

117. Different Methods of Design. — It is impossible to lay down a fixed set of rules to be followed in the design of dynamo electrical machinery. This is because the specified conditions of operation and construction are seldom alike in two cases. A designing engineer may be called upon to design a machine of a given output at a given voltage, the field frame, however, to be chosen from one of a set already in stock; and again it may be required that the machine shall be direct connected, the output, the voltage, and the speed of rotation being given; still, again, the capacity, the maximum gross weight, and the efficiencies of operation at various loads, may be specified, as in the case of an automobile motor; or he may be called upon to design a machine of a given output and voltage, which shall operate at a satisfactory efficiency, and which shall have a first cost which will enable the manufacturer to successfully compete with others in the sale of his products. Throughout the calculations the engineer is obliged to refer to his experience or the experience of others in determining the values of different quantities which must be assumed before there can be any further progress on the design. Furthermore, after having assumed certain values, results which are arrived at later on in the work will necessitate the rejection of these values and the assumption of new ones.

Oftentimes what one might desire as a value for one quantity is undesirable, because it conflicts with the adoption of a value for some other quantity which is more desirable. In the following paragraphs a method is given for designing a machine under the conditions specified.

118. Specifications. — The following specifications are given and must be complied with:

The type of machine as regards the shape of its field frame, its bearings, and the method of its being driven; its output in kilowatts; its terminal voltage at full load and at no load; the materials from which are to be constructed its field frame, its pole pieces, its armature core, its brushes, its shaft, its bearings, its armature spider, and its conductors; and the insulation throughout its various parts.

119. Preliminary Assumptions. — The design will be based upon an assumption of the values of four different quantities.

The first assumption is that of the value of the flux density in the air gap, which will be represented by $\mathcal{B}_g$. The value which will be chosen will depend somewhat upon the method to be employed for obviating armature reaction. Almost all designers rely upon a *stiff, bristly field* to assist in preventing a distortion of the field when under load, and therefore higher flux densities are being used now than were a few years ago. Higher densities are used when the pole pieces are made of wrought iron or of cast steel than when they are made of cast iron. The densities are greater in the case of multipolar machines than in the case of bipolar; and they increase, within limits, with the size of the machine. A value between 4000 and 7500 should be chosen.

The second assumption is a value for the peripheral velocity V' of the armature in feet per minute. The common assumption in the case of drum armatures for all sizes above five K.W. is 3000 feet per minute. High-speed ring armatures have a higher value, ranging between 4000 and 6000. The larger value is to be used in the case of large machines.

The third assumption is a value for the current density in the armature conductor at full load. Inspection of a large number of machines shows the use in many of them of from 500 to 800 circular mils per ampere. Sometimes as small a cross-section as 200, and in other cases as large as 1200 circular mils per ampere, have been found. The low value is used in the case of machines subjected to periodic loads of short duration. This is the case with elevator motors, pump motors, sewing-machine motors, dental drill motors, and motors on special machinery. The high value is used on machines to be used in central stations for lighting or power purposes. The specified output in watts when divided by the full-load terminal volts gives the total current output of the machine at full load. This, divided by the number of armature circuits, gives the current which must be carried by each conductor at full load. This current multiplied by the assumed value of the number of circular mils per ampere gives the cross-section of the conductor in circular mils. Oftentimes a single armature conductor is made up of several wires in multiple. The multiplicity of wires affords pliability in winding, and obviates, to a certain extent, eddy currents. Again, the use of copper bars for windings is common, they being insulated by the use of micanite, fuller board, or other sheet insulating materials. A cross-section sketch of a single conductor should be made in which the dimensions are given of the copper and of the insulating material.

The fourth assumption is the value s to be given to the polar span. s represents the percentage of the armature circumference which is covered by the faces of the poles. This value varies considerably within narrow limits, but unless there is some special reason for the assumption of another value 0.8 may be taken.

120. Design of the Armature. — I. *To determine the specific induced E.M.F. in volts per foot of active conductor.*

$$E' = \frac{V'\,30.5}{60} \times s\mathfrak{B}_g \times 30.5\,\frac{1}{10^8}\ \text{volts.}$$

where the first term in the right-hand member represents the velocity of the moving conductor in centimeters per second, the second term represents the average induction density of the flux which enters the armature, and the third term consists of constants to reduce feet to centimeters, and *c. g. s.* units to volts.

II. *To obtain the length of active conductor l' in feet.*

$$l' = \frac{E}{E'} \times \text{number of armature circuits.}$$

III. *To obtain the number of active conductors S upon the armature.*

Let ly = the number of layers in the armature winding.
ρ = the assumed ratio of the length to the diameter of the armature core.
d = the mean winding diameter of the armature in inches.
w = the specific peripheral width of one armature conductor in inches. (In the case of a smooth-core armature w represents the width of the armature conductor

plus the double thickness of its insulation, both in inches, while in the case of tooth armatures w represents the width of one tooth plus the width of one slot divided by the number of conductors in one slot in one layer.)

The length of the armature core $= \rho d$ inches $= \frac{\rho d}{12}$ ft. and the circumference of the core $= \pi d$ inches. The number of armature conductors in one layer $= \frac{\pi d}{w}$ hence the total number of armature conductors $S = \frac{\pi d l y}{w}$. Since

$$l' = ly\frac{\pi d}{w} \times \frac{\rho d}{12},$$

$$d = \sqrt{\frac{l' w 12}{\pi l y \rho}}.$$

$$\therefore\ S = \frac{\pi l y d}{w} = \frac{\pi l y}{w} \times \sqrt{\frac{l' w 12}{\pi l y \rho}} = \sqrt{\frac{\pi^2 l y^2 l' w 12}{w^2 l y \pi \rho}}$$

$$= \sqrt{\frac{12\pi l y l'}{w \rho}}.$$

In practice the width of the tooth ranges from 50 per cent to 80 per cent, the width of the slot. In some cases it has a width equal to that of the slot. The value for S yielded by this formula must, in nearly all cases, be altered by either the addition or subtraction of a few conductors in order to make it possible to employ the type of winding which it seems desirable to adopt. The change may necessitate a slight alteration of one of the assumed values, and as a result the values derived from it.

For machines whose speed is prescribed, as is the case with direct connected machines, one may use the form of the formula $S = \frac{\pi d l y}{w}$, where d is to be obtained as described in the end of the next paragraph.

IV. *To obtain the diameter of the armature d in inches.*

$$d = \frac{\frac{Sw}{ly}}{\pi} \text{ inches.}$$

In case the speed of the armature in revolutions per minute V be prescribed, as is the case with direct connected machines, the preliminary assumption of the peripheral velocity V' immediately gives a value for the armature diameter.

$$d = \frac{V'}{V\pi} \text{ ft.} = \frac{V' \, 12}{V\pi} \text{ inches.}$$

V. *To determine the length of the armature l in inches.*

$$l = d\rho.$$

VI. *To determine the internal diameter of the armature core d′ in inches.* In determining this quantity a value for the flux density in the armature core $\mathfrak{B}_a$ must be assumed. Wiener states that in incandescent dynamos, in railway generators, in machines for power transmission and distribution, and in stationary and railway motors, the density varies from 5,500 to 15,500. Ring armatures have higher densities than drum armatures, low-speed machines higher densities than high-speed machines, and bipolar machines have larger densities than multipolars. $\mathfrak{B}_a = 8000$ is a good assumption.

If the machine have p pairs of poles, the flux which enters the armature through one pole

$$\phi_a = \frac{l \pi d \mathfrak{B}_g s \, (2.54)^2}{2p},$$

that is, the surface of the armature in square centimeters times the average gap density divided by the number of poles. Considering that but 75 per cent to 80 per cent of the length of the armature core is made up of iron, the rest being due to the spaces between the laminations and the width of the ventilating ducts, the radial depth of the armature core is

$$d - d' = \frac{\phi_a}{\mathcal{B}_a l \, 0.75 \, (2.54)^2}.$$

$$\therefore \; d' = d - \frac{\phi_a}{\mathcal{B}_a l \, 0.75 \, (2.54)^2}.$$

VII. *To determine the armature losses.* The armature as already determined would theoretically operate satisfactorily, but there is a possibility of its heating excessively when running under full load. There are the two constant supplies of heat, namely, that due to ohmic resistance and that due to hysteresis and eddy currents. There are also two avenues for the escape of heat, namely, radiation and air convection. An equilibrium is established when that temperature is reached which will make the escaping heat per unit of time equal to the amount of heat generated in the same time. Concerning the escape of heat by radiation, it should be borne in mind that the watts radiated vary as the difference in temperature between the radiating body and the surrounding atmosphere and as the emissivity and the area of the radiating surface. There is also on starting a conduction of heat to neighboring bodies. After a short time, however, a static temperature condition will be established. The power loss in hysteresis in the armature is

$$P_h = \frac{1}{10^7} \eta p \, \mathcal{B}_a^{1.6} \frac{V}{60} v \text{ watts,}$$

where η equals the hysteretic constant of the iron (0.002), v equals the volume of the armature core in cubic centimeters. The assumption is made that the flux density in the armature core is uniform. This is not true for the main core, as was shown by Goldsborough, and in the teeth the density is much greater. When the volume of the latter is a relatively large amount of the total core volume, a correction should be made. When making many designs, in which the same quality of iron is to be used, it is much easier to get the hysteresis loss per cubic inch at various densities from tables made up to suit the iron. The power loss due to ohmic resistance

$$P_r = \left(\frac{I_{max}}{\text{number of armature circuits}}\right)^2 R_a,$$

where I_{max} is the full-load current of the machine in amperes, and R_a is the resistance of all the armature conductors arranged in series. Before getting P_h and P_r one must determine the values in VIII. to XI.

VIII. *To obtain the armature speed V in revolutions per minute.* This quantity is prescribed in the case of direct connected machines. In other cases in may be determined by the formula

$$V = \frac{12\ V'}{\pi d}.$$

IX. *To obtain the volume of the armature core v in cubic centimeters.*

$$v = zl\pi\left(\frac{d^2 - d'^2}{4}\right)(2.54)^3,$$

where z is a coefficient which represents that part of the armature core length which is occupied by iron. In ordinary laminations the space occupied by air and insulating oxide on the plates amounts to 10 per cent, therefore under these circumstances $z = 0.9$. The introduction of ventilating ducts reduces this value by an amount which can be readily determined.

X. *To obtain the resistance of the armature wire in ohms.* The total length of the armature wire,

$$l_t = l' \times k,$$

where k is a constant greater than unity, which takes into account the amount of dead wire employed in making the end connections. This value depends upon the value of ρ and upon the method of winding. In the case of formed coils its value may be determined from measurements upon a single coil. This value is generally slightly greater than 2. Considering that the resistance of a hot mil foot is 11.5 ohms, the resistance of the armature

$$R_a = \frac{11.5 \; l'k}{\text{cross-section in circular mils.}}$$

XI. *To obtain the area of the armature radiating surface A in square inches,*

$$A = \pi \, ld + \pi\left(\frac{d^2 - d'^2}{2}\right).$$

XII. As 2 to 2¼ watts can be radiated per square inch of armature surface without excessive heating, the value of $\dfrac{P_h + P_r}{A}$ determines whether the armature is properly designed or not. If the fraction is less than 2, the armature is needlessly large, and should be redesigned. If the fraction is greater than 2¼, the armature will heat excessively, and should also be redesigned.

121. Design of the Field. — XIII. *Dimensions of the poles and field frame.* The design of a field requires judgment and experience on the part of the designing engineer, and an acquaintance with the various machines of the type being designed. One must assume values for the following quantities: the flux density in the poles $\mathfrak{B}_p$, the flux density in the magnet frame $\mathfrak{B}_f$, the coefficient of magnetic leakage λ, and the ratio of the length of a pole to its diameter in case it has a circular cross-section, or to some other dimension in case it is not circular. The assumption is made here that the field frame is of a circular type, and that the pole is of circular cross-section. It is customary to choose such a value for $\mathfrak{B}_p$ that the magnetization will be carried over the knee of the magnetization curve. In the case of $\mathfrak{B}_f$, however, it is customary to choose a value somewhat below the knee. The coefficient of magnetic leakage for this type of machine is 1.4. A careful design really requires a knowledge of the distribution of the leakage flux. Long experience enables one to make allowance for this. From these assumed values one gets a value for the cross-section of a pole,

$$A_p = \frac{\phi_a \lambda}{\mathfrak{B}_p} \text{ sq. centimeters,}$$

whence it follows that the diameter of the pole in inches $d_p = \frac{1}{2.54}\sqrt{\frac{4\,A_p}{\pi}}$ inches, and the cross-section of the frame,

$$A_f = \frac{\phi_a \lambda}{2\,\mathfrak{B}_f} \text{ sq. centimeters.}$$

XIV. *Reluctance of the magnetic circuit.* After making a provisional scale-drawing of the field-magnet frame with its poles and the armature core, exercising judgment derived from experience or from the inspection of other drawings, determine the average length in centimeters of the path of the magnetic lines in the frame, in the poles, in the air gap, in the teeth, and in the armature core.

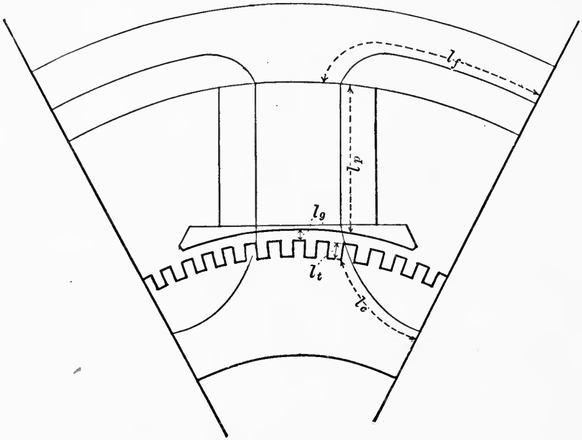

Fig. 176.

Represent by l_f, l_p, l_g, l_c and l_t the length in centimeters of the parts marked in Fig. 176. From the assumed values of the flux density, and from the magnetization curves of the metals from which the various parts of the magnetic circuit are constructed, one can get the respective permeabilities. The reluctance may then be calculated as follows:

Reluctance of the pole $\mathcal{R}_p = \dfrac{l_p}{\mu_p A_p}$.

" of $\frac{1}{2}$ section of field frame $\mathcal{R}_f = \dfrac{l_f}{\mu_f A_f}$.

" of the air gap $\mathcal{R}_g = \dfrac{2\,p l_g}{s l \pi d\,(2.54)^2}$.

" of $\frac{1}{2}$ section of the armature core,

$$\mathcal{R}_a = \frac{l_c}{\mu_a z\, l\,(d - d')\,(2.54)^2}.$$

To determine the reluctance offered by the teeth and winding-slots, it is convenient to assume that the total flux is carried by the teeth alone. Owing to the fringing of the field at the pole tips, not merely the teeth immediately under the pole face carry the flux from that pole, but, with very short air gaps, an extra tooth takes part in the trans-

TABLE OF TOOTH-DENSITY CORRECTIONS.

Corrected Iron Density.	Densities on the Assumption that the Iron Transmits the Entire Flux.		
Lines per Sq. Centimeter.	Tooth Width = Slot Width.	Tooth Width = ¾ Slot Width.	Tooth Width = ½ Slot Width.
17050	17200	17380	17510
18000	18450	18600	18800
19050	19680	20000	20200
20000	21050	21300	21850
21020	22200	23000	23700
22000	24000	24800	25500
23100	26000	26800	28400

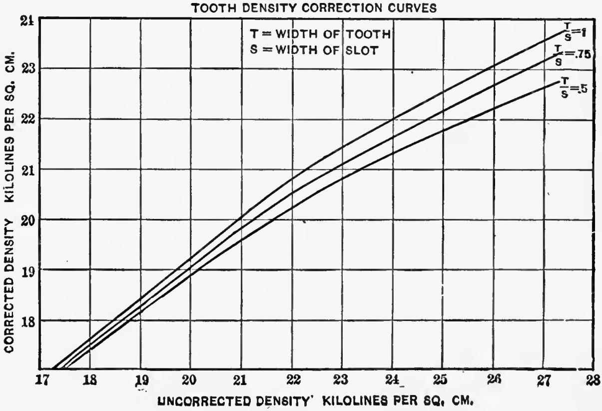

Fig. 177.

mission. With large air gaps two or three extra teeth may take part. The value of the permeability obtained from the flux density which is calculated upon the above assumption would be too small. The value of the reluctance based upon it would in consequence be too large. The flux density arrived at will have to be corrected by reference to the table on page 243.

The permeability, μ_t, corresponding to the corrected density and to be obtained from Fig. 178, should be inserted in the formula for the reluctance of the teeth,

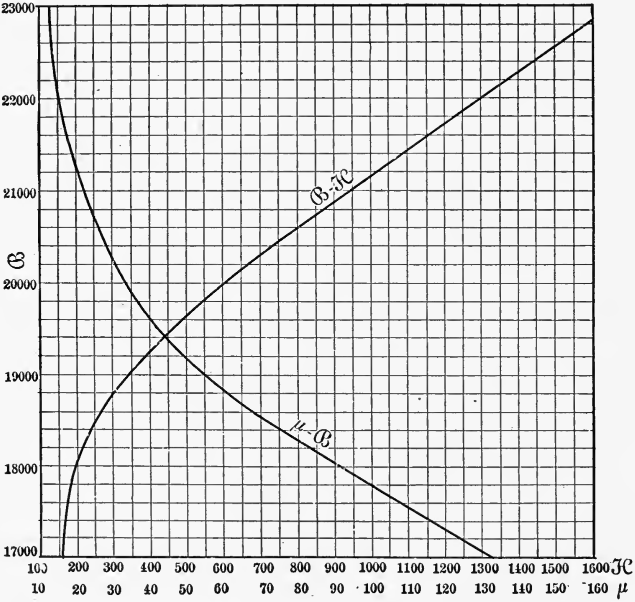

Fig. 178.

$$\mathcal{R}_t = \frac{l_t}{\mu_t A_t},$$

where A_t is the net iron cross-section of the teeth under one pole corrected for fringing. The reluctance, the flux through which must be maintained by the field-windings on one pole, is made up of a bi-parallel path in the armature and a bi-parallel path in the field frame, both arranged in series with the pole, the gap, and the tooth reluctances. This reluctance is equal to

$$\frac{\mathcal{R}_f}{2} + \mathcal{R}_p + \mathcal{R}_g + \mathcal{R}_t + \frac{\mathcal{R}_a}{2}.$$

XV. *Magneto-motive force.* The ampere turns per pole nI_{sh} necessary to produce the flux ϕ_a in the armature at no load is equal to

$$\frac{10\,\phi_a}{4\,\pi}\left[\mathcal{R}_g + \mathcal{R}_t + \frac{\mathcal{R}_a}{2} + \lambda\mathcal{R}_p + \frac{\lambda\mathcal{R}_f}{2}\right].$$

These ampere turns are furnished by the shunt coil on one pole.

XVI. *Shunt Coils.* Assuming that E_b volts are consumed in the field regulating rheostat,

$$R_{sh} = \frac{E - E_b}{I_{sh}\,2\,p} = \frac{11.5\,\dfrac{nI_{sh}}{I_{sh}}\,l_{sh}}{\text{circular mils}}.$$

Whence,

The cross-section in circular mils $= \dfrac{11.5\,nI_{sh}l_{sh}\,2\,p}{E - E_b}$.

Where n = number of turns in shunt coil,

I_{sh} = the current in the shunt at no load, and

l_{sh} = the mean length of one field turn in feet.

Assuming 1,000 circular mils per ampere in the shunt coil,

$$I_{sh} = \frac{\text{circular mils}}{1000}, \text{ and}$$

$$n = \frac{1000\,nI_{sh}}{\text{circular mils}}.$$

From a wire table the space occupied by the n turns can be attained; and, with due allowance for insulation, reference to the preliminary drawing will enable one to determine whether the assumed length of the pole l_p is too small or too great. Space must be left for the compound coil. This occupies about one-half as much space as the shunt coil. If l_p seems of unsuitable length it should be altered, and the calculation should be again gone over.

XVII. *Compound Coils.* The method of calculating the number of compounding turns is so similar to that in the case of shunt coils that it need not be gone into in detail. The compound coils have to compensate at full load for drop in the armature, for drop in the series coil, for drop in the line in case of overcompounding, for the demagnetizing armature ampere turns, and for changes in reluctance due to skew by saturation. The back armature ampere turns, when multiplied by the coefficient of magnetic leakage, give the series ampere turns necessary to compensate for them. It should be borne in mind that the maximum possible lead brings the brush no farther than the pole tip. To compensate for a drop of a certain percentage requires that the density in the air gap be raised by that same percentage. This necessitates an increase of all the densities. The increase of each reluctance and the increase of each corresponding flux must be cared for by the series windings. The coefficient of magnetic leakage varies with the load. The manner of its variation may be unknown. The reluctances, into which it enters, are such a small per cent of the total, that its variation may often be neglected.

The following blank form, to be filled in by students in designing, is self-explanatory.

POLYTECHNIC INSTITUTE OF BROOKLYN.

DEPARTMENT OF ELECTRICAL ENGINEERING.

Data sheet to be filled in by students taking Electrical Engineering 8, and covering the work of the first semester. This must be accompanied by the following scale drawings: end elevation, longitudinal cross-section, plan, and important details. A diagram of the armature-winding must also be given. Assumed values are to be entered in red ink.

..............................Designer   Submitted.......................

SPECIFICATIONS.

1. Type of Machine
2. Number of poles
3. Capacity in kilowatts
4. Terminal volts at no load
5. Terminal volts at full load
6. Amperes at full load
7. Revolutions per minute

MATERIALS.

8. Armature core
9. Armature spider
10. Armature end plates
11. Armature shaft
12. Commutator segments
13. Commutator spider
14. Magnet frame
15. Pole piece
16. Pole shoe
17. Brushes
18. Brush-holders
19. Brush-holder yoke
20. Commutator insulation
21. Armature conductor insulation
22. Field-coil insulation

DIMENSIONS.

Armature.

23. Diameter over all
24. Diameter at bottom of slots
25. Internal diameter of core
26. Length over conductors
27. Length of core over laminations and ducts
28. Net length of iron
29. Number of ventilating-ducts
30. Width of each ventilating-duct
31. Thickness of sheets
32. Number of slots
33. Depth of slots
34. Width of slot at root
35. Width of slot at surface
36. Width of tooth at root
37. Width of tooth at armature face
38. Size and shape of bare conductor
39. Size of conductor insulated
40. Pitch of winding, No. of teeth
41. Arrangement of wires or bars per slot
42. Number in parallel per slot
43. Number in series per slot
44. Total insulation between conductors
45. Thickness insulation between conductors

Air Gap.

46. Length in center

47. Length maximum
48. Bore of field
49. Minimum clearance

Pole Shoe.

50. Length parallel to shaft
51. Length of maximum arc
52. Length of minimum arc
53. Minimum thickness

Poles.

54. Length of pole
55. Width or diameter of pole
56. Length parallel to shaft

Magnet Spool.

57. Number of spools
58. Length over all
59. Length of winding-space
60. Depth of winding-space

Magnet Frame.

61. External diameter
62. Internal diameter
63. Thickness
64. Diameter over ribs
65. Thickness of ribs
66. Length along armature

Commutator.

67. Diameter
68. Number of segments
69. Width of segment at commutator face
70. Width of segment at root
71. Useful depth of segment
72. Thickness of mica insulation
73. Available length of surface of segments
74. Total length of commutator
75. Peripheral speed

Brushes.

76. Number of sets of brushes
77. Number in one set
78. Length
79. Width
80. Thickness
81. Area of contact one brush

ELECTRICAL.

Armature.

82. Voltage at no load
83. Total voltage at full load
84. Total current
85. Number of sections
86. Turns per section
87. Number of layers
88. Total number of inductors
89. Type of winding . . . circuits
90. Style of winding
91. Circular mils per ampere
92. Mean length of one turn
93. Total length of arm wire
94. Resistance of armature cold at 20° C. . . . ohms
95. Resistance of armature hot at 70° C. . . . ohms

Shunt Coils.

96. Size of wire, No. B. & S. Gauge
97. Turns per layer
98. No. of layers
99. Turns per spool
100. Mean length of one turn
101. Total turns
102. Total length of wire
103. Total weight of wire
104. Total resistance at . . . 20° C. ohms
105. Total resistance at . . . 70° C. . . . ohms.
106. Volts allowed for rheostat
107. Maximum current . . . amperes
108. Total ampere turns
109. Circular mils per ampere

Series Coils.

110. Size and shape of conductor
111. Number of conductors in multiple
112. Arrangement
113. Turns per layer
114. Number of layers
115. Turns per spool
116. Mean length of one turn
117. Total turns
118. Total length of conductor
119. Total resistance at . . . 20° C. . . . ohms.
120. Total resistance at . . . 70° C. . . . ohms.
121. Maximum current . . . amperes
122. Total ampere turns
123. Circular mils per ampere

HEATING.

Armature.

124. Area of drum radiating surface . . . sq. in.
125. Area each end radiating surface . . . sq. in.
126. Total radiating surface . . . sq. in.
127. I^2R full load . . . watts
128. Hysteresis . . . watts
129. Eddy currents . . . watts
130. Total . . . watts
131. Total I^2R and core loss at full load . . . watts
132. Watts per sq. in. radiating surface, full load
133. Estimated rise of temperature at full load . . . C.
134. Friction of windage and bearings . . . watts

Field Coils.

135. Radiating surface (heads) . . . sq. in.
136. Radiating surface (periphery) . . . sq. in.
137. Total radiating surface . . . sq. in.
138. I^2R shunt coils and rheostat . . . watts
139. I^2R series . . . watts
140. Total I^2R . . . watts . . . %
141. Watts loss per sq. in. . . . radiating surface
142. Estimated rise of temperature at full load . . . C.

Commutator.

143. Brush friction . . . watts
144. Brush contact . . . watts
145. Other commutator losses . . watts

MAGNETIC.

146. ϕa at open circuit
147. ϕa at full load
148. Leakage coefficient
149. ϕf at open circuit . . . ϕf at full load
150. Ampere turns required for shunt
151. Ampere turns required for series

	LENGTH.		AREA.		ℛ		MAGNETIC DENSITY.				AMP. TURNS REQUIRED.	
							NO LOAD.		FULL LOAD.			
	INCHES.	CMS.	SQUARE INCHES.	SQUARE CMS.	FULL LOAD.	NO LOAD.	PER SQ. IN.	PER SQ. CM.	PER SQ. IN.	PER SQ. CM.	NO LOAD.	FULL LOAD.
152 Armature Core												
153 Pole												
154 Magnet Frame												
155 Air Gap												
156 Teeth uncorrected												
157 " corrected												
158 Ampere turns required for armature reaction												
Total												

EFFICIENCY.

159 Total output in watts	163 Efficiency at full load
160 Total losses at full load in watts	164 Coefficient of conversion at full load
161 Electrical losses at full load in watts	165 Economic coefficient at full load
162 Conversion losses at full load in watts	166 Load at which maximum efficiency occurs in K.W.

CHAPTER XIV.

TESTS.

122. Determination of a $\mathfrak{B}\,\mathfrak{H}$ Curve. — The most exact laboratory method of finding this curve is by the ballistic galvanometer or ring method. Fig. 179 shows the arrangement of apparatus for this method. X is the test piece in the form of an annular ring, having a mean circumference of l centimeters and a radial cross-section of a sq. centimeters. It is wound uniformly with n primary turns of wire. Over these three or four secondary *test turns* of wire lead off to the ballistic galvanometer G. A series circuit is formed of a storage battery or other suitable source of $E.M.F.$, B, a variable resistance R, the primary coil of the test piece, an ammeter A, and a commutating switch C. The last is used for reversing the direction of the current in the primary coil.

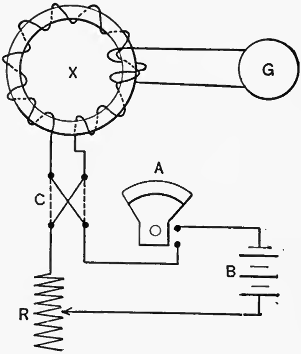

Fig. 179.

If R be adjusted to give a current I, then the magnetizing force, or $\mathfrak{H}$, by § 21 is represented by the formula

$$\mathfrak{H} = \frac{4\pi n I}{10 l}.$$

If now the current be suddenly commutated, all the lines of force will be withdrawn, and as many more set up in the opposite direction. Each of these lines will induce, upon commutation, a pressure in each turn of the test coil. This induced *E.M.F.* furnishes a means of measuring the flux of lines in the test piece or the flux density $\mathcal{B}$. By application of the formula given in § 16, one may obtain the expression for this quantity,

$$\mathcal{B} = \frac{10^8 R_t}{2\,a n_2} k\theta.$$

Where

$R_t =$ the resistance of the test coil, the galvanometer, and the secondary circuit;

$a =$ the area of a radial section of the test piece in square centimeters;

$n_2 =$ the number of turns in the test coil;

$k =$ a constant of the galvanometer; and

$\theta =$ the throw of the galvanometer which accompanies the commutation of the primary current.

Though the most accurate method, the ring method is not generally employed in commercial practice because of the cost and the time required in preparing a test piece.

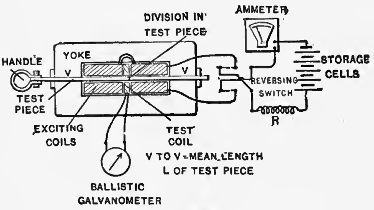

Fig. 180.

The divided-bar method admits of the use of a bar of iron of ordinary shape as a test piece. This is cut into two pieces. A heavy wrought-iron yoke, Fig. 180, has a magnetizing coil wound inside of it. Through snug-fitting holes in the ends of the yoke, the two halves of the test piece are inserted, one being secured, and the other being fitted with a handle. The test coil is so mounted on springs as to fly suddenly to one side when the test pieces are slightly separated by a pull on the handle. It thus cuts all the flux in the piece, and affords a means of measuring it. The yoke is so massive, and has such a small reluctance as compared with that of the test piece, that the formula $\mathcal{H} = \frac{4\ \pi n I}{10\ l}$ is practically true, where l is the mean length of the test piece which is traversed by magnetic lines. For $\mathcal{B}$ the formula is twice what it was in the ring method, since the test coil cuts the flux but once, or

$$\mathcal{B} = \frac{10^8 R_t}{a n_2} k\theta.$$

The method of reversals could be used equally well with this apparatus, requiring the formula used in the ring method.

The permeameter is a machine for measuring the flux in a test piece by measuring the force necessary to detach it from another part of the magnetic circuit. Fig. 181 shows in simple such a machine. The magnetizing force is supplied by the coil *C* the same as in the divided bar method. The test coil and galvanometer are done away with. The bottom of the yoke *Y* is surfaced to receive flatly the end of the test rod *T*. When the proper current is flowing in the coil, the force necessary to separate the test piece from the yoke is found by means of the spring-balance *S*. Since the force required to break

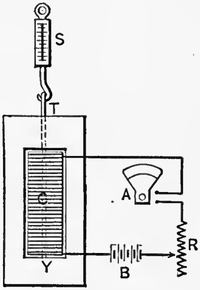

Fig. 181.

any number of lines of force varies as the square of that number, it is easy to calculate the flux, and since

$$\phi = \text{area} \times \mathcal{B},$$

the magnetic density is readily found. The value of $\mathcal{H}$ is obtained as in the preceding case.

123. Determination of the Ballistic Constant. — The standard condenser affords the most convenient and accurate means of determining the constant of a ballistic galvanometer. If the capacity of the condenser C, and the voltage at which it is charged E, be known, then the quantity of electricity that will flow when the circuit is closed through the galvanometer is also known. It is equal to EC. By observing the galvanometer throw θ, the value of the constant k is determined from

$$Q = EC = k\theta.$$

$$\therefore\ k = \frac{EC}{\theta}.$$

The coil of a d'Arsonval ballistic galvanometer moving in its field has an *E.M.F.* induced in it, which tends to send a current in a direction opposite to that of the current that produces the throw, and which, therefore, shortens the throw or damps the galvanometer. The magnitude of this damping current depends, of course, on the resistance of the galvanometer circuit; hence the constant k should be determined with the same external resistance in the galvanometer circuit as there will be when the test for the value of $\mathcal{B}$ is being made.

To accomplish this an arrangement of apparatus such as is shown in Fig. 182, may be employed, the particular feature of which is the quadruple contact key. This key is normally held up against a contact. In this position the galvanometer circuit is open, and the condenser is in series with a charging battery. As the key is pressed down, three things occur. First the battery circuit is broken, then the condenser is discharged through the galvanometer, and lastly the galvanometer circuit is closed through an appropriate amount of resistance in the rheostat.

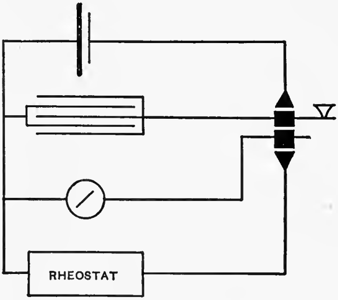

Fig. 182.

The ballistic constant may also be determined by the use of a long solenoid, with a few turns about its center for a test coil. A series circuit is formed (Fig. 183) of a battery, a variable resistance, an ammeter, the solenoid, and a key. The ends of the test coil are attached to the galvanometer through proper resistance. On closing the circuit the current I sets up a field at the center of the solenoid, whose intensity,

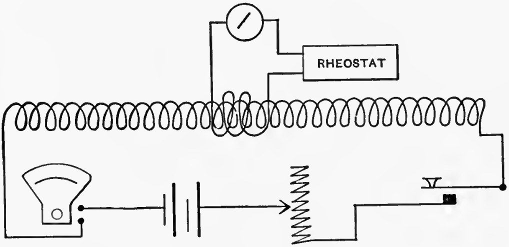

Fig. 183.

$$\mathcal{H} = \frac{4\pi n I}{10 l},$$

where l is the length of the solenoid in centimeters, and n the number of primary turns.

If A be the area in square centimeters of a cross-section of the solenoid perpendicular to the axis, then

$$\phi = \mathcal{H} A.$$

If n_2, be the number of turns in the test coil, and R be the resistance of the galvanometer circuit in ohms, then upon closing the circuit and upon establishing the flux ϕ, a quantity of electricity will pass around the secondary circuit which is equal to

$$Q = k\theta = \frac{n_2\phi}{10^8 R} = \frac{4\pi n n_2 I A}{10^9 R l},$$

where θ is the throw of the galvanometer corresponding to the current I. Therefore,

$$k = \frac{4\pi n n_2 I A}{10^9 R l \theta}.$$

If the solenoid be less than ten diameters long, this result is not accurate, owing to the influence of the ends of the solenoid upon the value of $\mathcal{H}$.

There have been described numerous methods for determining k which depend upon a constant and definite intensity of the earth's magnetic field. Nowadays the fact that the earth's field is constantly changing, both in direction and magnitude, due to the prevalence of iron and steel buildings, and the extensive use of electric currents for trolley, lightning, and other purposes, makes these methods practically worthless.

124. Determination of the Hysteretic Constant. — The hysteresis curve for any sample of iron may be found most accurately by the *step-by-step* method. The arrangement of apparatus is in all respects similar to that of Fig. 179, save that the rheostat R must be so designed that the circuit does not open, even for an instant, in passing from one resistance point to another. The method of operation is as follows: The rheostat is set for a maximum current strength which is determined by means of an ammeter. The rheostat handle is then quickly moved back one point. This reduces the current and the dependent magnetizing force proportionately. There is an accompanying decrease of flux in the sample. This decrease is determined by the galvanometer throw, the formula being as before,

$$\text{Change in } \mathcal{B} = \frac{10^8 R}{a n_2} k\theta.$$

The ammeter current is again read; and, as soon as the galvanometer comes to rest, the resistance is increased by another step, and the throw of the galvanometer is observed. After the current has been reduced step by step to zero, it is then commutated, and increased by steps until the maximum magnetization is obtained in a direction opposite to that at the beginning. The current is again cut down by steps to zero, is afterwards commutated for a second time, and is again increased until the magnetic condition of the iron which prevailed at the start is again attained. Giving to $\mathcal{B}$ a plus or minus sign, according to the direction of the galvanometer throw, the algebraic sum of all the changes of $\mathcal{B}$ must equal zero. Therefore the algebraic sum of all the galvanometer throws should equal zero. A simple addition serves as a check on all observations. In practice, the sum of the plus throws may differ from the sum of the minus ones by three per cent without seriously affecting the final result. Having the maximum value of $\mathcal{B}$, the $\mathcal{B}$'s corresponding to each can readily be found by subtracting the changes in $\mathcal{B}$ from the maximum $\mathcal{B}$. Upon plotting a cyclic curve of the various values of $\mathcal{B}$ and the corresponding values of $\mathcal{H}$, one obtains a hysteresis loop, as in Fig. 184. The area of this loop in $\mathcal{B}\mathcal{H}$ units, when divided by 4π, gives the ergs loss of energy in carrying one cubic centimeter of the iron under test through a cycle of magnetization between the limits of $+\mathcal{B}_{max}$ and $-\mathcal{B}_{max}$. According to the Steinmetz formula,

$$h = \eta \mathcal{B}^{1.6}{}_{max},$$

where h is the loss by hysteresis in ergs per cycle per cubic centimeter. Hence, to find the hysteresis constant η of the sample used in the foregoing test, one uses the formula

$$\eta = \frac{A_h}{4\pi V \mathcal{B}^{1.6}{}_{max}},$$

where $A_h =$ area of hysteresis curve expressed in $\mathcal{B}\mathcal{H}$ units,
and $V =$ volume of iron in cubic centimeters.

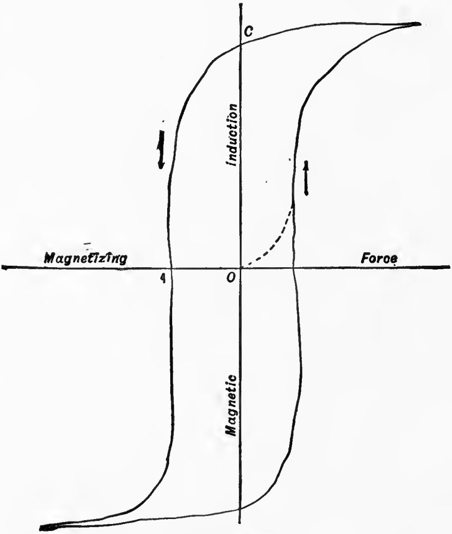

Fig. 184.

A much less laborious method of measuring η, and one which does not introduce the errors attending the measurement of the area of a curve, is the wattmeter method. Since the iron to be tested is generally for use in alternating current apparatus, this method has the additional advantage that the test occurs under the conditions which the iron will meet in its working.

If the ring be made of annular stampings of sheet metal well shellacked before assembling, then the loss due to eddy currents will be negligible. The arrangement of apparatus, shown in Fig. 185, consists of a source of alternating current, a wattmeter, an alternating current ammeter, an alternating current voltmeter, and the test ring, all connected as shown.

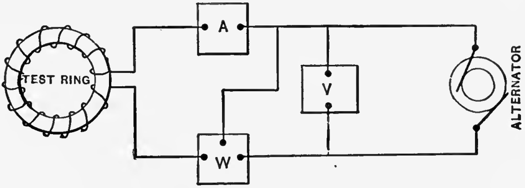

Fig. 185.

Let R = the resistance of the coil on the test ring;
n = number of turns in this coil;
W = the watts indicated by the wattmeter;
I = the current indicated by the ammeter;
E = the pressure indicated by the voltmeter;
V = the volume of the iron in cubic centimeters;
A = the area of a radial cross-section in square centimeters; then, assuming the current to be sinusoidal, and of frequency f cycles per second,

$$\eta = \frac{10^7(W - I^2R)}{Vf} \left(\frac{\sqrt{2}\,\pi n f A}{E\,10^8}\right)^{1.6}.$$

Ewing's machine for hysteresis tests is shown in Fig. 186. Its chief advantage lies in the fact that the test piece needs to consist of but half a dozen pieces of sheet iron $\frac{5}{8}''$ by $3''$. This test piece is made to rotate between the poles of a permanent magnet, which is mounted on knife edges on an axis coincident with the axis of revolution of the test piece. The resulting angular displacement of the magnet, as marked by a pointer on a divided scale, is proportional to the hysteresis loss in the specimen. A calibration curve is plotted by using two different specimens having known hysteretic constants. It is found that small variations in the thickness of the test piece do not affect the results, and that no correction need be made for such variations. The machine yields but comparative results.

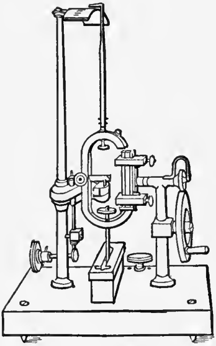

Fig. 186.

125. Determination of Leakage Coefficient.— The ratio of the total flux generated by a field magnet to the flux passing through the armature, that is, the *leakage coefficient*, which is always greater than unity, may be found with an arrangement of apparatus as shown in Fig. 187 where the machine is a yoke-wound bipolar. A test coil of a few turns is passed around the center of the field magnet, and through it all the lines generated may reasonably be assumed to pass. A similar coil is passed around the armature, in a plane perpendicular to the direction of the flux, through which all the armature flux must pass. In the case of a small machine, normal exciting current is passed through the field magnet, with arrangements for rapid commutation. In this case, if one test coil have its ends attached to a galvanometer or a low-voltage voltmeter, and if the current in the field coil be commutated, a deflection, which is proportional to the change of flux, will be observed. The same will happen if the other coil have its terminals connected to the galvanometer. If θ_f and θ_a be the deflections observed with the field and the armature test coils respectively, then, as before,

$$\phi_f = \mathfrak{B}_f a = \frac{10^8 R}{2\,n_2} k\theta_f, \text{ and}$$

$$\phi_a = \frac{10^8 R}{2\,n_2} k\theta_a.$$

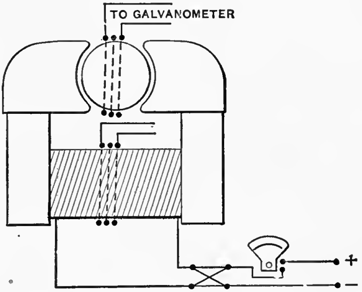

Fig. 187.

If the two test coils be constructed alike as regards number of turns and resistance, then the values of R, n_2, and k are the same in both equations, and we have the leakage coefficient

$$\frac{\phi_f}{\phi_a} = \frac{\theta_f}{\theta_a}.$$

Hence the ratio of the galvanometer throws gives the coefficient without further calculation.

This method may be employed to obtain the flux in any part of the magnetic circuit, and it serves to locate the points of greatest leakage. It may also be modified to apply to any type of machine. In the case of large machines, whose field currents cannot be commutated, a cyclic increase and decrease of exciting current can be produced by means of cutting out and in of resistance in the field circuit. Even then the time constants of large field coils are so great as compared with the period of swing of ballistic galvanometers, that the method is impracticable.

126. Magnetic Distribution in the Air Gap. — Since armature reactions distort the magnetic field, it is desirable to know the actual distribution of the flux. This may be determined by the use of a *pilot brush*, as shown in Fig. 188. A voltmeter is connected between one of the main brushes and the pilot brush, and the latter is moved through equal angular intervals until the opposite brush is reached. The difference in the voltage of any two consecutive readings is proportional to the magnetic flux within the angular distance moved over between those two readings.

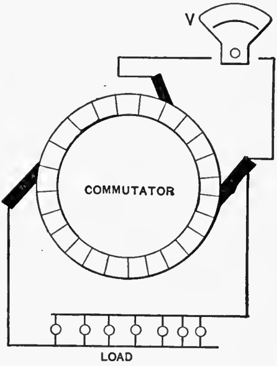

Fig. 188.

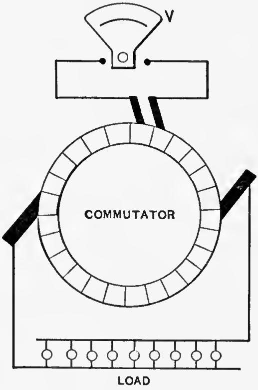

Fig. 189.

Two pilot brushes may be used as in Fig. 189. In this case the voltage is proportional to the flux corresponding to the angular distance between the two brushes. By applying these brushes at successive intervals through 180° the flux distribution can be determined.

127. Measurement of Resistance.—*a. By voltmeter alone.* For insulation resistances, or any resistances lying between about 5000 and 100,000 ohms, a fairly accurate result may be obtained by arranging the unknown resistance x and a 0–150 voltmeter in series with a source of constant potential of about 115 volts. The reading θ is noted. The resistance is then short-circuited and the deflection θ' noted. If R be the resistance of the voltmeter, then

$$x = \frac{\theta' - \theta}{\theta} R.$$

Maximum accuracy is obtained when $x = R$.

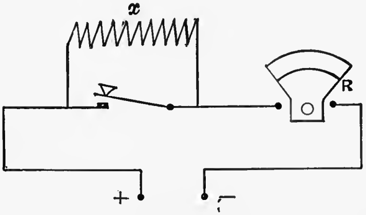

Fig. 190.

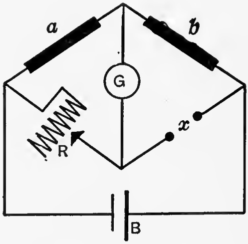

Fig. 191.

b. By the Method of Wheatstone's Bridge. If an unknown resistance x, two known resistances a and b, and a known adjustable resistance R be connected as shown in Fig. 191, with a galvanometer G and a battery cell B, a Wheatstone's bridge is formed; and, if the resistance R be so manipulated as to prevent a flow of current through the galvanometer, then the following relation is true:

$$a : b :: R : x.$$

It is usual to make the ratio $a : b$ equal to some multiple or submultiple of 10. In this case the value of X is read directly from R with the decimal point suitably placed.

This method permits of great accuracy.

C. By ammeter and voltmeter. Resistances of ordinary magnitudes are most conveniently measured by measuring the pressure impressed on the resistance and the current caused to flow thereby. This is the most practical method for finding the resistances of armature and field-windings of dynamos.

It is a method so rapid that the value of hot resistances may be found, and fields can be measured even while the machine is in operation. Fig. 192 shows an arrangement of apparatus for measuring the resistance of an armature, including the brush and contact resistances. If I be the ammeter reading, and E be the voltmeter reading, then by Ohm's law

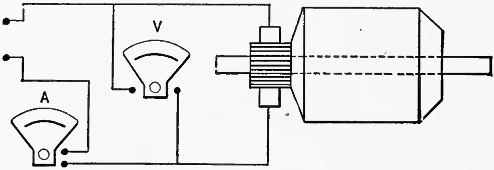

Fig. 192.

$$R = \frac{E}{I}.$$

128. Test of Dielectric Strength. — In order to test the voltage necessary to break down a sample sheet of insulating material, the sample is placed between two flat metallic surfaces, which are connected respectively with the two terminals of a high-voltage transformer, whose voltage can be varied at will. An air gap between needle-point terminals which can be adjusted in length is connected in parallel between the two terminals. The distance between these points serves to limit the voltage which can be impressed upon the conductors on each side of the insulating material. For small variations of gap length the voltage necessary to produce an arc between the needle-points is

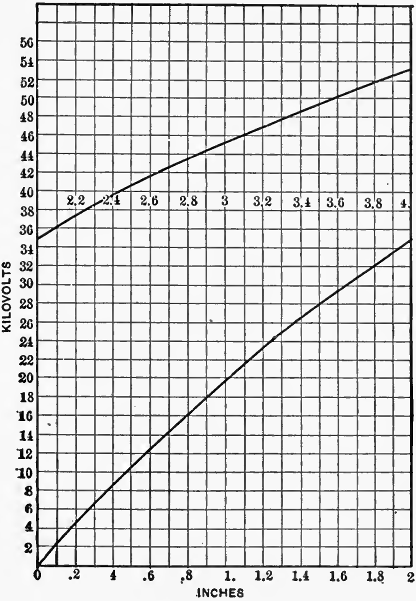

Fig. 193.

nearly proportional to the length. The following table, taken from the Standardization Report of the American Institute of Electrical Engineers, shows the relation which exists between air-gap length and the voltage necessary to produce a disruptive discharge. The relations are also exhibited in the curve of Fig. 193.

TABLE OF SPARKING DISTANCES IN AIR BETWEEN OPPOSED SHARP NEEDLE-POINTS, FOR VARIOUS EFFECTIVE SINUSOIDAL VOLTAGES, IN INCHES AND IN CENTIMETERS.

Kilovolts.	Distance.		Kilovolts.	Distance.	
Sq. Root of Mean Square.	Inches.	Cms.	Sq. Root of Mean Square.	Inches.	Cms.
5	0.225	0.57	60	4.65	11.8
10	0.47	1.19	70	5.85	14.9
15	0.725	1.84	80	7.1	18.0
20	1.0	2.54	90	8.35	21.2
25	1.3	3.3	100	9.6	24.4
30	1.625	4.1	110	10.75	27.3
35	2.0	5.1	120	11.85	30.1
40	2.45	6.2	130	12.95	32.9
45	2.95	7.5	140	13.95	35.4
50	3.55	9.0	150	15.0	38.1

In carrying out the test, the needle-points are adjusted at a certain minimum distance apart. The voltage impressed upon the terminals is raised until a spark passes between the points. The air gap is then increased in length, and the operation repeated until the sample breaks down, and the spark passes through it instead of across the air gap. The break-down voltage is then taken from the table or curve corresponding to the last position of the needle-points.

The sample should project considerably beyond the edges of the compressing surfaces. Owing to surface leakage a spark will pass over a very much greater distance of the surface of an insulator than it will in free air.

For the purpose of obtaining a voltage any form of high-potential transformer may be used, the primary being supplied by an alternating current. Fig. 194 illustrates a 10,000 volt transformer manufactured for this purpose by the General Electric Co. Its core is of the H type, and upon one branch of it is wound the low-tension circuit, while upon the other is wound the secondary, consisting of four coils, each wound and insulated independently. The four coils are assembled upon a sleeve of heavy insulating

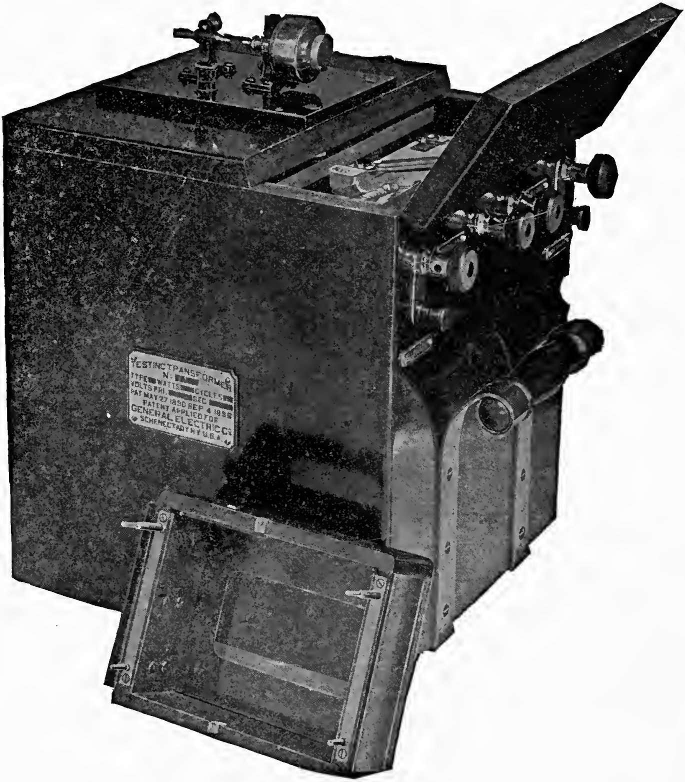

Fig. 194.

material. The transformer is immersed in oil, and its primary is wound in two parts so that it may be used upon a 52 or a 104 volt circuit. The adaptation to either of these circuits is rendered possible by means of a porcelain series multiple connection board which is placed inside the inclosing case. On the top of the apparatus is a box with a glass window, which incloses a micrometer spark gap, which is connected in shunt across the high-potential terminals. This box or cover carries four long contact studs which fit into sockets. In the transformer box the apparatus is so arranged that the lifting up of this cover for the purpose of adjusting the spark gap entirely disconnects the spark gap from the high-potential circuit. The connections of this apparatus to a sample under test are shown in Fig. 195.

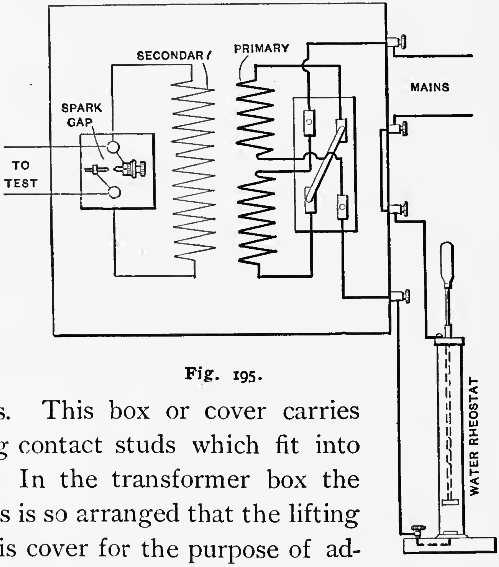

Fig. 195.

This apparatus may also be employed in determining whether a given sample of insulation will withstand an impressed electromotive force without breaking down. The length of the gap is set so as to represent the value of the prescribed electromotive force, and the sample is subjected to the pressure which maintains a spark across the gap. In case of break-down the spark at the gap will cease.

In case it is desired to test the dielectric strength of the sample at some other than normal temperature, the sample may be pressed between two surfaces of the apparatus shown in Fig. 196, which was described by Mr. Charles F. Scott. Two carefully faced blocks of cast iron are recessed so as to receive coils *D* and *D′* of asbestos-wound wire. These coils are supplied with alternating current which raises the temperature of the disks by means of eddy currents and hysteresis losses. Upon shutting off the current, the disks and insulating material soon assume a uniform temperature, which can be measured by means of a thermometer whose bulb is inserted in a hole in the upper disk. The two disks are made the terminals of the high-tension circuit. Connections with the circuit which is used for heating purposes must of course be removed during the test.

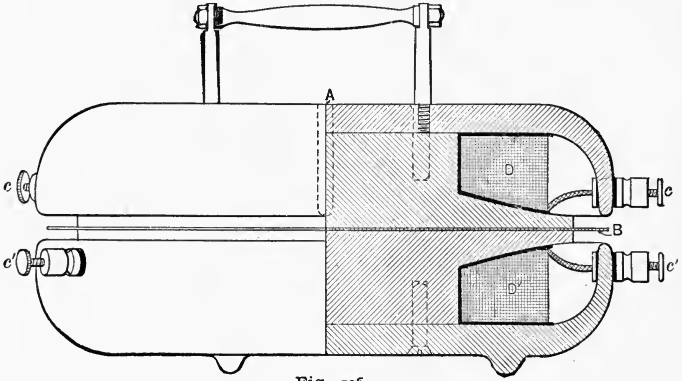

Fig. 196.

The report of the committee on standardization of the American Institute of Electrical Engineers gives the following: "The dielectric strength or resistance to rupture should be determined by a continued application of an alternating *E.M.F.* for five minutes."

"The test for dielectric strength should be made with the completely assembled apparatus and not with its individual parts, and the voltage should be applied as follows: 1st, Between electric circuits and surrounding conducting material, and 2d, between adjacent electric circuits where such exist."

The report further recommends for apparatus, not including switchboards and transmission lines, the following testing voltages:—

RATED TERMINAL VOLTAGE.	CAPACITY.	TESTING VOLTAGE.
Not exceeding 400 volts	Under 10 K.W.	1000 volts.
Not exceeding 400 volts	10 K.W. and over	1500 volts.
400 and over, but less than 200 volts	Under 10 K.W.	1500 volts.
400 and over, but less than 800 volts	10 K.W. and over	2000 volts.
800 and over, but less than 1200 volts	Any	3500 volts.
1200 and over, but less than 2500 volts	Any	5000 volts.
2500 and over	Any	Double the normal rated voltages.
Synchronous motor fields and fields of converters started from the alternating current side		5000 volts.

The values in the table above are effective values, or square roots of mean square reduced to a sine wave of *E.M.F.*

When machines or apparatus are to be operated in series, so as to employ the sum of their separate *E.M.F.*'s, the voltage should be referred to this sum, except where the frames of the machines are separately insulated both from ground and from each other.

129. Determination of the Magnetization Curve of a Shunt-Dynamo. — To find the relation between the exciting current and the no-load terminal volts of a shunt machine, excite tne shunt fields, Fig. 197, from an external source, first passing the current through a variable resistance and an ammeter. Run the machine at a constant speed throughout the test. If a voltmeter be placed across the armature terminals a pressure can be read corresponding to each exciting current, and a curve can be plotted using volts as ordinates and amperes as abscissæ. Because of residual magnetism there are some volts with no exciting current, and hence the curve, Fig. 198, does not pass through the origin.

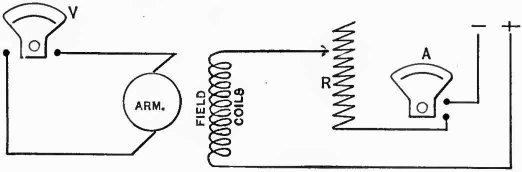

Fig. 197.

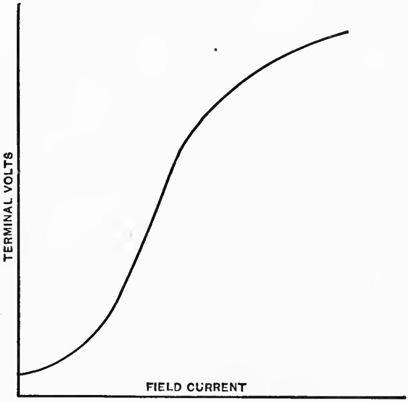

Fig. 198.

If the voltmeter be read while the current is *increasing* by steps to the maximum, and again while the current is *decreasing*, step by step, the two curves will not coincide; the descending curve will lie above the other as in Fig. 199. This is because of the hysteresis or magnetic retentivity of the iron of the magnetic circuit.

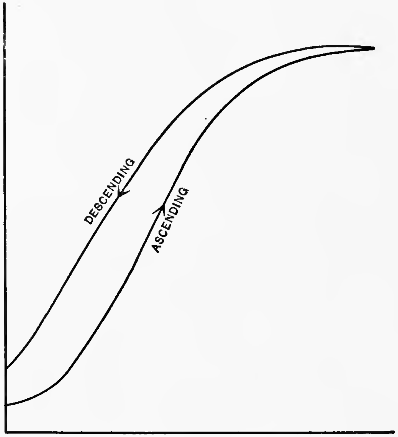

Fig. 199.

130. Efficiency of Dynamos and Motors.—The efficiency of these machines can be determined by any one of the following methods:—

a. Run the machine at its proper speed as a separately excited motor. Let the excitation be normal. By means of ammeter and voltmeter readings determine the electrical input, the motor having no load upon it. The arrangement of apparatus is shown in Fig. 200. The power put in represents the I^2R losses in the armature and the field plus the losses which are generally considered as constant at all loads. These constant losses are those due to friction, hysteresis, Foucault currents, and windage. They are equal to the no-load input minus the no-load I^2R armature and field losses. The I^2R losses can be calculated at any useful load. The efficiency at that load is equal to the load divided by the load plus the sum of the constant losses and the load I^2R losses. The machine at the time of no-load test should have the same temperature as it would have under the load for which the efficiency is being calculated.

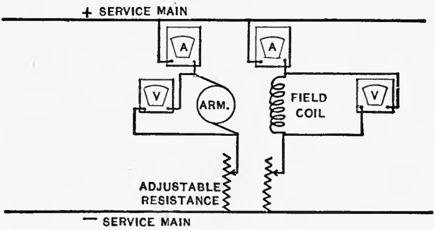

Fig. 200.

b. Run the machine as a motor at its rated speed and temperature. Measure the electrical input by a voltmeter and an ammeter. Measure the mechanical output by a Prony brake. Then the efficiency,

$$\eta = \frac{\text{watts at brake}}{\text{watts input}}.$$

There are many kinds of brake or absorption dynamometers that may be used for this test. The most satisfactory one for motors of small size is the strap-brake shown in Fig. 201. A piece of leather belting and two spring balances are all that is necessary. The formula for the absorbed power is,

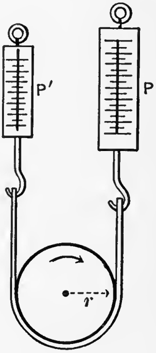

Fig. 201.

$$\text{Watts} = \frac{2\pi r V(P - P')}{33000} \times 746,$$

where $r =$ the radius of the pulley *in feet*;

V = number of revolutions per minute;
$(P - P')$ = the difference of the two-scale readings *in pounds.*

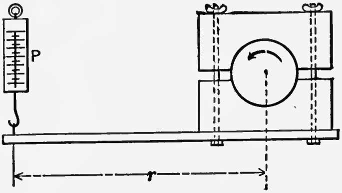

Fig. 202.

Fig. 202 shows a form of brake applicable to larger machines. The formula for the power absorbed is,

$$\text{Watts} = \frac{2\pi r V P}{33000} \times 746,$$

where r is the perpendicular distance from the center of the pulley to the line of action of the scale in feet, P the scale reading in pounds, and V the number of revolutions per minute. The brake should be so poised as to give no reading on the spring at no load.

The brake may be made with a metal strap having spaced blocks on its under surface that screw down against the wheel, and for the spring balance one may use a platform scale having a prop extending to the lever arm of the brake. For large machines the heat generated by the absorption of considerable power at the face of the pulley causes an excessive rise of temperature. It is necessary to find some means of carrying the heat away. This is generally accomplished by flanging the inside of the brake wheel, forming a trough in which water is kept running. Centrifugal force throws the water against the internal circumference of the wheel and prevents spilling. The water is removed either by a properly placed scoop, or it may be allowed to boil out.

c. A convenient method of finding and separating the losses of a machine is one which makes use of a rated motor, i.e., a motor whose mechanical output is known for any given electrical input. By reading the volt-ampere input of the motor the power expended on the machine to be tested can be found. Run the machine by the rated motor at the proper speed. If the brushes be removed from the machine, and no current be flowing in the field coils, then the power expended on it is the loss due to friction at the bearings and to windage. Now let the brushes be set, then the power expended is the loss due to windage, bearing friction, and brush friction. By subtraction the brush-friction loss is found. This is greater, particularly in small machines, than is generally supposed. Now let the fields be separately excited by the normal current, and the losses due to hysteresis and eddy currents are included in the power expended on the machine. From a knowledge of the hot resistances of the machine, one can calculate the I^2R loss for any useful load in both armature and field windings. This useful load divided by the sum of the useful load and all the losses, gives the efficiency of the machine at that load.

d. The methods *a*, *b*, and *c* all require some outside electric power. This requirement can be avoided by the use of a transmission dynamometer to measure the power input of any machine, and the power output can be read by a voltmeter and an ammeter. This method is seldom resorted to, since transmission dynamometers are often unreliable, they are expensive to set up, and some forms have but a limited power range.

Professor Goldsborough has recently devised a very ingenious dynamometer which consists simply of a coiled or helical spring with the center line of the helix corresponding with the center of the shaft. This spring connects the driving and driven members. Readings are made by means of two instantaneous contact points mounted, one on the driven and one on the driving-shaft, which are connected in series with each other and with a battery and telephone receiver. As the spring becomes deflected by a load, the contact on the driven shaft falls back, and the corresponding brush must be set back by the same angle in order to obtain a click in the telephone. This angle is a direct measurement of the torque, and can be calibrated at standstill.

e. The efficiency of direct connected units can be found by using the indicator card from the steam-engine to determine the power input, and by using a voltmeter and an ammeter for determining the electrical output. Even if the engine losses were exactly known, the measurements yielded by an indicator card are hardly exact enough to afford a fair basis for testing the efficiency of a generator. In other than direct-connected units it is not frequent that one finds a generator driven by an engine that does no other work.

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