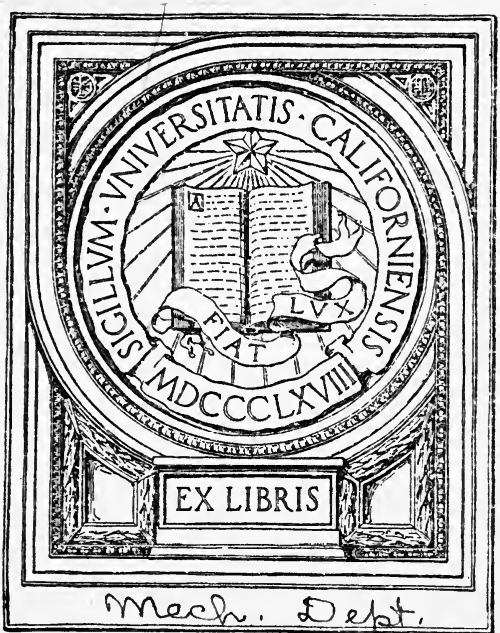
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THE MOTOR AND THE DYNAMO.

THE MOTOR AND THE DYNAMO

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PREFACE.

This book is the result of many year's experience in presenting the essentials of electrical science both to college students and practical electricians. It embodies the substance of laboratory conferences and class room explanations. In every instance these are based on modern types of machines, to the exclusion of antiquated models. An unusually large number of illustrations are inserted for the purpose of dispensing with lengthy descriptions; and thanks are due to various manufacturing companies whose bulletins have furnished numerous half-tones for these pages.

The author hopes that the book may be found practical and direct and sufficiently exhaustive by both college men and electricians.

J. L. ARNOLD.

NEW YORK UNIVERSITY,
November, 1912.

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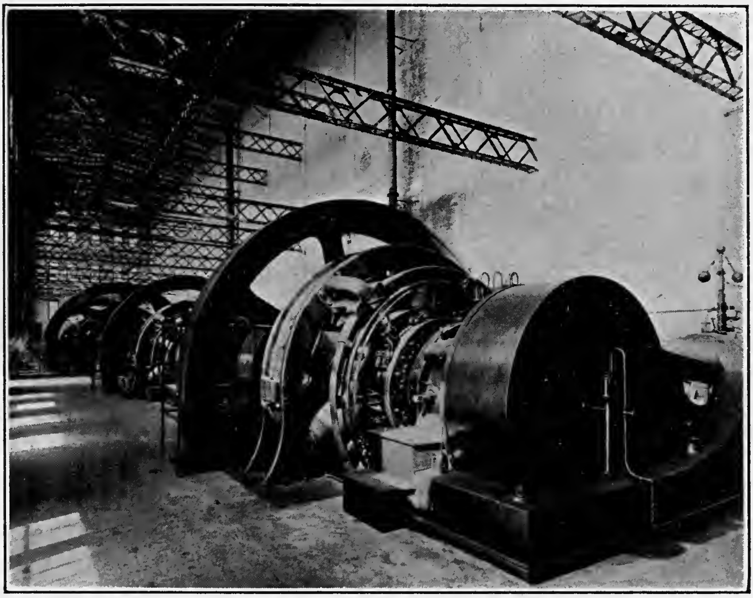


Fig. 1.—View in 146th Street Power House, New York City.

THE MOTOR AND THE DYNAMO.

CHAPTER I.

INTRODUCTION.

In 1820 Oersted discovered that a magnetic needle is affected by the presence of an electric current.—That is, the electric current produces a magnetic field. In 1831 Faraday discovered the induced current.—That is, when a wire is so moved in a magnetic field as to cross the direction of the influence of that field, an electro-motive force is induced in the wire so long as it is in motion. On these two principles depends the action of the modern dynamo, or generator. And if we add to these Ampere's researches into the motion produced by a magnetic field on a current-bearing wire, we shall have the underlying principle of the modern electric motor.

An apparatus for illustrating these effects is shown in Fig. 2.

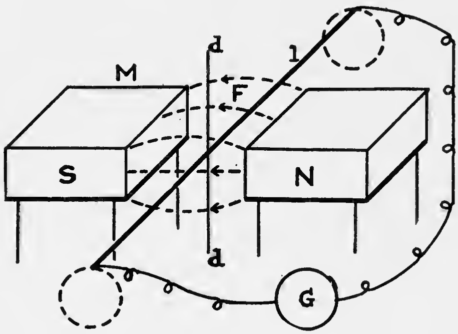


Fig. 2.

M is an electro-magnet, excited from some outside source. The magnetic field F is indicated in the conventional way by lines representing the so-called lines of force, whose direction coincides with the directive influence of the field, and whose number at any point is proportional to the field strength. The direction of the lines of force outside the magnet is considered to be from the north pole to the south pole of the magnet.

If now the wire *l* be moved vertically downward with a quick motion in direction *d d*, there will be a deflection of the galvanometer G, which will begin to oscillate toward rest about its original position the instant that the wire stops moving. The more rapid the motion or the more powerful the magnet, the greater in a general way will be the deflection of the galvanometer. An upward motion of the wire (toward *d*) will cause a deflection to the opposite side, showing that the current in *l* is now in the reverse direction. If the wire *l* be moved continually down and up, or if it be given a rotatory motion so that its ends trace the dotted circles, which amounts to the same thing, there will be induced in the wire an alternating current.

The wire *l* corresponds to one element of the winding of a drum-type armature—the usual form in direct-current machines. The electro-magnet corresponds to the field magnet of the dynamo. The only thing required to cause the current through the galvanometer to be always in the same direction is the interposition of a pole-changer, known as the commutator.

Ampère's rule for the direction of the induced current may be most easily expressed by Fig. 3, which represents the right hand with the index finger, thumb, and middle finger held at right

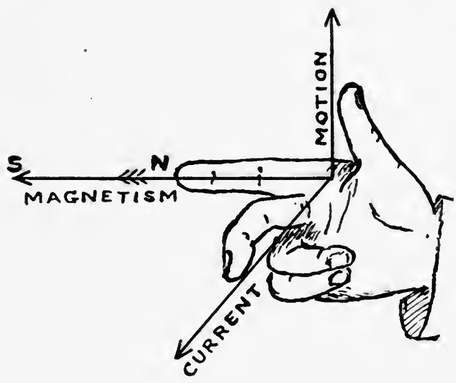


Fig. 3.—Ampere's rule for induced current.

angles to one another. It will be seen at once that a reversal of any one of these factors necessitates a reversal of one other.

Conversely, if the wires be disconnected from the galvanometer in Fig. 3 and attached to a source of current, a force will act between the current in wire *l* and the magnetic field in a direction perpendicular to both, that is, parallel to *d d*. The wire *l* will therefore tend to move upward or downward according to the direction of the current. From this it is evident that by continually reversing the current sent into *l* from some outside source, this wire *l* may be made to oscillate up and down across the magnetic field. If it be fastened to the surface of a cylinder whose ends are represented by the dotted circles, the cylinder may be made to rotate about its central axis by changing the direction of the current in *l* at every half revolution. For this purpose a pole changer or commutator is used. The apparatus then represents the elemental direct-current motor.

Ampère's rule for the direction of the motion of *l* in respect to the field, etc., is the same as in the preceding case, that of the induced current, except that the fingers of the left hand are used instead of the right.

From Ampère's rules it can be seen that in every case, the current induced in a wire by moving it in any given direction in a magnetic field is such that the force exerted between this current and the field tends to push the wire in the reverse direction. If we consider the resistance of the wire to be zero, then the force required to move the wire through the field is equal and opposite to the force with which the induced current in the wire opposes this motion. The converse is also true. This principle follows directly from the doctrine of the conservation of energy and is one application of what is known as Lenz's law.

In order to study quantitatively the phenomena thus far mentioned and to deduce the fundamental formulae of the dynamo and the motor, a few mathematical considerations are required. The next chapter must be devoted to this purpose.

CHAPTER II.

MATHEMATICAL PRINCIPLES.

(a) Definitions.

The space surrounding a magnet in which its influence is felt is known as a magnetic field.

The field is usually considered as made up of lines of magnetic force whose direction at each point is that in which the magnetic influence tends to act.

A unit magnet pole is one of such strength that it will repel a like pole placed at a distance of one centimeter from it in air with the force of one dyne.[1]

The intensity of a magnetic field at a given point is equal numerically to the force in dynes with which the field acts on unit pole placed at that point. The unit of field intensity is termed the gauss. Field intensity in air is denoted by the letter H, in other materials by the letter B. The force with which a field in air acts on a pole of strength m is expressed by the formula $F = mH$. The relative ease with which lines of force traverse various materials such as iron, nickel, etc., air being the standard, is denoted by the greek letter μ, and is called the permeability of the substance in question, so that

$$B = H\mu. \qquad \text{For air then, } \mu = 1.$$

A field of unit intensity, or of one gauss, is considered as having one line of force per square centimeter of sectional area.

Lines of magnetic force are called maxwells, and the number of maxwells in a field is known as the magnetic flux, and is denoted by the symbol Φ. The number of maxwells per unit area (of one square centimeter) is the flux density (ϕ) and is equal numerically to the intensity of field H or B. Hence $\Phi = \phi \times$ area of cross-section of field in square centimeters.

By Coulomb's law the force in dynes between two magnet poles in air is equal to the product of the number of units in each pole

[1] The dyne is such a force as will give to a gram mass an acceleration of one centimeter per second. It is the so-called absolute unit of force. The acceleration due to the force of gravity is 980 times as great.

(that is the product of the pole-strengths) divided by the square of the distance between them, and so for all materials,

$$F = \frac{mm'}{r^2\mu}.$$

It follows from the preceding definitions that a unit magnet pole must create at the distance of one centimeter from it on all sides a field of unit strength, or one having one maxwell per square centimeter area. Since the area of a sphere of one centimeter radius is 4π square centimeters, unit magnet pole must have 4π lines of force proceeding from it. The total magnetic flux Φ from a pole of strength m then equals $4\pi m$.

Unit electric current may be defined as follows: When unit current flows in one centimeter of wire in unit magnetic field, perpendicular to the lines of force, the force between wire and field and perpendicular to both is one dyne. [The mental picture may be formed by a reference to Fig 3.] Hence current strength (denoted by i) is force per unit length of wire per unit field intensity, or

$$i = \frac{F}{lH} \quad \text{and} \quad F = ilH.$$

This is the absolute unit of current. The practical unit, the ampere, is $^1/_{10}$ as large as this, so that current strength in practical units is

$$I = \frac{10F}{lH}.$$

The absolute unit of electro-motive force is the e. m. f. induced in a conductor when it cuts a magnetic field at the rate of one line of force per second. Being a rate of cutting the flux, it may be expressed thus

$$e = \frac{\Phi}{t} \quad \text{or better} \quad e = -\frac{d\Phi}{dt},$$

where $d\Phi$ = a small portion of the flux cut and dt = corresponding small portion of time. The negative sign signifies that the e. m. f. sends a current through the conductor in such a direction as to demagnetize the field.

This unit is extremely small, it taking 10^8 or 100,000,000 of them to make one volt. Hence

$$E \text{ volts} = \frac{\Phi}{10^8 t}.$$

(b) The Induced Current.

To find the e. m. f. induced in a straight wire moving sidewise across a uniform magnetic field in a direction perpendicular to the lines of force. Let the dots in Fig. 4 represent lines of force passing vertically through the page.

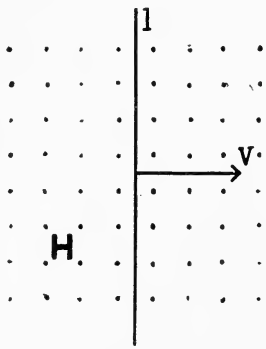


Fig. 4.

Consider the wire of length l centimeters to be moved with velocity v centimeters per second in the direction of the arrow. In field of strength H $(= \phi)$ lines per square centimeter the whole wire in time t will move vt centimeters and describe an area lvt and cut $Hlvt$ lines of force $= \phi lvt = \Phi$. The rate of cutting would be $\frac{Hlvt}{t} = \frac{\Phi}{t} = e$ absolute units of e. m. f., also $e = Hlv$.

Now if there be a current i caused to flow in this wire by the induced e. m. f., a force F, will act in a direction opposite to the arrow, tending to prevent the motion of the wire. The rate of overcoming this force will be Fv ergs[1] per second.

[1] An erg is the absolute unit of work, being the work accomplished by a dyne acting through the distance of one centimeter.

But ei also expresses this rate of working, current multiplied by e. m. f. being power. Hence

$$Fv = ei = liHv, \quad \text{whence} \quad F = ilH$$

as before. Now lH is the flux cut in each centimeter of the motion, and if we let d be the number of centimeters moved over, the total flux cut will be $lHd = \Phi$ and $Fd = i\Phi$.

But force times distance is work; hence the work of moving the wire so as to induce in it a current i is $i\Phi$ ergs. Conversely, the work done by a flux Φ in causing a wire, bearing current i, to move so as to cut all the lines of Φ is $i\Phi$ ergs. This follows from Lenz's law, the directions of motion in the two cases being opposite.

In practical units, ei ergs per second becomes $10i\dfrac{e}{10^8}$ volt amperes or watts. Since one watt is 10^7 ergs per second, the number of units of this denomination in any given power must be multiplied by 10^7 to equal the number of absolute units expressing the same power.

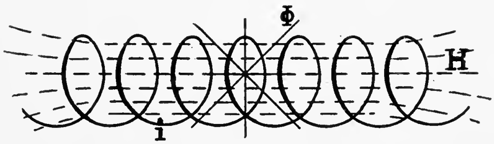
The preceding discussion is again one aspect of Lenz's law. The work of maintaining an induced current, except for the electrical resistance of the conductor, consists in overcoming the opposing force which the induced current itself sets up in conjunction with the field. From this it is at once evident where the power of the engine goes which drives the dynamo of a central station. The converse of this proposition will be found on a later page in the more detailed discussion of the motor.

(c) **Induced Magnetic Flux.**

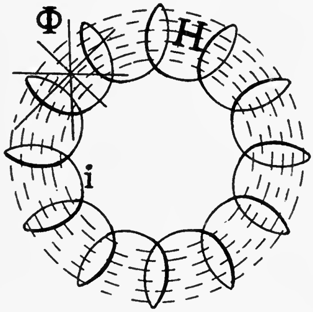
It remains for the present chapter to investigate the formation of the magnetic flux by the field coils of the dynamo machine.

Consider the magnetic field inside a long solenoid, or better, in order to avoid the problem of the ends, consider the field within a toroid.

Suppose the field to be uniform, and let the number of turns of wire be denoted by N. If unit pole be carried once around the circular axis of the toroid, its 4π lines of magnetic force will cut N turns, inducing in them a current i. We have seen that the work done, when a conductor carrying a current i cuts Φ lines of force, is $i\Phi$ ergs. Hence, considering the electrical resistance of the wire to be zero, the total work done in carrying unit pole once around the circuit will be $4\pi Ni$ ergs. According to Lenz's law, this work is done against the opposing force of the



Solenoid.



Toroid.

Fig. 5.

strength of field within the toroid, due to current i, namely H. But H is also the force in dynes between unit pole and field H. Hence, if l centimeters is the length of the circular axis, the total work = force × distance = $Hl = 4\pi Ni$ ergs.

This must be the work done by current i in the coil of N turns to maintain a strength of field H, and is known as the magnetomotive force, M.M.F.

After the analogy of Ohm's law for the electric current, we have for the magnetic circuit the formula

$$\text{Flux} = \Phi = \frac{\text{M.M.F.}}{\text{reluctance}}.$$

If s be the area of the field, in the present case the area of a loop of a toroid, then $\Phi = Hs$ for air and $\Phi = Hs\mu$ for other substances whose permeability μ is different from unity. Hence we may write

$$Hl s\mu = 4\pi N i s\mu$$

or $$\Phi = \frac{4\pi N i}{\frac{l}{s\mu}}$$ or if I = amperes, $$\Phi = \frac{4\pi N I}{10\frac{l}{\mu s}}.$$

The reason for putting the formula in this form is that the numerator is M.M.F. and the denominator $\frac{l}{s\mu}$ is the reluctance of the magnetic circuit. This reluctance, like electrical resistance, varies directly as the length (l), inversely as the cross section (s), and inversely as the permeability (μ), which last is in a way similar to the conductivity of an electric conductive material.

Knowing these last mentioned quantities of a magnetic circuit, as for instance of a dynamo machine, it is possible to compute the number of ampere turns (NI) required to produce a given flux (Φ).

(d) Magnetization Curves.

Suppose a piece of iron, such as the ring of the toroid already

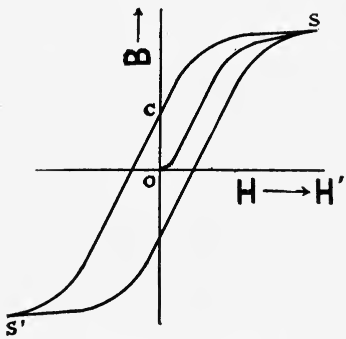


Fig. 6.—B and H curve.—Hysteresis.

used, to be initially unmagnetized, and imagine a constantly increasing magnetizing force to be applied to it, such as the current in the winding. If the varying values of H represent the intensity of field that would be produced in air by this increasing M.M.F. and B represent at each instant the field intensity produced in the iron core, then a curve plotted between H and B would have the form O*s* of Fig. 6.

Since $B = \mu H$, and the curve is not a straight line, the permeability of the iron, μ, must be a varying quantity. Unlike its electric opposite, resistivity, or specific resistance, it changes with the flux-density of the iron. At the point *s*, when H has the value H′, the increment of H is no greater than the increment of B, that is, the iron has no longer any multiplying effect on the flux and has reached its saturation point.

If now the magnetizing current be gradually decreased to zero, reversed and increased again in the reverse direction, the B and H curve will return from *s* along line *scs′*. If the current be again decreased, reversed and increased to its maximum value the curve *s′c′s* will result. The open space between these curves represents the difference between the work done in producing a flux in the iron and the returned energy furnished by the dying out of part of this flux. In order to demagnetize the iron completely, the current must be reversed, producing a value of H equal to the distance from *o* to where the curve cuts the H axis. This is known as the coercive force and results from the retentivity for magnetism possessed more or less by all forms of iron at ordinary temperatures, but in the largest degree by hard steel. In the complete cycle represented, a portion of the M.M.F. goes to overcoming this retentivity; and in a succession of reversals, as in the case of an alternating current, the loss of energy results in heating the iron. Its value in ergs is represented by the area enclosed by the curve and is known as hysteresis.

The empirical hysteresis formula of Steinmetz for various sorts of iron is $w = yB^{1.6}$, where w is the loss in ergs per unit volume of iron per magnetic cycle, B is the maximum value obtained by induction during the cycle, and y is a constant depending on the quality of iron used.

(e) The Flow of Current.

Ohm's law states that current strength is proportional directly to the e. m. f. and inversely to the resistance. In practical units this is

$$\text{Amperes} = \frac{\text{volts}}{\text{ohms}}.$$

Whenever current flows through a conductor overcoming the resistance, it is at the expense of pressure, or there is always present an IR drop. This is a fundamental law of all electrical circuits. Without this IR drop in voltage no current can flow.

Since IR = E and IE = power, substituting, I^2R = the power lost when a current I flows through resistance R by virtue of pressure E. If the denominations are amperes and ohms, then I^2R = watts. These lost or consumed watts go to heating the conductor, and the number of calories of heat developed is 0.24 I^2R_t, where t is the time in seconds.

The resistance of a conductor varies directly with the length and inversely as the cross-section. It also varies with the material and with temperature. The specific resistance of a conducting material is the resistance per mil foot. A mil foot is a wire one foot long and a circular mil in cross-section. A circular mil is the area of a circle $^1/_{1000}$ inch in diameter. The specific resistance for hard drawn copper wire at 0° C. is 9.7 ohms.

As to temperature the formula states that

$$R_{t^\circ} = R_{0^\circ}(1 + at),$$

where a is known as the temperature coefficient. For copper $a = 0.0042$; for manganin, an alloy of manganese, a = almost 0. For carbon a = minus 0.0004 (about). At 20° C., therefore, the resistance in ohms of a copper wire is

$$R = 10.5 \times \frac{\text{feet}}{\text{circ. mils}}.$$

CHAPTER III.

THE DYANMO MACHINE.

This chapter is devoted to a general description of the direct-

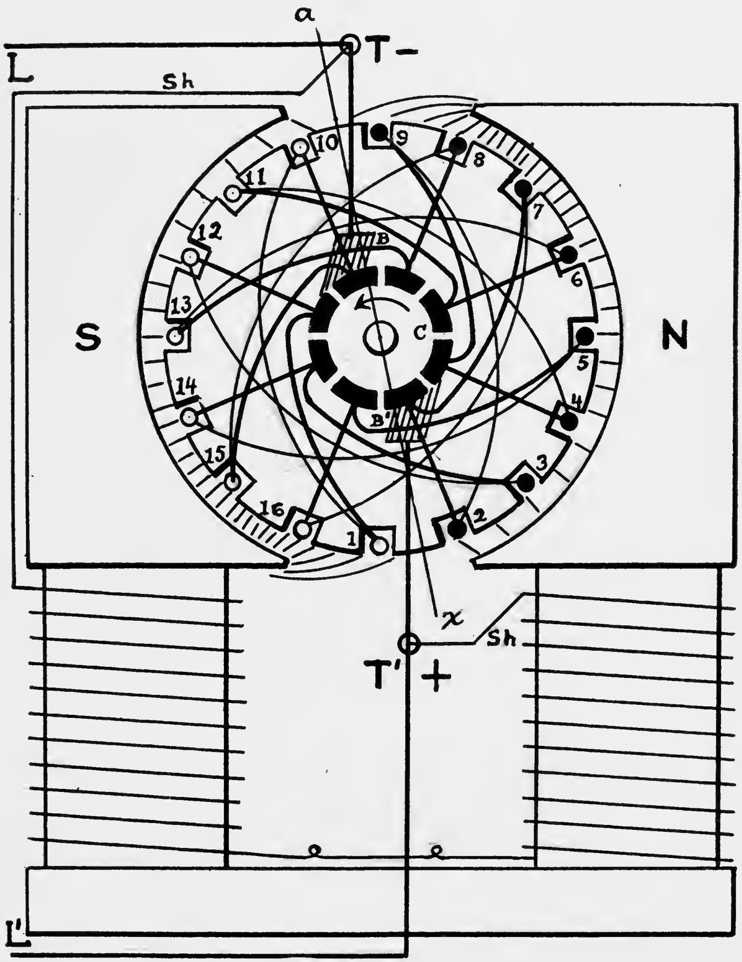


Fig. 7.—The D. C. generator.

current dynamo machine and to a detailed explanation of its various organs, their functions, and the materials used in their construction.

Fig. 7 represents the general arrangement of the parts of the most common type of machine. It is a two-pole shunt-wound dynamo, and may be used either as motor or generator indifferently. We will consider it as a generator.

By the term shunt-wound is signified the method of exciting the field coils, the current for them being tapped from the machine terminals T T′ by a circuit which forms a shunt, or by-path *sh;* to the main line-circuit L L′. The armature of this machine is drum-wound, its wires, or inductors, being on the surface of a rotating iron cylinder which forms the armature-core. These wires are carried in sixteen slots on the lateral surface of the core and form by themselves a closed circuit. They are connected at regular intervals to the eight bars of the commutator C. The current is taken off from the commutator by the brushes BB′.

By applying Ampère's rule for direction, it will be seen that in those inductors whose section is represented thus ●, the current is flowing toward the observer; and in those represented thus o, it is flowing from the observer.

Though the diagram shows only one inductor to a slot, it is to be understood that there are usually several wires in each slot, the windings of two connected slots, as 15 and 8 or 4 and 11, being repeated a definite number of times before proceeding to the next, such a group constituting an armature-coil or winding-element.

Starting with the commutator bars touching the upper brush and attached to inductor (or winding-element) No. 10 or 1 it will be seen that we may proceed by two paths and finally arrive at a bar which touches the opposite brush, namely, by numbers 12, 3, 14, 5, 16, 7, also 2 and 9, or by numbers 15, 8, 13, 6, 11, 4, also 9 and 2.

Proceeding thus from the negative to the positive brush, the e. m. f. generated in each inductor or winding-element is added to that generated in the next one connected with it, so that the effect is the same as that of two series chains of voltaic cells, the two chains being in parallel from brush to brush.

Although in any one inductor or winding-element the current is an alternating one, changing direction twice in each revolution of this bi-polar machine, yet the inductors to the left of the axis of commutation *ax* always generate an e. m. f. in one direction and those to the right of *ax* in the other direction. The rotating armature is thus a sort of double electric pump, in which the two cylinders work in unison converting mechanical energy into electrical energy. In a machine of 100 per cent. efficiency this conversion of energy would be perfect according to Lenz's law.

The elementary alternating-current dynamo does not differ from the machine just described except in two particulars. First, the commutator is replaced by two insulated rings connected each to diametrically opposite armature inductors, as 8 and 16, or 4 and 12, etc., all other inductors being connected as in the diagram, but not directly to the rings. The other difference is that the field is excited by a different current, either from some outside source or by aid of a special commutator for the field current alone. Alternating-current machinery is treated in later chapters.

We are now in a position to write the general formula for the e. m. f. generator in a direct-current dynamo in accordance with principles laid down in Chapter II. Let

Φ = the total flux passing from any one pole to the neighboring part of the armature core, or vice versa.

p = the number of poles.

N = the total number of inductors on the lateral surface of the armature, that is, in the slots.

p' = the number of parallel paths through the armature windings from the — to the + terminal of the machine.

n = the revolutions per second.

Then the generated e. m. f. in volts $= E_{\text{gen.}} = \dfrac{\Phi p N n}{10^8 p'}$, because the total flux cut by the armature windings is Φp, and the flux cut each second by one wire on the lateral surface of the armature is $\Phi p n$. The number of such wires in series is $\frac{N}{p'}$.

Now this amount of e. m. f. is generated whether the machine be turned by some outside agent, such as a steam engine, or whether it rotate as a motor through the agency of current fed into its armature, because of the field flux. In the latter case, in order to feed this current into the armature, therefore, a slightly higher e. m. f. is required than that generated, and in the reverse direction, sufficient indeed to overcome the resistance of the armature windings, brushes, brush contacts, etc., which we may denote as R_a. This additional e. m. f. may be designated $I_a R_a$, where I_a is the armature current. In this instance, namely that of the motor, the generated e. m. f. is termed a counter electro-motive force, being opposed in direction to the e. m. f. of the line which supplies the driving power.

Similarly the e. m. f. at the terminals of a dynamo never is as high as the generated e. m. f., when the dynamo is furnishing current, because a part of this generated e. m. f. is used up in forcing such load-current through the resistance of the armature, etc., R_a.

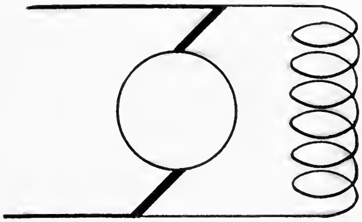
Thus the formulae for the shunt dynamo furnishing current and for the motor are as follows: For the former the terminal voltage $E_t = E_g - I_a R_a$ or

$$E_t = \frac{\Phi p N n}{10^8 p'} - I_a R_a,$$

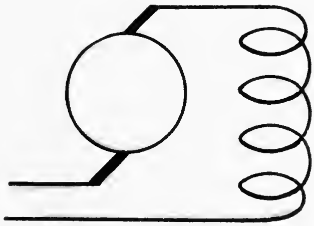
and for the shunt motor the line voltage $E_l = E_g + I_a R_a$ or

$$E_l = \frac{\Phi p N n}{10^8 p'} + I_a R_a.$$

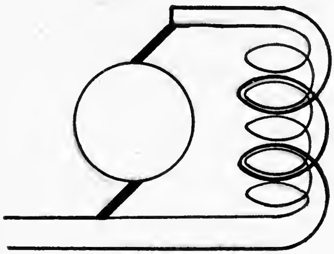
In order to make the formulae general for all direct current machines, it becomes necessary to notice here the two other ways used to excite the field. Instead of letting the field circuit form a shunt or by-path, the full armature current may be directed through the field windings, forming a series machine, or a combination of these two methods may be used, as in the compound machine. In the last case the shunt winding of the field is augmented by a few turns in series with the main circuit. Fig. 8 represents the three usual methods of field excitation.



Shunt.



Series.



Compound.

Fig. 8.

Letting R_s represent the resistance of the series field windings, the preceding formulae appear as follows for both series and compound machines.

For the dynamo $E_t = E_g - I_a R_a - I_a R_s$.

For the motor $E_t = E_g + I_a R_a + I_a R_s$.

The parts, or organs, of the direct-current dynamo to be treated of in detail are as follows: frame and field cores, armature cores, field windings, armature windings, commutator, brushes,

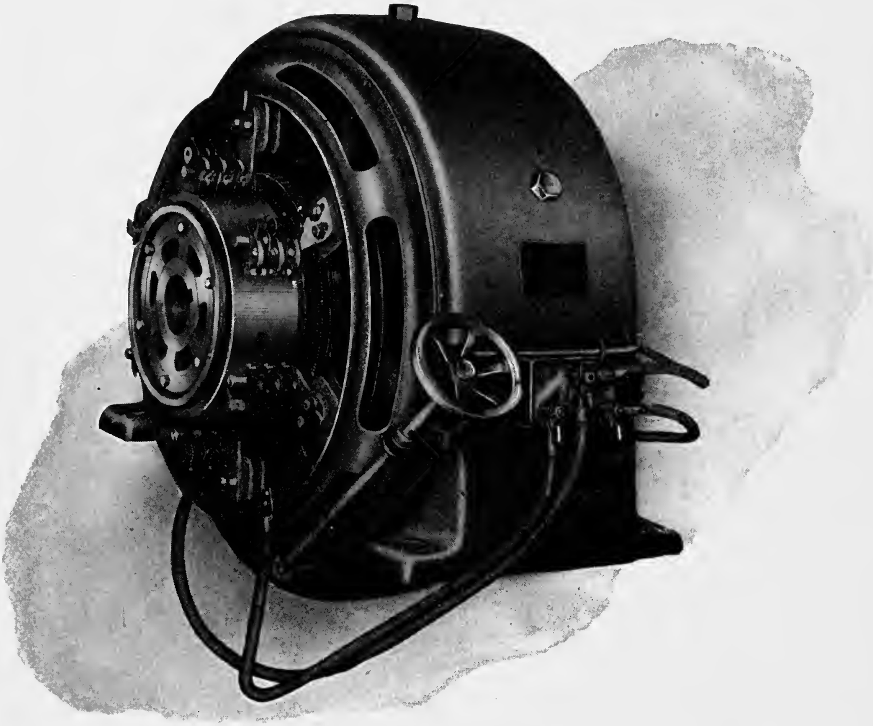


Fig. 9.—General Electric Co. 50-kilowatt generator.

brush holders, bearings, lubricating devices, insulating materials.

(a) Frame and Field Cores.

The various shapes of dynamo frames are shown in. Figs. 10, 11, 12 and 13. The bipolar type is seldom made larger than 5 kilowatts. The particular advantages of the multipolar type may be enumerated as follows:

1. The length of the magnetic circuit is shorter in the multipolar type, thus making the machine more compact and reducing the weight.

2. The lower reluctance of the multipolar machine reduces the ampere turns required for excitation, which results in a saving of copper.

3. The number of revolutions per minute is reduced by in-

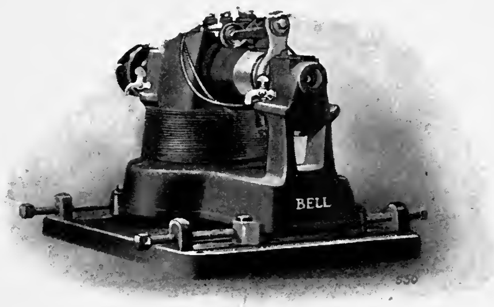


Fig. 10.—Bell Motor Co. Early model. Open form.

Fig. 11.—Crocker-Wheeler Co. Enclosed form, now used by many manufacturers.

creasing the number of poles, thus rendering the generator better adapted for direct coupling to a reciprocating engine. Furthermore with the same peripheral speed the larger armature renders the centrifugal force less. For instance, if the number of poles be made say four instead of two, the pole-face not being reduced in size, in order to have the same number of inductors under one pole, the armature will have to be doubled in circumference. But with the same peripheral speed, the revolutions per minute would be only half as great; and the centrifugal force, which is $\frac{mv^2}{r}$, would also be reduced to half. This ideal advantage, however, does not occur in practice, the gap between the poles being necessarily larger in a multipolar machine than in

Fig. 12.—Enclosed type. Four-pole frame.

a bipolar, in order to avoid magnetic leakage. In direct-current machines it is the custom to let the pole-faces span from 60 per cent. to 75 per cent. of the total armature circumference. The frame is usually cast in sections and bolted together. The pole cores are sometimes made of laminated iron, and in some machines they are capped by a projecting plate or "shoe."

The material of frame and cores is chosen with reference to its magnetic properties. The B and H curve mentioned in chapter II for various sorts of iron is shown in Fig. 14.

Cast iron, although the cheapest of the varieties mentioned, requires more ampere turns than any other to magnetize it to the proper flux-density. Hard steel is never employed for any

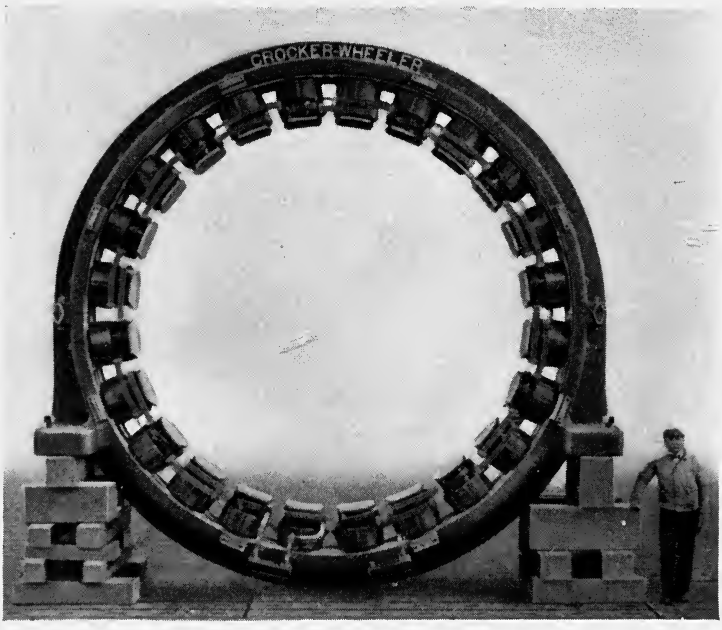


Fig. 13.—Complete field frame of 600 k.w. generator. G. E. Co.

but permanent magnets, such as are used in magnetos and electrical measuring instruments. Its hysteretic qualities render it especially valuable for such purposes. The best material for field cores is mild steel, and this is often employed for the frame as well. The base of the machine, however, and remote parts of the magnetic circuit are not infrequently made of cast iron.

(b) Field Windings.

The shunt field windings of a direct-current machine are designed to carry from about 2 per cent. to 8 per cent. of the full load current of the machine. The number of ampere turns required for field excitation can be determined from a formula of Chapter II, namely.

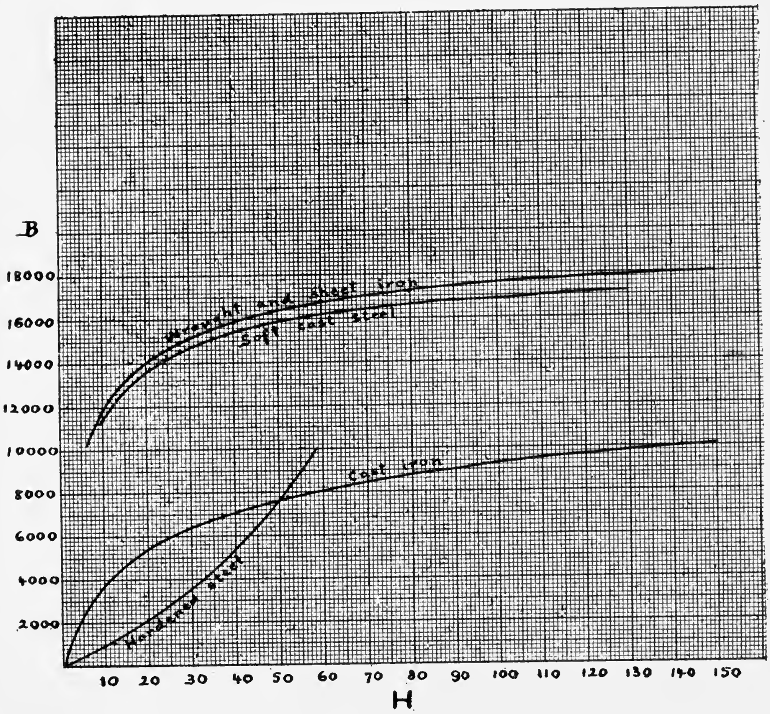


Fig. 14.

$$\Phi = \frac{4\pi NI}{10\dfrac{l}{\mu s}} \qquad \text{or} \qquad NI = \frac{10B\dfrac{l}{\mu}}{4\pi}.$$

The magnetic circuit is made up of various parts, each of which must be separately computed, owing to the different values of flux density commonly employed in each. For instance let the field cores be of soft cast steel and their dimensions be as follows: $l = 50$ centimeters, $s = 1{,}525$ square centimeters, $\Phi = 23{,}000{,}000$ maxwells. Hence B numerically $= \frac{\Phi}{s}$ is approximately 15,000 units. Consulting Fig. 14 it will be seen that for soft cast steel, when $B = 15{,}000$, $H = 35$ and hence $\mu = \frac{B}{H}$ $= 430$ (about). Thus NI becomes $\frac{10 \times 15{,}000 \times \frac{50}{430}}{4\pi} = 1430$ ampere turns.

For the other parts of the circuit such as the field-yoke or frame, the armature core and teeth, and the air-gap, for which the permeability is one, individual computations have to be made. The sum of the various ampere turns found is then the total number required, for each pair of poles. Dividing by 2 gives the ampere turns for one field coil of the series or the shunt machine. Magnetic leakage has not been considered in this calculation: see page 48.

The size of wire used and the dimensions of the coil depend on the allowable rise of temperature. The formula for heat developed by an electric current, given in chapter II, is H in calories $= 0.24\ I^2Rt$, where R is the resistance of the wire in ohms. The allowable temperature rise is 50° C. above the ordinary machine-room temperature of 25° C., or a maximum temperature of 75°. When this point is reached, the exposed surface of the coil should be sufficient to radiate in the cooling breeze furnished by the rotating armature all heat energy which would tend to elevate the temperature above 75°. Manufacturers have various empirical formulae for approximating the relative dimensions of the spool.

The winding of the field may be round copper wire or in the form of ribbon. The insulation is usually of cotton and occupies from 30 per cent. to 60 per cent. of the total cross section of the winding. The coils are usually held in shape by paper or cord, and the surface is covered with moisture-proof varnish. See Fig. 15.

(c) Armature Core.

The armature core is made of iron or steel, being a very considerable part of the magnetic circuit. Since the core cuts lines of magnetic force as well as the armature windings, in a solid core there would be nothing but the resistance of the iron to

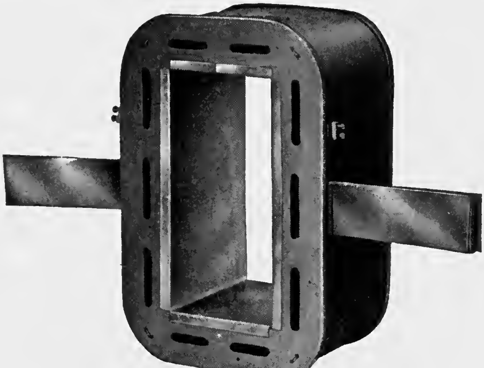


Fig. 15.—G. E. Co.—Field-coil of D.C. generator, 200 K.W. and above.

Fig. 16.—Edgewise field winding. Crocker-Wheeler Co.

prevent a heavy induced current from flowing longitudinally down one side of the core and back on the other side, wasting the energy of the machine and heating the iron. Such currents do in a measure occur and are known as eddy, or Foucault, currents. They are, however, to a large extent prevented by building up the core of sheet iron, the laminations being at right angles to the shaft. Their thickness in higher priced machines varies from 0.014 to 0.02 inch. For insulating electrically the laminations from one another some manufacturers use varnish, others simply depend on the oxidation of the iron surface. Because of the continual reversal of the magnetic flux through the rotating core, a sheet iron or steel with a low hysteretic constant *y* is desirable.

Two general shapes of armature core prevail in direct-current machines, the drum and the ring. In the original machines built and operated by Gramme at Vienna the ring armature was used. The disadvantage of this type is that wires on the outer sur-

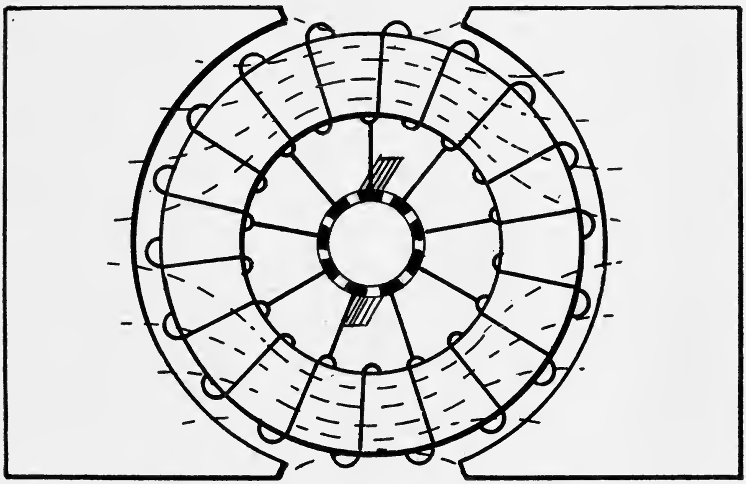


Fig. 17.—Gramme ring.

face only cut the field flux, the return wires through the ring serving merely as connectors. See Fig. 17. The advantage of this type of armature core is the superior ventilation and cooling.

In all but the smallest machines, armature cores are now cooled by radial ducts, and the drum-wound core is the prevailing form. The ring-shaped core is sometimes used wound as a drum, the laminated portion being supported on a star-shaped cast-iron frame secured to the shaft, but in small machines the laminations for the drum-winding set directly on the shaft. In the earlier machines the windings were secured to the core surface by wooden pins. The modern method is to insert the inductors into lateral grooves or slots on the core surface.

Fig. 18 shows a number of shapes of these armature laminae or punchings. The parts between the grooves are known as the armature teeth. As the machine rotates, the field flux sweeps across in tufts from tooth to tooth cutting through the inductors in the slots. The narrowest possible air space between armature

Fig. 18.

surface and field magnet face is therefore not always the most effective.

(d) Armature Windings.

The armature inductors must be of sufficient thickness to carry the full load current of the machine without undue heating. They are usually of circular cross section and cotton insulated, but on larger machines and particularly in alternating-current generators they are in the form of ribbon. They are usually wound on forms independently of the armature core, a number of turns of wire constituting a winding-element. These elements are then placed into position in the armature slots and properly secured and taped. The ends are finally connected to the commutator bars according to the design of the winding. The slots are sometimes lined with strips of paper or insulating fiber before the introduction of the wires, and in certain cases the inductors are held in position behind a strip of insulating material that fits in a groove in either tooth, thus covering the slot. See Fig 18. The even distribution of the windings within the slots is a matter of great importance, especially in high speed machines, as any inequality renders the armature poorly balanced and causes jarring. When all the slots are filled, the inductors are secured firmly against displacement from centrifugal force by means of circular bands of brass or even steel wire. Figs. 19, 20, 21, and 22 show various types of armatures.

Fig. 19.—Complete armature. Fort Wayne Electric Co.

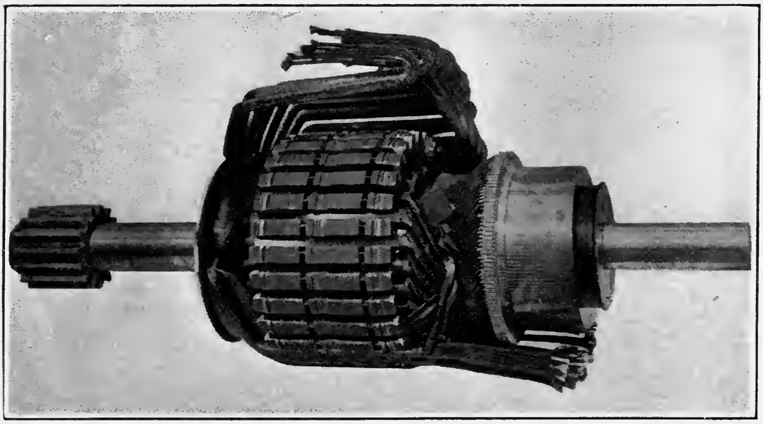


Fig. 20.—Armature in process of winding. G. E. Co.

The succession of inductors on the armature surface, that is, the methods of connecting the winding elements into a system, are various; but in the closed coil type two chief forms of armature winding prevail. They are the lap winding and the wave

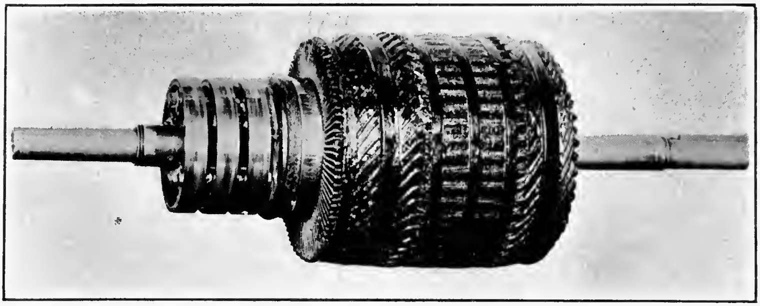


Fig. 21.—Complete A. C. armature. G. E. Co.

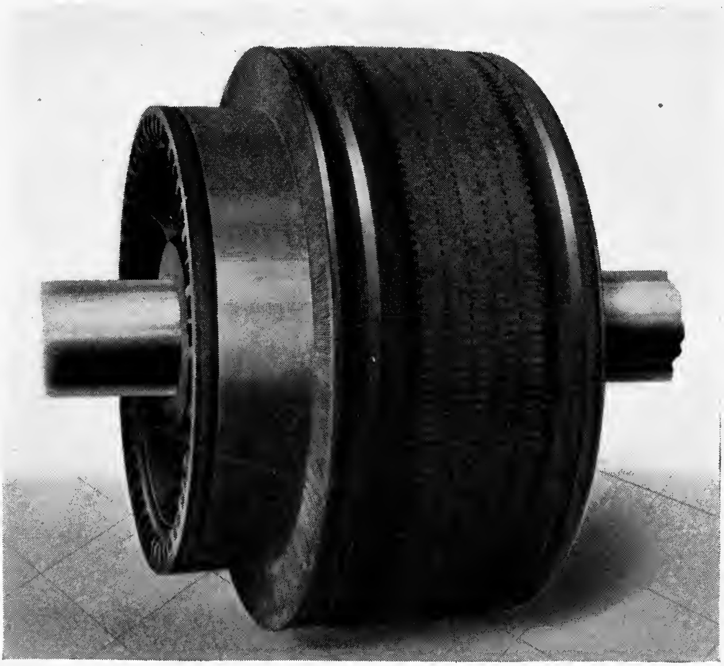


Fig. 22.—Low speed armature. 150 r.p.m. Crocker-Wheeler Co.

winding. The open circuit type, namely that in which the armature windings do not in themselves make a closed circuit, occurs only in arc-lighting generators, and must be treated later. The armature depicted in Fig. 7 is of the drum type. It will be observed that in proceeding around such an armature the alternate slots only are used, the intermediate ones being left free for the return wires of some other winding element. Thus 12 and 3 are followed, not by 13 and 4, but 14 and 5. The necessity for this arrangement becomes at once apparent from Fig. 23, which represents an attempt to wind an armature using successive slots. It will be observed that one must pass twice around the core to form a closed coil winding. This can be easily proven by trying it with a ball of string.

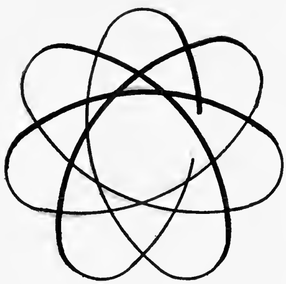
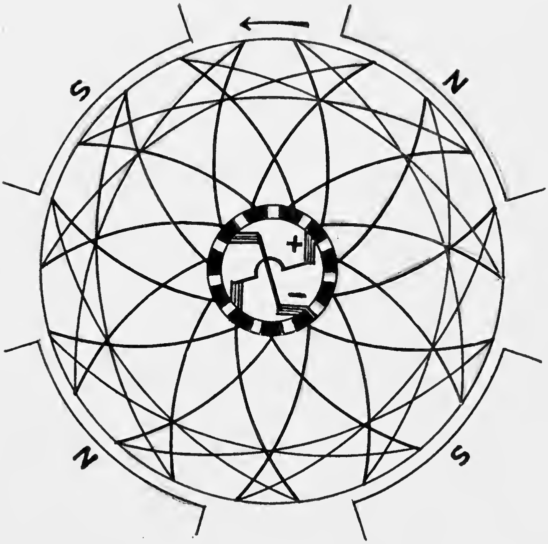


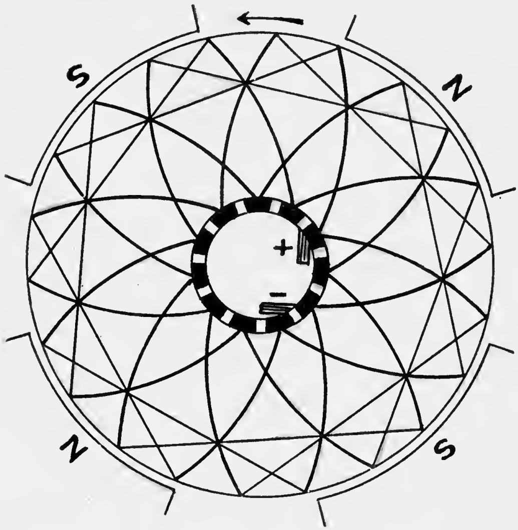
Fig. 23.

The drum armature is a development of the ring type, the return wires through the center of the ring being carried instead to the opposite side. In the ring wound armature, every inductor or every second or third, etc., inductor may be connected to a commentator bar, making the maximum number of bars equal to the number of inductors or groups of inductors. In the drum type, on the other hand, there can be only one bar for every two inductors or bundles.

The essential differences between the lap and the wave winding for armatures may be best appreciated by a study of Fig. 24. The brushes are diagramed on the inside of the commutator so as not to obscure the windings.



Lap wniding.



Wave winding.

Fig. 24.

General observations applicable to both windings:—

(a) There are half as many commutator bars as there are inductors (or bundles of conductors) on the armature surface.

(b) The space or "pitch" between two directly connected inductors or bundles, which thus form a winding-element, is approximately such that when the one is entering the flux from a north pole, the other is entering the flux from the south pole, etc. This causes oppositely directed e. m. f. to be induced in the two sides of the winding-element. It follows that the distance between two such inductors must be neither so small as the width of a field pole face nor so large as to reach much beyond corresponding points of two consecutive pole-faces. Otherwise, the e. m. f. induced in the two sides of a winding would be in the same direction.

(c) In the simplex winding the spacing or pitch must always be an odd number, otherwise all the slots will not be filled.

(d) It would be perfectly possible to have either half the number of slots in the armature surface, there being two winding-elements to a slot, or twice the number of slots, there being then half a winding-element in each slot.

(e) It would be possible to sandwich in between the slots and bars represented a second set of slots and bars equal in number and carrying a second and independent winding. This would be known as a *duplex winding* and the brushes would be wide enough to cover two commutator bars instead of one. In a similar way a *triplex winding* could be formed, the brushes then covering three consecutive commutator bars. By this means each winding would be made to carry only a half or a third of the entire current. Such types of winding as close upon themselves forming a single continuous circuit are said to be *singly re-entrant*. All simplex windings are so. A duplex winding such as described, on the other hand, would be doubly re-entrant. It could be made singly re-entrant by connecting the two distinct windings in series.

(f) The commutator's position on the shaft with reference to the windings is immaterial so long as the bars and slots are in proper sequence. That is, the wires extending from each commutator bar to the periphera of the armature may be of equal length, curving equally in either direction, or the one wire may extend radially out to the nearest slot, the other being longer and curving around to its proper slot. The appearance of the end of the armature and the position of the brushes with respect to the field poles will be different in the two cases.

(g) The winding may be either "right-hand" ("progressive") or "left-hand" ("retrogressive"), according as we proceed around the armature clockwise or counter-clockwise.

(h) The number of slots chosen (for example 22) is not exactly divisible by the number of poles (4), in order that there may be no synchronous vibration in e. m. f., as might be the case if at every instant each of the four groups of inductors had exactly the same position with reference to each of the four poles.

In reference to the lap-winding the following observations may be made:—

(a) The number of brushes is equal to the number of poles. It will be seen by a study of the diagram that this number is necessary in order that the same voltage may be developed in each armature path. In the special case of the figure, if we pass from a commutator bar in connection with a brush to a brush of the opposite polarity, either 4 or 6 inductors, that is, either 2 or 3 winding-elements, connected in series, are passed over.

(b) The number of paths in parallel is then equal to the number of poles or in simplex winding $p' = p$. The number of inductors in series is therefore approximately N/p.

(c) In the diagram the forward pitch, that on the commutator end of the armature, is 5, the backward pitch, that on the farther end, is 7. The average pitch is therefore 6. Taking two slots to a winding-element, as here, it will be readily seen that in the lap-winding, any even number of slots may be used. In a duplex or triplex winding, 2 times or 3 times such even number respectively may be used.

In reference to the wave-winding, the following corresponding observations may be made:—

(a) Only two brushes are necessary. In the figure, if we pass from a commutator bar in connection with one brush to the brush of opposite polarity, we must pass over 10 or 12 inductors, that is, 5 or 6 winding-elements, essentially double the number of the lap-winding. To be sure, four brushes could be used, connected as in the lap-winding. But since the opposite side of the commutator is already connected with each brush through an armature winding, the only advantage of the extra brushes would be to divide the current passing through each brush, which would have a tendency to reduce sparking.

(b) The number of paths in parallel through the armature is only 2 in a simplex winding, or $p' = 2$. The number of inductors in series is therefore N/2.

(c) In the diagram, the pitch is 5, the forward and backward pitches being alike, although this is not always necessarily the case. Taking two slots to a winding-element, it will be evident that the number of slots must not be evenly divisible by the number of poles, otherwise the winding would close in proceeding only once around the armature. It must, on the contrary, lap over one commutator bar or fall short by one as here, thus adding or subtracting two slots from an evenly divisible number. Hence the number of slots = pitch $\times$ number of poles $\pm$ 2. In a duplex or triplex winding 2 or 3 times this number would be used.

A comparison of the two forms of winding makes it evident that in anything above a two-pole machine, the e. m. f. will be higher with the wave-winding, other conditions such as flux, r. p. m., etc., being the same. In a four-pole machine the e. m. f. would be essentially twice as much with a wave-wound as with a lap-wound armature. For this reason the wave-winding was formerly called series winding and the lap-winding was called parallel winding. Traction motors are usually wave-wound. Fig. 25 shows another form of diagram. It corresponds to the wave-winding of Fig. 24.

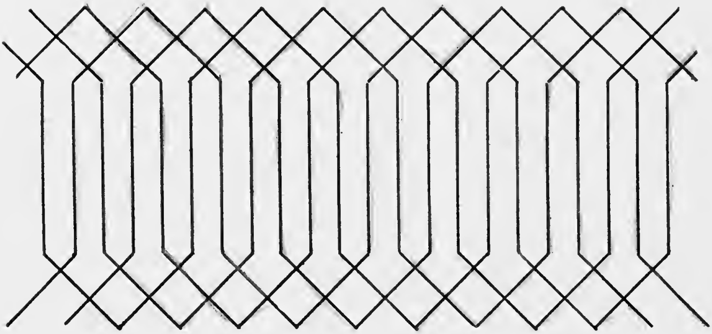


Fig. 25.—Straight diagram of armature winding.

(e) The Cummutator.

The commutator consists of wedge-shaped bars of copper insulated from the shaft. These bars are held in place by a retaining ring from which they are also insulated.

Fig. 26.—Commutator. Electro Dynamic Co.

Hot forged copper is sometimes used, but cold rolled bars are preferable, because for one reason, they can be shaped more accurately.

The insulating material between the bars is mica, the amber mica being preferred. The thickness varies from 0.02 to 0.06 inch. A material known as miconite, consisting of powdered mica, formed into sheets under high pressure, is much employed.

Accuracy in the thickness of the insulation is thus more easily secured than with mica in the natural state.

When the bars and insulators have been assembled, they are forced tightly together either by a ring and clamping screws or by means of hydraulic pressure. The retaining-rings are then put in place.

The armature windings are usually attached to the commutator bars by soldering the ends into grooves. Although there are

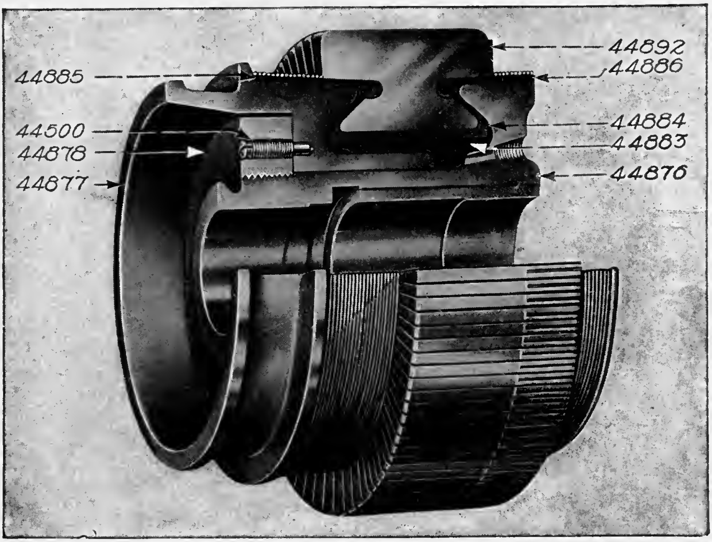


Fig. 27.—Structure of a commutator. G. E. Co.

objections to this method, owing to the high temperatures reached sometimes by commutators, yet it is more sure than the employment of clamps or screws, which are likely to work loose.

The size of the commutator, number of bars, etc., depend directly upon the style of armature winding employed. In a general way, however, it may be remarked that high speed machines usually have armatures of comparatively small diameter, high voltage machines may usually be detected by the comparative narrowness of the commutator bars and their large number, and machines for supplying large current, such as electro-plating dynamos, usually have rather long commutators, to permit several brushes to be placed abreast.

(f) The Brushes.

In some of the earliest types of dynamos, steel brushes in the form of solid bars were employed, because of the low friction. Later, brushes made of strip-copper were used and still later of copper gauze folded into several thicknesses. These are now employed only on low voltage machines furnishing large current, such as plating dynamos. The lower resistance of the copper renders it better fitted for such generators than carbon.

On the ordinary direct-current dynamos and motors, however, graphitic carbon pressed and shaped into block form is the type of brush universally employed. The chief advantage of this material is that its high resistance aids to prevent sparking (see p. 58). Besides this it keeps the commutator fairly clean, does not wear out the copper very rapidly, and is sufficiently soft to be readily shaped to the curved commutator surface. These brushes are usually copper-plated where they make contact with the brush-holders.

Carbon brushes are sometimes set radially to the commutator, but usually at a slight angle, even in machines designed to operate in either direction. It makes little difference whether a machine operate with or against carbon brushes.

The area of brush-contact depends upon the current to be carried and determines the size of brush to be employed. The approximate current density per square inch of contact area is from 50 amperes in 110 volt machines to 30 amperes in 550 volt machines. In cases where these figures would call for a very wide brush, several are placed abreast, thus insuring better contact and more even wearing of the commutator.

(g) Brush Holders.

Types of brush-holders are represented in Figs. 28, 29 and 30. The springs are adjustable so as to maintain the proper pressure of the brushes against the commutator. A slight variation of the pressure being often sufficient to correct the defect of sparking. It

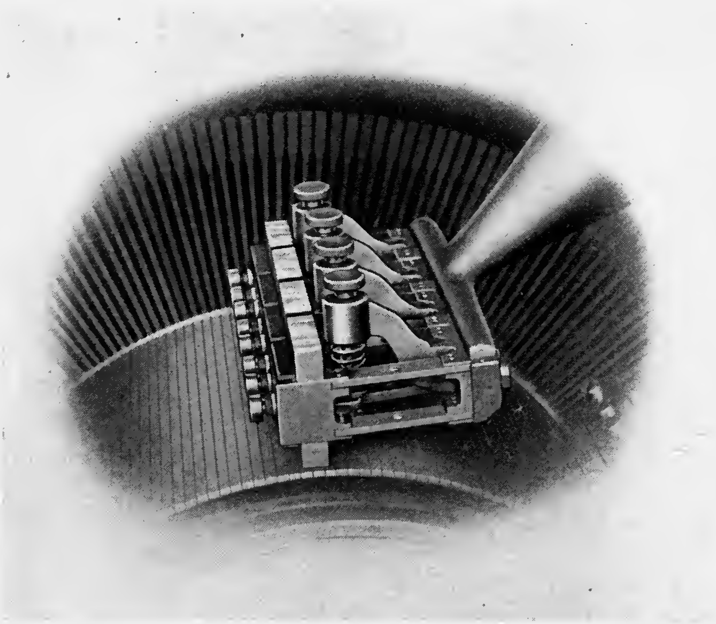


Fig. 28.—Brush and holder. Crocker-Wheeler Co.

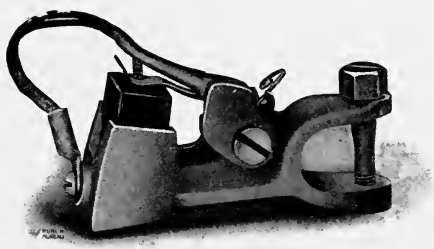


Fig. 29.—Brush and holder. G. E. Co.

will be observed that a flexible conductor carries the current from the brush so that it shall not pass through the spring, which might otherwise become heated and lose its elastic properties.

The brush-holders are connected to a rocker, enabling the brushes to be shifted in position around the commutator. The rocker consists of a lever or a collar, which bears both positive and negative brushes, and may be rotated through a few degrees

Fig. 30.—G. E. Co.

around the axis of the commutator. In small machines it is operated by a handle, in larger ones by a wheel and gearing. When in the proper position, it may be clamped. In interpolar variable speed motors, when the rocker has been adjusted in the factory, it is fixed in position by pins.

(h) The Bearings.

Fig. 31 shows an approved type of bearing, consisting of a

Fig. 31.—Bearing housing open, showing bearings, oil wells, and oil rings. Westinghouse Co.

brass or bronze collar set in Babbitt metal in the iron support.

The figure also shows the oil-rings used for lubricating. They rest upon the shaft, and the oil is contained in wells through which they rotate.

Recently ball-bearings have been employed in small machines with great success. They require little attention and the lubricant is applied only when they are first set up or cleaned.

CHAPTER IV.

OPERATION AND CHARACTERISTICS OF THE D. C. DYNAMO.

(a) Preliminary Tests.

Before starting a dynamo or motor which has not been recently operated, it is desirable to make an inspection embracing the following points.

(1) Does the armature turn easily with perfect clearance?

(2) Is the commutator clean? If not, clean it with fine sandpaper. Do not use emery paper, as this is likely to leave conducting material bridging across the insulation between the bars.

(3) In case the commutator surface is much worn by the brushes, these cannot be fitted properly to the surface; and the machine will have a tendency to spark when loaded. In this event, remove one of the bearings, take out the armature, and have the commutator turned down in a lathe. Great care must be taken not to injure the inductors on the armature surface. When replacing the armature, the oil rings will have to be lifted into position.

(4) The commutator surface being even and clean, ascertain whether the contact surface of every brush is smooth and fits the commutator perfectly. If not, lift the brush, insert a strip of sandpaper beneath it with the cutting side against the brush, and draw the paper back and forth. In this way the brush may be made to conform perfectly to the shape of the commutator.

(5) Ascertain that the brushes are set by the rocker approximately in their neutral position. If the armature windings are visible, the neutral commutator bars can be ascertained as those immediately connected to inductors that are midway between two pole-faces. In case the armature is covered, the neutral position can often be approximately determined as the middle of the space allowed for play of the rocker.

(6) See that a moderate and yet sufficient pressure is exerted

by the springs upon the brushes. A little experience will enable an operator to judge of this quite accurately.

(7) Is there sufficient oil in the bearings or oil-cups?

(8) Do all electrical connections within the machine appear to be correct? Whether or not they are correct cannot always be determined without operating the machine, as will be described presently. In the case of the motor, particular care must be exercised to see that the field connections are in good shape and that the shunt field circuit through its controlling rheostat (resistance coils) is perfect. Should the shunt field circuit become open when the motor is in operation, the machine may be destroyed.

(9) Before starting to operate the shunt dynamo, it should be ascertained that the external circuit is either open or not set for excessive load, otherwise the machine will not build up, and that the field rheostat is turned to the point of *highest* resistance.

(10) Before closing the switch feeding a motor, it should be ascertained that the handle of the starting box or controller is in the proper starting position, and in the case of a shunt motor that the field rheostat is turned to the point of *lowest* resistance.

After everything has apparently been put in order up to this point and the dynamo has been started and is being driven at its rated speed, if it fails to build up, even when the field rheostat is turned to the point of lowest resistance, and the switch to the load circuit is open, this may be due to any one of several causes. It is an easy matter to enumerate a long list of so-called diseases of the dynamo. Experience, however, suggests the following methods of procedure, taking each in turn until the fault is discovered.

(11) Shift the brushes slightly forward and backward by means of the rocker, watching the voltmeter meanwhile to observe any tendency toward building up.

(12) Slightly increase the pressure on the brushes, which in low-voltage machines may be done with the hand, watching the voltmeter meanwhile. This may be combined with paragraph 11, and sometimes reveals a faulty brush.

(13) If the machine still fails to build and the voltmeter leads

are assuredly connected and the right way around showing a readable voltage, then open the shunt-field circuit. If this causes a slight increase in voltage, it is a sign that the current in the field coils caused by the residual magnetism is in a direction such as to reduce this magnetism rather than to build it up. The leads from armature to shunt-field must therefore be reversed. Or the fault may be corrected by driving the dynamo in the reverse direction, which will reverse the polarity of the armature terminals.

(14) If operation No. 13 causes the voltmeter needle to drop slightly, it is a sign that the field is correctly connected to the armature terminals and the fault lies elsewhere, possibly in the field-coils themselves. Before testing out these, however, it would be well, slightly to increase the speed of the machine, if this is not too difficult. A slipping belt or a badly governed prime-mover is sometimes the sole cause of annoyance.

(15) If operation No. 13 causes no change in the voltmeter reading, it is probable that no spark appears on closing and opening the field circuit, and that the circuit is somewhere broken, except in the case to which paragraph 16 applies. It is not impossible to get the effect noted in this paragraph, even with the presence of a spark on opening the field circuit, if just half of the field coils should happen to be connected the wrong way around, giving the wrong polarity to half of the field poles. This, however, is not at all likely unless the field has been taken apart and reassembled.

(16) It sometimes happens that the residual magnetism of the field iron disappears or becomes reversed. In the latter case, the machine would operate perfectly, the polarity of the terminals alone being reversed, making the switch-board meters read backwards. In the case of lost magnetism, however, the voltmeter would show no voltage on operation. In that event paragraphs 13 to 15 would not apply. Disconnect one armature lead from the shunt field so that the only path between the terminals of the field will be through the field coils and rheostat, and by means of wires from some outside source of similar

voltage to that generated by the machine itself send a current through the coils for a few seconds, so as to excite the field and restore the residual magnetism. The direction of this current will determine the future polarity of the machine, but will not otherwise affect its operation. In machines of say over 25 kilowatts capacity great care must be exercised in opening the shunt-field circuit when fully excited, as the inductive voltage so produced is likely to pierce the insulation. This danger can be avoided by short-circuiting the field through a rheostat before removing the wires of the charging current. In case the dynamo is one of 220 or 550 volts, sufficient residual magnetism may usually be induced in the field by a 110 volt source of supply, if the higher voltage is not at hand. The utter loss of residual magnetism by the field iron is not a frequent source of trouble.

If the dynamo still fails to build up, the trouble is likely of a serious nature, such as to require the rewinding of field or armature. As a means of locating these more serious faults, the following tests are described. Paragraphs 17, 18 and 19, however, might well be considered a part of the original inspection of a dynamo and the test should be made on new machines or those which have been recently taken apart and reassembled.

(17) Test for "grounds" (a) between field and frame and (b) between armature and core. For these tests connect the voltmeter and machine to a source of supply of similar voltage to that of the machine, according to Fig. 32.

In case the insulation has been rubbed off one of the windings at any point so that the bare wire lies against the iron, forming what is known as a "grounding" of the wire, a voltmeter connected as shown on a 110 volt circuit would read 110 volts. If the voltmeter reads anything less than the circuit voltage, only a partial "ground" is indicated. The resistance of the wire covering not being infinite, the voltmeter will always read something, sometimes so little, however, that a special low-voltage meter is required to get an exact reading. If the resistance of the meter be known (R_m), the resistance of the ground (R_g) may be found as follows:

Let V_l = line voltage, or voltage of the source, and let V = the voltage read. Since the deflection on the scale is proportional to the current passing through the meter, the instrument becomes in this usage an ammeter, and we may write

$$V_l : V :: \frac{V_l}{R_m} : \frac{V_l}{R_m + R_g},$$

whence $$\frac{V_l^2}{R_m + R_g} = \frac{V\,V_l}{R_m} \text{ or } \frac{V_l}{R_m + R_g} = \frac{V}{R_m},$$

and $$V_l R_m = VR_m + VR_g,$$

and $$R_g = R_m \left(\frac{V_l}{V} - 1\right).$$

The insulation between field and frame and between armature and core varies greatly with the size and type of machine and

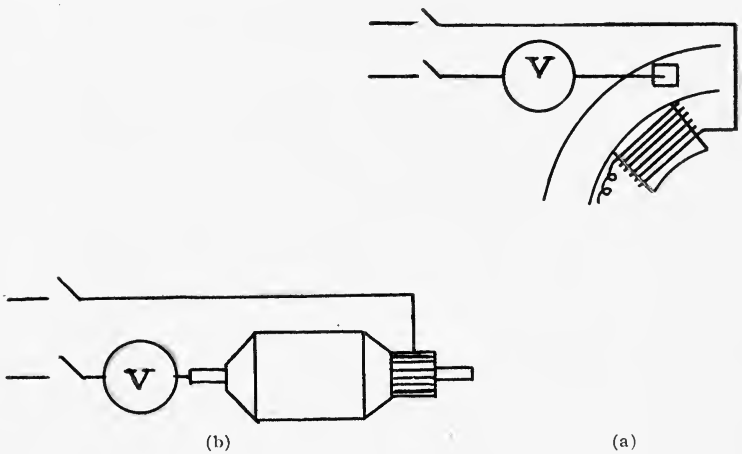


Fig. 32.

with the particular voltage for which it is wound. According to the standard rating of the American Institute of Electrical Engineers (1902) "The insulation resistance of the complete apparatus must be such that the rated voltage of the apparatus will not send more than 1/1,000,000 of the full load current, at the rated terminal voltage, through the insulation. Where the value found in this way exceeds 1 megohm, 1 megohm is sufficient." Substituting this value in the formula, if the circuit voltage is 110 and the voltmeter have a resistance of 20,000 ohms, a normal value, then since $V = \frac{V_l R_m}{(R_m + R_g)}$ we should have

$V = \frac{110 \times 20{,}000}{1{,}020{,}000} = 2.15$ volts. So the voltmeter on a 110 volt machine could read 2.15 volts sum total in the tests just described and the machine still come within the rating.

If a serious ground is discovered in any machine, perhaps the first point of suspicion is the binding posts. It may also be suggested here that by separating the field coils from one another, each may be tested separately. Should a serious ground be detected at two different points, this would mean that part of the windings are made inoperative, a large part of the current naturally flowing by the path of low resistance, namely, the grounds.

(18) Taking the resistance of the field winding sometimes reveals a fault, and in any event is a desirable preliminary test on any machine. It can be easily determined by taking the potential difference between field terminals with the voltmeter when a known current is flowing through the coils. By baring the connections between the spools, the drop across each individual spool may easily be obtained. In case any spool gives a markedly different reading from the others, it is a sign that the winding has been injured at some point, causing either an excessively high resistance or a short circuit within the spool. The resistance of the field coils can be more accurately determined by means of the Wheatstone bridge, and the current used will not be sufficient to heat the windings and change their resistance during the test.

(19) Taking the armature resistance is also a desirable preliminary test on any dynamo machine. The best method to employ is the potential difference method as above. The armature resistance is made up of three essential parts, namely, the resistances of the armature winding, of the brush contacts and of the leads to the machine terminals. The last are very small

and may be included in that of the brush contacts. The method of obtaining these values is indicated in Fig. 33.

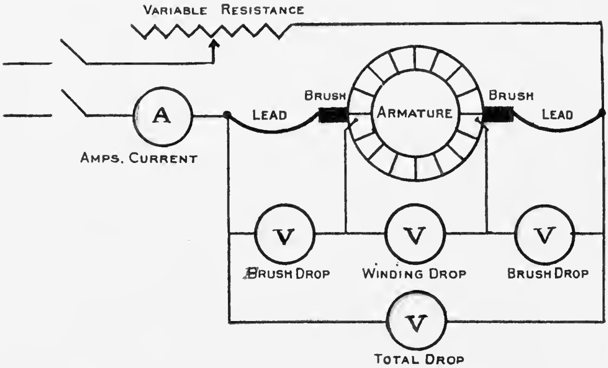


Fig. 33.

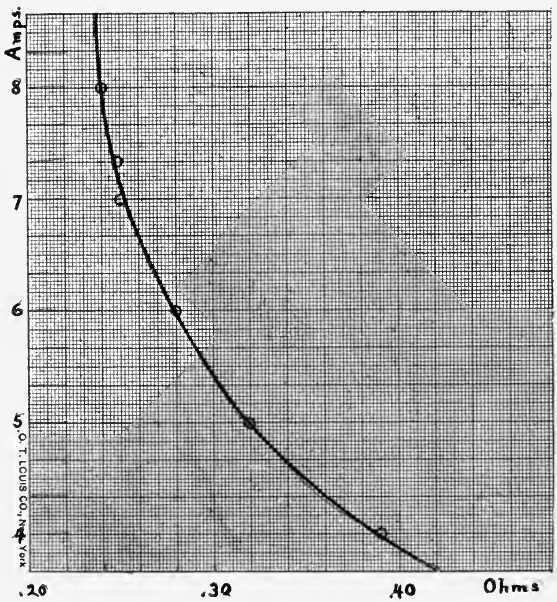


Fig. 34.—Carbon brush resistance curve.

The total armature drop ought to be small, as the armature resistance materially affects the voltage at the terminals and the efficiency of the machine. The brush drop, the sum of the two sides, varies from about 1.2 to about 2.8 volts. It is greatly influenced by the strength of the current. The accompanying curve (Fig. 34) was obtained on a 3 horse-power interpole motor of the Electro-Dynamo Co. The current used in obtaining the resistance of the armature circuit should be as near as may be to the full-load current of the machine. The armature must not be allowed to rotate as, the field not being excited, the machine might attain a dangerous degree of speed.

This test may be extended in the following way in order to reveal any defect in the armature winding. Hold one of the voltmeter leads on a commutator bar in contact with a brush and keeping the current constant, touch the other lead to each succeeding bar in turn. The increments in voltage drop should be constant. Any increment less than the constant indicates a short circuit in the corresponding winding-element. A zero increment may also indicate an open circuit in the armature.

(b) The Building-up Curve.

If a shunt generator with the field circuit open be brought up

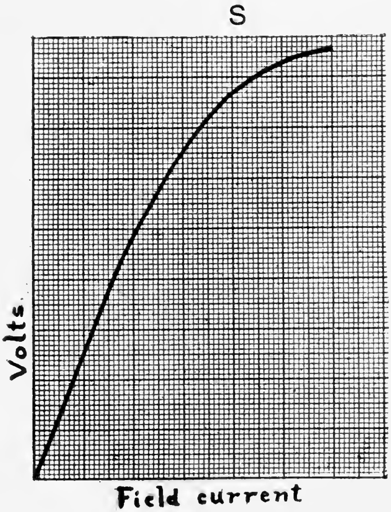


Fig. 35.—Building-up curve.

to constant speed and the field circuit be then closed, the terminal voltage of the machine and the field current as the generator builds up will be so related as to give the curve of Fig. 35. The shape of this curve depends upon the iron of the magnetic circuit. The saturation point is at S. Owing to the hysteresis of the iron, the time required for building up varies from a few seconds in small machines to a minute or so in very large ones. The curve must be plotted from simultaneous readings.

(c) Magnetization Curve.

This curve, showing also the character of the magnetic circuit of the dynamo machine, is easier to obtain than the preceding. The method is to excite the field from some outside source, a variable rheostat controlling the strength of the exciting current, and to read the voltage developed at the terminals at each value of the field. Then, since $\Phi = \dfrac{4\pi NI}{10\,\dfrac{l}{s\mu}}$, in which I is varied at will and the only other variable is μ, depending on the flux density induced in the iron, it follows that the m. m. f., which is $\dfrac{4\pi NI}{10}$, varies as I. Since m. m. f. is also Hl, the field current I plotted as abscissae is proportional to H. (See Chapter II.) Again since e. m. f. $= \dfrac{\Phi p N n}{10^8 p'}$ in any dynamo machine, and since for any one machine driven at constant speed the only variable in the second member of this equation is Φ, it follows that the terminal voltage varies as Φ. Now since $\Phi = \phi s$, or Bs, when we plot the e. m. f.'s as ordinates, we are plotting values proportional to B. Hence the curve described is essentially a B and H curve, and the only reason it is not a straight line is because of the varying values of μ. See Fig. 36.

The lower curve is drawn with gradually increasing values of I, the upper one with the values of I again decreasing. The two curves are not identical because of hysteresis. The proper working part of the curve during the operation of the machine is somewhat below the saturation point, say about the region 110 v.

It would not be economical of iron to operate the machine much below this region besides other disadvantages of having the iron poorly saturated, to be explained later. To operate the machine

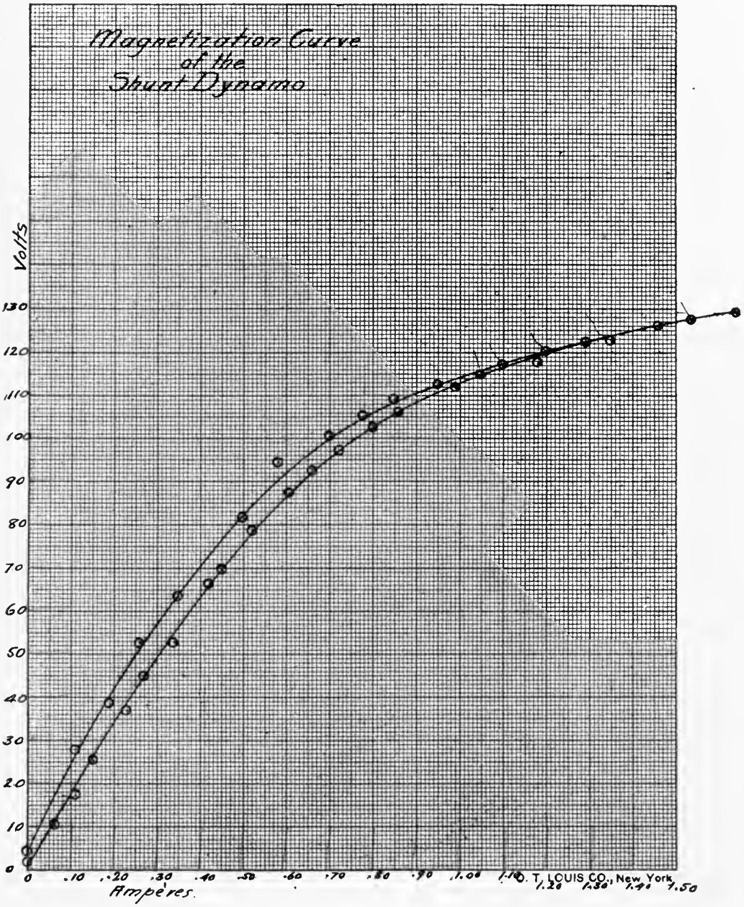


Fig. 36.

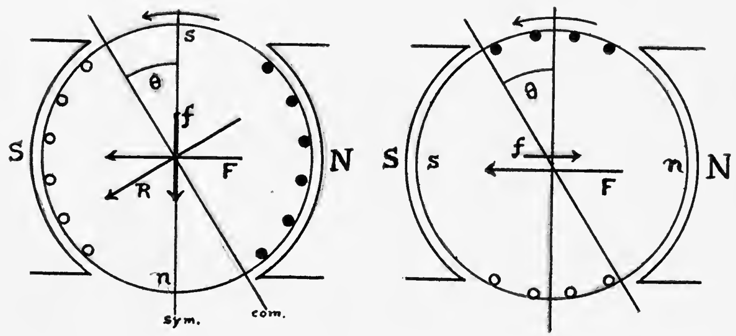
much above the region would mean poor control of the voltage generated, even if greatly varying the field current.

There is one flaw in the reasoning of the preceding paragraph, and the curve is not strictly a magnetic curve. This is because of magnetic leakage, by which is meant the stray field extending from pole to pole out around the armature and not ever cut, therefore, by the armature inductors. The ratio of the total flux set up by the field winding to that part of it which actually passes through the armature iron is known as the coefficient of magnetic leakage; 1.25 might be given as a normal value for this quantity, although in small machines it may exceed this and in very large multipolar machines it is often less.

(d) Armature Reaction.

In a generator furnishing current and in a motor under operation another factor enters in to interfere with the flux produced by the field circuit. This is the magnetic flux due to the current in the armature. This flux may be divided into two components: the one (A) is caused by the cross magnetization of the armature, distorting the field flux; and the other (B), is caused by the so-called back ampere turns in the armature circuit and may be termed a reverse magnetization by the armature circuit, weakening the flux from the field.

Figs. 37 and 38 show how these two effects are brought about on bipolar machines.



(A) (B)

Fig 37.—Generator.

The part of the armature winding represented in Fig. 37 (A) sets up a cross magnetization, much as if the wires formed a continuous vertical helix, the north pole being on the lower side of the armature, at *n*. If the magnitude and direction of the field flux be indicated by arrow F (N to S in the air), and of the armature flux by arrow *f* (*s* to *n* in the iron), then R will represent the direction of the resultant lines of force, the field flux being to this extent distorted. The axis of commutation, being at right angles to this resultant flux, is given a lead from the line of symmetry between the pole faces in the direction of rotation by the amount θ, the angle of lead. This lead given to the brushes causes the current in the remaining armature inductors to be as shown in Fig. 37 (B). The current in these inductors creates a magnetic flux much as if the wires formed a continuous horizontal helix, the north pole being on the right side of the armature at *n*. In this case the arrows F and *f* are directly opposed to each other, the result being a weakening of the field flux.

In Ampère's rule of directions, the right hand applies to the generator and the left hand to the motor. Effect (A) in the motor is therefore just the reverse of the generator as is shown in Fig. 38, but effect (B) is the same in both machines. In the

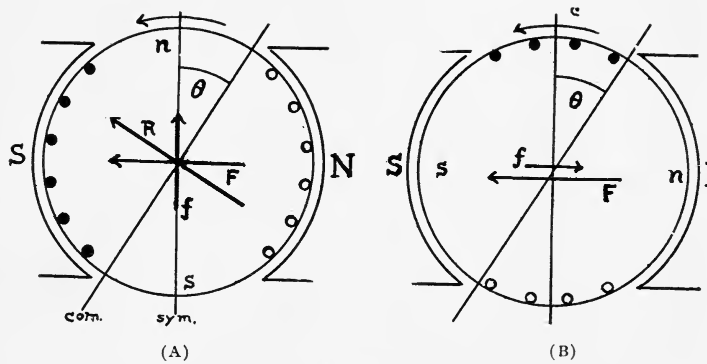
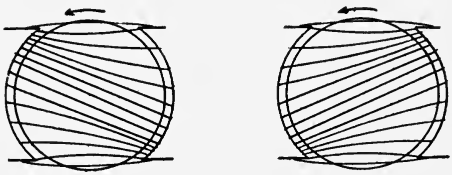


Fig 38.—Motor.

motor the brushes are given a lagging position with reference to the axis of symmetry in order to bring them into the neutral position.

The final shape of the field flux due to the influence on it or armature reaction is shown in Fig. 39. It will be observed that the tendency is for the flux density to be increased in the trailing pole-tip of the generator and in the leading pole-tip of the motor.



Motor. Generator.

Fig. 39.

In designing a machine, the weakening of the flux caused by armature reaction has to be compensated for by an increase in the ampere turns of the field.

(e) External Characteristics.

Let a shunt generator be driven at constant speed with the field rheostat fixed in some definite position, and let load be gradually added to the external circuit by means of a bank of lamps in parallel or by a variable rheostat. As the external current is increased, the voltage at the machine terminals will be found to fall. This is due to three causes.

(1) *The IR drop in the armature winding.* As the load current I increases, the e. m. f. required to send it through the constant armature resistance R increases in the same ratio. This e. m. f. is used up in the armature and is subtracted from the generated volts thereby rendering the terminal volts less.

(2) *The consequent weakening of the shunt field current.* With fixed field rheostat the resistance of the field circuit is essentially constant, and a weakened terminal voltage sends through it a correspondingly weaker current. This lessens the flux cut by the armature inductors, causing a still further voltage-decrease. After each addition of load, this interaction is set up and continues till a balance is obtained.

(3) *The Armature Reaction.* It has been shown in the pre-

ceding section (*d*) how this phenomenon decreases the field flux, an effect which is almost immediately followed by a fall in terminal voltage.

Fig. 40 is the external characteristic of a 2 horse-power 110-volt Bell motor, operated as a generator, the curve being plotted between the load current and the terminal voltages. The part of the curve which returns toward the origin is formed when the de-

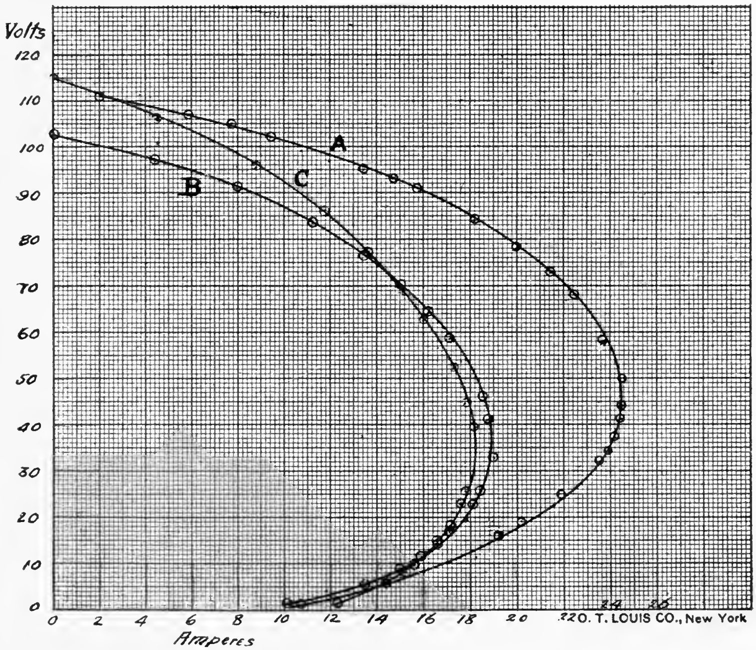


Fig. 40.—External characteristic of a shunt generator. Curve A, at rated speed and field current. B, at rated speed and increased field resistance. C, at increased speed and still greater field resistance.

creased resistance in the external circuit so reduces the terminal voltage that a weaker rather than a stronger current flows through this decreased resistance. This phenomenon is termed in power-house vernacular "lying down." It sets in with a very unsteady condition of the two meters and is accompanied by violent sparking at the brushes.

(f) Armature Characteristics.

In the practical operation of a shunt dynamo, a decrease in

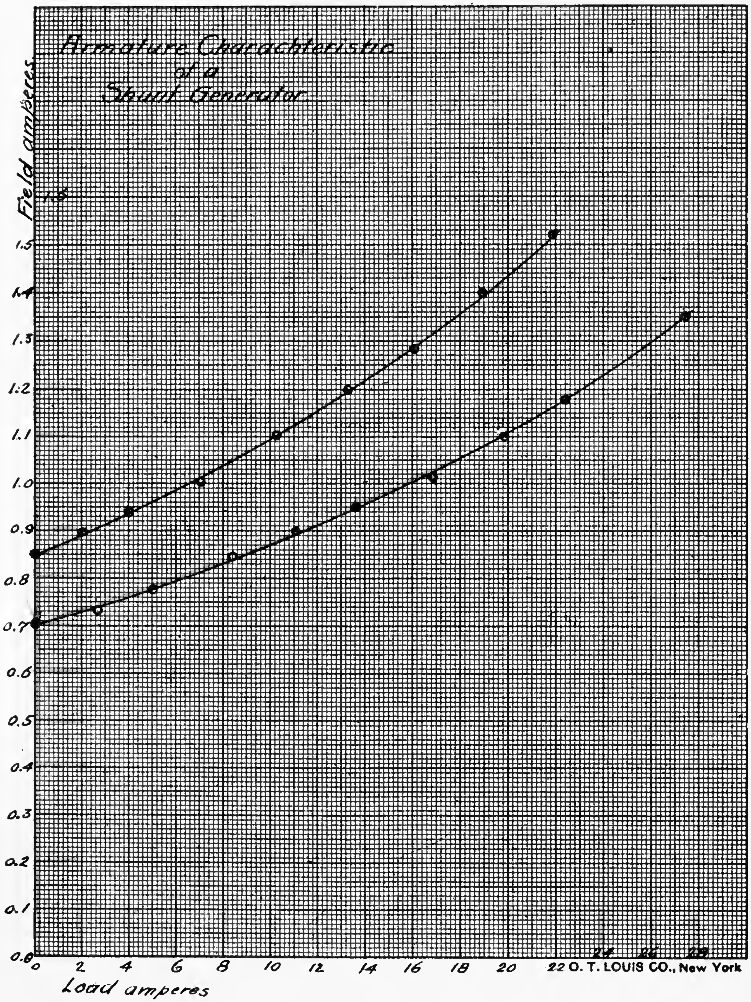


Fig. 41.—Armature characteristics of a shunt generator.

terminal voltage due to load can up to a certain limit of output be compensated for by a decrease in the resistance of the shunt field rheostat. This increases the field current and strengthens the field flux to such a degree as to overcome the tendency of the terminal voltage to decrease. A curve plotted between load currents and field currents when the speed and terminal voltage are kept constant is known as the armature characteristic. For the generator of the preceding section operated at 110 volts and again at 115 volts constant e. m. f., the armature characteristics are shown in Fig. 41.

(g) The Compound Generator.

From the external characteristic of a shunt generator, it is at once apparent that in order for such a machine to furnish constant voltage under varying loads, the services of an attendant would be constantly in demand. For this reason various automatic field regulating devices have been invented. By far the

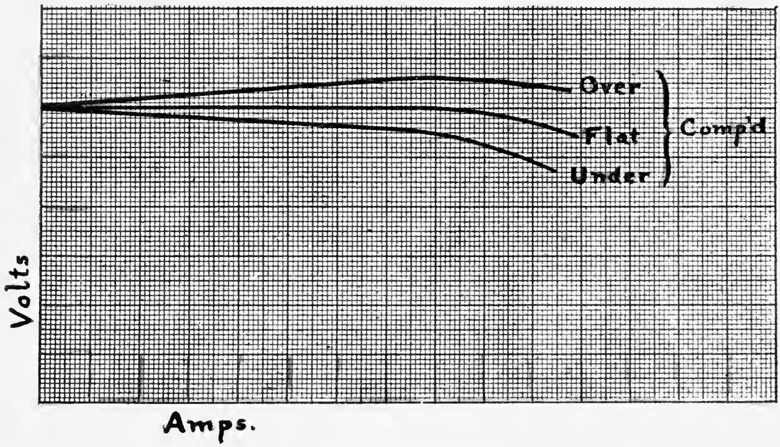


Fig. 42.—External characteristics of compound generators.

simplest and most practical of all these is that by which the varying load-current is carried around the field poles on what is known as the series field winding. This varying load-current then adds its m. m. f. to that of the shunt field current, thus producing an increase of flux with increase of load. By having in these series field coils the proper number of turns, the terminal e. m. f.

of the machine may be kept constant or may be made to increase slightly or may be allowed to decrease slightly with increase of load on the machine. Thus we have flat compounding or over compounding or under compounding of the generator. A simple calculation will make this clear, as follows:

From an inspection of Fig. 41 it will be seen that for a load of 16 amperes the shunt field current must be increased from 0.85 ampere at no load to 1.28 amperes, an addition of 0.43 ampere, in order to mantain constant terminal voltage. If this

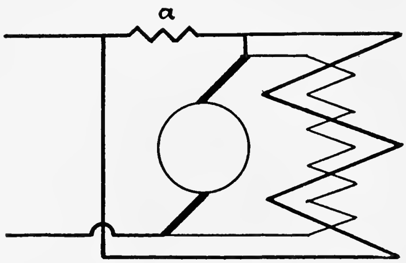


Fig. 43.—Short shunt.

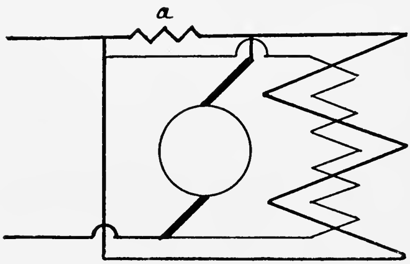


Fig. 44.—Long shunt.

particular field winding has in it 4,000 turns, this means an increase of $4,000 \times 0.43 = 1,720$ ampere turns, or the load current of 16 amperes must encircle the poles $1,720 \div 16 = 108$ times to produce the required additional flux, the shunt field remaining constant at 0.85 ampere. For a bipolar machine this means 54 turns to each pole in the series winding. Fig. 42 represents the external characteristics of a compound generator with three different values of series field winding.

In order to overcome the IR drop that always occurs in line wires of any considerable length, it is the custom to build generators of the over compounded type, and then by inserting a cross shunt of the proper size at *a* (see Fig. 43) to regulate them to the desired degree of compounding. There are two styles of connecting the shunt field, termed short shunt and long shunt.

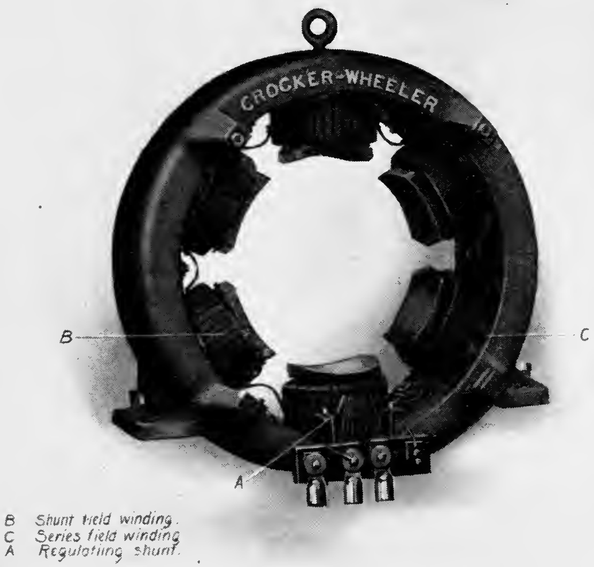


Fig. 54.—Complete field frame of 50 k. w. generator.

There is very little difference between these two styles of connection as regards the behavior of the machine.

(h) Sparking.

The cause of sparking at the brushes of direct-current generators and motors and the means of obviating the same, particularly in the latter, have received more attention from manufacturers and have given origin to more types and styles of apparatus than any other feature of dynamo electric machines. The chief objections to sparking are (1) the little electric arc burns and mars the edges of the commutator bars and so increases this form of trouble and (2) the counter e. m. f. of the little arcs interferes with the e. m. f. of the generator and the speed of the motor.

A study of Fig. 46 will serve to explain the cause of sparking and the immediate remedy for it.

The figure represents part of a gramme ring armature with a commutator bar to every second turn about the ring, the brush being placed on the axis of symmetry (*xx*) between the poles. An application of Ampère's rule for direction reveals the course of the generated current through the windings to either side of this axis, as indicated by the small arrow-heads, the rotation

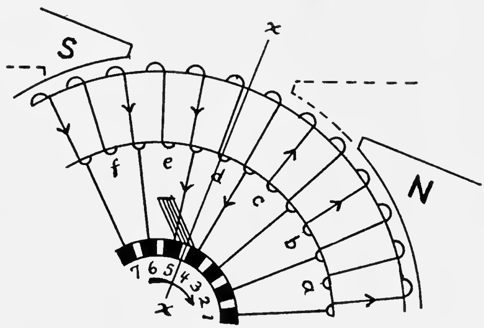


Fig. 46.

being clockwise. Six winding-elements, *a, b, c, d, e, f,* are shown with commutator bars 1, 2, 3, 4, 5, 6, 7. Winding-element *d,* being in the neutral position, has generated in it no e. m. f., the elements to the right of it sending their current into the brush through bar 4, and those to the left of it sending their current into the brush through bar 5. As bar 4 leaves the brush, this circuit on the right will be broken at the brush-tip, causing an electric arc. For when this circuit is broken, although element *d* has no e. m. f. generated in it, yet it will not readily become a path for this current from the right like a sort of side-track, as the connections would indicate, because of self-induction.

Self-induction or inductance is a property of electric circuits which tends to oppose any change in the current of the circuit. It is particularly strong in those circuits which, because of their helical shape or the presence of iron in their neighborhood, naturally develop a magnetic flux when they carry a current. Any change of this current and flux sets up a counter e. m. f. in the circuit, which retards the change and particularly interferes with a sudden reversal of the current. Now winding-element *d* has a moment before been in position *e* and had a current flowing in it from the left. It cannot therefore instantly take up the current from the right and so divert the flow entering the brush-tip through commutator bar 4.

Two things may be done, however, to remedy this difficulty, as follows: First, the brush may be made of high resistance material (carbon) which will aid the narrowing contact between brush and bar 4 to oppose the flow of current by this path and will further reduce to a minimum any current circulating around through the brush and the short-circuited element *d*. Secondly, if the poles be moved to the position of the dotted lines, or which is the same thing, if the brush be shifted slightly in the direction of the rotation, the winding-element at *d* will come under the influence of the next pole earlier than before, and the flux from this pole will generate in it an e. m. f. which will aid in reversing the current from the left so as to offer an unobstructed path to the current from the right. This current will thus be made to enter the brush partly or wholly from behind, through commutator-bar 5, thus obviating any arc between the tip of the brush and bar 4. More will be said under the subject of variable speed motors of the means employed for creating flux for reversal of the current in the short-circuited armature coil. The theory and remedy of sparking is identical in the case of the gramme ring and the drum-wound armature.

(i) Operation of D. C. Shunt Generators in Parallel.

All dynamo-electric machinery operates with greatest efficiency near its point of full load, the efficiency being lowest under light loads. For this reason, in generating plants where the load is subject to wide variations, it is more economical to have several smaller machines which can be run one or more at a time than to have one large machine which for several hours a day would be loaded to only a small part of its capacity. Hence the necessity of parallel operation.

Fig. 47 shows the connections for a pair of shunt generators feeding the bus bars of a distributing service. When the two machines are running, the switches shown in the figure being closed, the load may be distributed between the machines by the

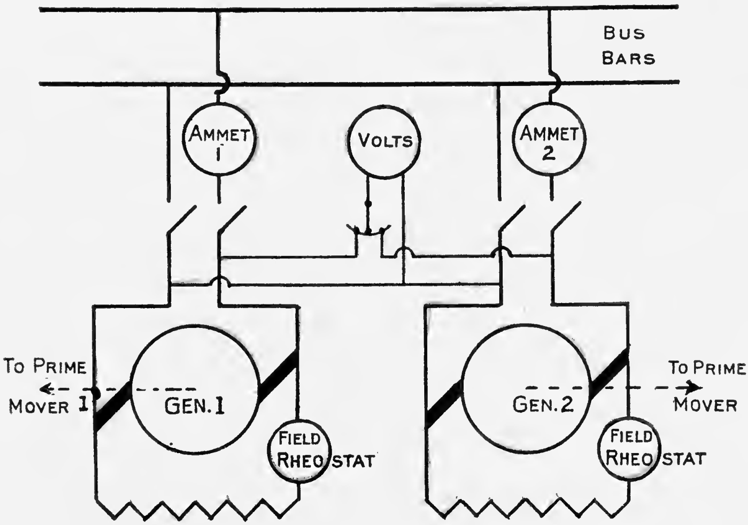


Fig. 47.—Shunt generators in parallel.

manipulation of the field rheostats. Being in parallel, the terminal voltage of the two machines will necessarily be the same, but a change of field which would cause an increase in the e. m. f. of one results in its taking on more of the load. Its ammeter will show that it is furnishing more current, and the load on the other machine may be so reduced that its ammeter will read less than zero, signifying that this generator is now drawing current from the bus bars and is being driven as a motor, its prime mover acting with a tendency to race. Such a state of things, should it occur in a generating plant, would be more or less dangerous to the machinery, there being a tendency on the part of some generators to become overloaded and on the part of those driven to spark violently at the brushes. For the brushes would not be in the correct motor position. The opening of a generator field circuit would cause such a condition, and very easily, since a shunt generator operates in the same direction as a motor, when the field and armature connections are unchanged.

If generators are to operate together in parallel, it is desirable that their external characteristics should be similar. Fig. 48 represents the external characteristics of two shunt generators that differ considerably. For convenience the current values are

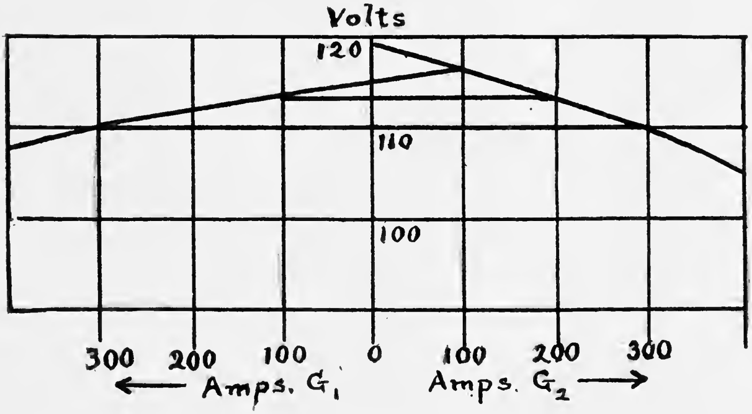


Fig. 48.

plotted in opposite directions. Suppose the total load to be 600 ampers at 110 volts, the field rheostats of the two generators having been adjusted so that each furnishes half. Let the total load be reduced to 300 amperes, the field rheostats being unaltered. The result will be a rise in voltage to 113 volts; but the external characteristics of the machines being unlike, the points on the curves coresponding to the new load and voltage show one machine furnishing twice as much current as the other, 200 amperes to 100 amperes. Should the load be reduced to zero, the voltage would evidently rise to about 117 at the point where the curves cross, and generator number 2 would furnish about

100 amperes to generator number 1, driving it as a motor. Hence such dissimilar machines, when operating in parallel under a varying total load, would require constant attention at their field rheostats.

In a power plant when one of the generators is to be removed from service, the procedure is to reduce its field till its ammeter reads zero. The switch can then be opened without in any way changing the loads on the other machines. Similarly, to bring an idle machine into service, start its prime mover, bring it up to rated speed, increase its voltage to that of the bus bars. (The voltmeter of the switch-board is made to serve for any machine desired by a rotating switch shown in the figure.) The switch can then be closed connecting it to the bars, and its field can be adjusted until it takes its share of the load. The machine switches are not intended to be opened when any current is flowing through them or to be closed when conditions are such that current would immediately flow through them.

(j) Operation of D. C. Compound Generators in Parallel.

Except for the peculiar action of the series fields, the operation of compound generators in parallel is similar to that of shunt generators. The connections for two machines are represented in Fig. 49.

Consider first the machines to be in operation without the equalizer bus, only the outside blades of the three-pole switches being closed, and consider G_1 by a slight increase in speed momentarily to take on more load than G_2. The result will be to increase the series field of G_1 above that of G_2, which results in increasing the e. m. f., thus still further increasing the load on G_1. The load on G_2 being thus decreased, its series field is weakened, thereby accentuating this effect till G_2 is actually driven as a motor. And not only so, but because of the reversed direction of the current in its series field, G_2 acts as a differentially wound motor (see p. 77), increasing in speed the more current it draws.

Two compound generators in parallel are thus in unstable equilibrium. By the introduction of the equalizer bus, however, the current through the series fields becomes the same in all machines so connected, the resistances of the series fields being the same. It is therefore impossible for the phenomenon just described to take place. It is only by the introduction of this equalizer connection, Fig. 49, that compound generators can be

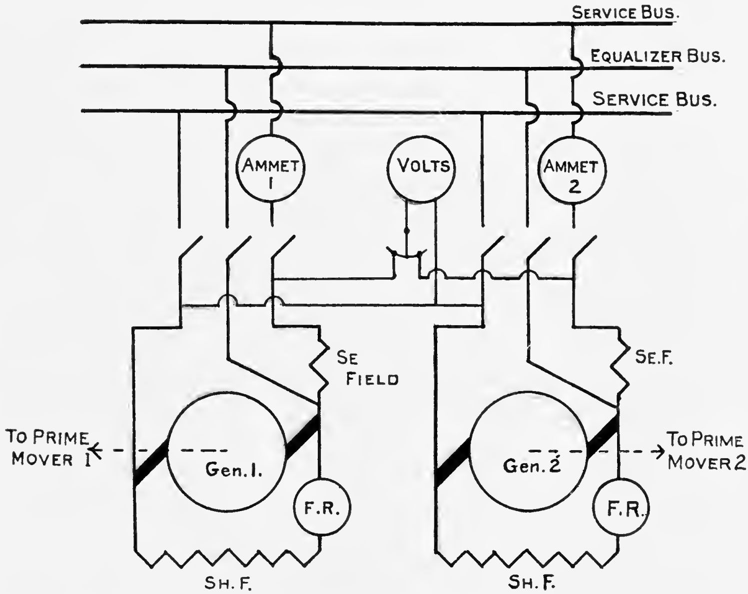


Fig. 49.—Compound generators in parallel.

operated in parallel. If the machines are not of the same size, the series field resistances must be in proper proportion.

(k) D. C. Generators in Series.

Direct-current generators are operated in series for the same purpose that batteries are joined in series, namely, to obtain increased voltage. There are three applications of this method of operation in general use: viz., in the Edison three-wire system, in the use of boosters, and in the multi-voltage power systems.

The Edison three-wire system is a device for saving copper in transmission lines. The connections are shown in Fig. 50.

The current in the middle wire is at every point the algebraic sum of the current in the outside wires. The saving in copper, if all three wires are of the same size, is 62½ per cent., proved as follows. Double the voltage gives the same power in watts with half the current. The I^2R loss in the conductors will be the same on a 220 volt system as on a 110 volt system, if R be made 4 times as great, or the cross-section of the wire ¼ as great. On a two-wire system this would mean a saving of 75 per cent. of copper in a 220 volt system as against a 110 volt system, but a third wire of the same size as the other two adds to the 25 per cent. used half again as much copper, or in all 37½ per cent., leaving the economy in copper a 62½ per cent. saving.

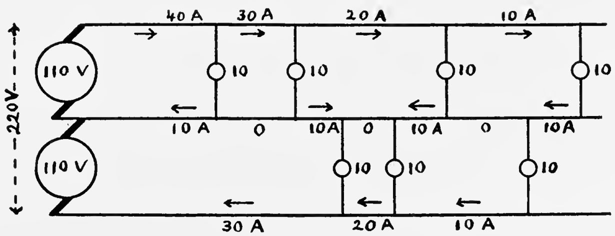


Fig. 50.—Edison 3-wire system.

In connection with the Edison system the three-wire generator ought to receive a mention. This is a 220 volt generator, whose brushes are connected to the two outside wires of the system. Besides the commutator, there are on the armature shaft two rings, tapped on to the winding as in a single phase alternating current generator. These are connected through a highly inductive circuit, known as a reactor, whose middle point leads out to the middle wire of the system. The current (direct-current) in this wire flows alternately through either half of the reactor circuit, thus forming part of the alternating current in the armature.

Boosters are low-voltage generators of large current capacity used in series with the main generator of a system for the purpose of stepping up the voltage a few points on special branches of the main system. For instance, where storage batteries are in use to operate in parallel with a generator, as is sometimes done in systems where there is great variation in load, during those hours of the day when the load is light and the battery is being charged, a voltage above generator voltage must be applied to the battery terminals in order to overcome the counter electromotive force of the battery. The additional volts would be obtained by means of a booster. Again in order to counteract the IR drop in line wires, the feeder system as illustrated in Fig. 51 is very efficient and convenient.

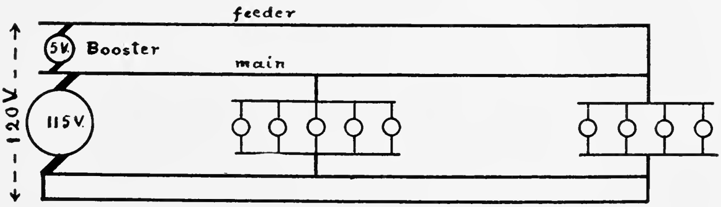


Fig. 51.—Booster-feeder system.

The booster need be only a fraction of the size of the main generator, as it supplies only a few additional volts to part of the load.

Multi-voltage power systems will be noticed under the subject of variable speed motors.

(1) D. C. Arc-light Dynamos.

The open arc-light operates best at 45 volts and requires from 6.5 to 10 amperes. Because of their low voltage and large current such lamps came to be arranged in series groups, and machines were devised which furnished constant current at a high voltage in distinction from the constant voltage generators for incandescent lighting service. These machines, however, are now rapidly passing out of use for two reasons: First, the enclosed arc lamp has been invented, which requires about 75 volts at the arc and takes 5 amperes, more or less, so that with a small rheostat in series with each lamp, these lamps operate very well in parallel on the usual 110 volt circuit. Secondly, where for any reason series lamps are preferred, alternating-current service has so many advantages over direct-current for series lighting, that the latter is being rapidly superceded. Since, however, such circuits are still occasionally met with, it may be best to introduce here a brief description of some types of constant current high potential direct-current generators.

Since the lamps are in series, when a lamp is shunted out of service, in order to maintain constant currents, the generator voltage must be decreased, and vice versa. Two ways of decreasing voltage are to decrease the field circuit by means of a rheostat or to shift the brushes so as to include fewer active armature coils between them. Either of these methods used alone causes violent sparking at the brushes, as is the case in the old Thomson-Houston dynamo which employs the second method. The Excelsior arc-lighting generator and the Brush machine use both methods combined and are more successful. In all these machines the field regulation or brush shifting, as the case may be, is accomplished by an automatic device more or less complicated in construction and adjustment. A fuller description of these will be found in such detail works as Crocker's "Electric Lighting," Vol. I, Sheldon and Hausmann's "Dynamo Electric Machinery," Vol. I, etc.

In conclusion it should be stated that there are numerous variations of the types of dynamos thus far treated, some to be found only in Europe, such as the disc dynamo, others used only as motors, which will be taken up later. The underlying principles of all these are not different from those described. The greatest divergence of design occurs in the case of alternating-current generators, which will be treated in the second part of this volume.

CHAPTER V.

THE D. C. MOTOR.

(a) Operation and Characteristics.

The fundamental equation of the shunt motor, as given on page 15, is

$$E_l = \frac{\Phi p N n}{10^8 p'} + I_a R_a ,$$

where E_l, the line voltage applied to the machine, is opposed by the counter e. m. f., leaving only a small remnant to send the working current I_a through the low resistance of the armature circuit R_a. For instance, in a certain 3 horse-power (so rated) shunt motor, 115 volts, 25 amperes, the field current is 1 ampere and the armature current at full load 24 amperes. The armature resistance is 0.45 ohms. Now the $I_a R_a$ drop $= 24 \times 0.45 =$ 10.8 volts. Hence this is the effective pressure, the potential difference required to send 24 amperes through the armature circuit when the machine is at rest. The c. e. m. f. developed by the rotating armature, that is, the e. m. f., with the same field and speed conditions which the machine would develop if operating as a generator is 115 minus 10.8, or 104.2 volts.

When the machine is running, this c. e. m. f. of 104.2 volts acts like a resistance, preventing the current from becoming excessive. But if the motor when at rest should be connected directly to the 115 volt mains without any starting device, the current in the armature would be $\frac{115}{0.45} = 2{,}555$ amperes, an amount which, if it should not open circuit-breakers or blow fuses, would burn up the armature circuit. While a direct-current motor is coming up to speed, therefore, a temporary resistance is thrown in between the armature circuit and the line, in the shape of a starting-box. The shunt field circuit, on the other hand, has in itself such a resistance that it can be connected directly to the mains without injury.

The connections of the ordinary starting-box are represented in Fig. 53.

When the switch S has been closed, the handle of the starting-box is slowly moved from stud to stud, cutting out the resistance-coils R, till the left-hand lead is directly connected to the armature and field like the right-hand lead. These resistance-coils, although at first interposed in the field circuit, have no appre-

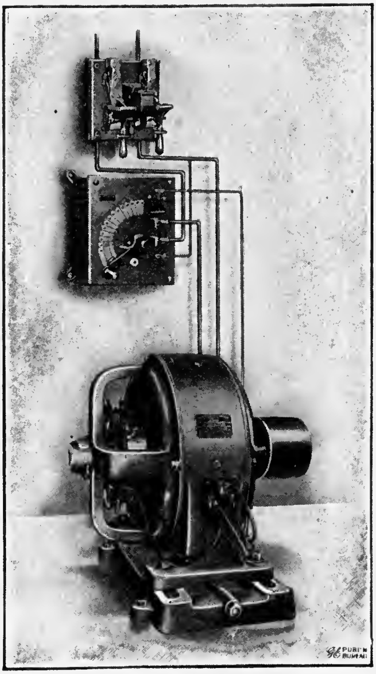


Fig. 52.—G. E. Co. 50 h-p. motor with starting-box and circuit breaker.

ciable effect on the shunt field current, because their resistance is infinitesimal as compared to that of the field. In some boxes, the field current does not pass through these coils at all. M is simply a retaining magnet, or no-voltage release, for the handle. When the motor is to be stopped, the switch S is pulled, M loses its magnetism, and the handle flies back by means of a spring to

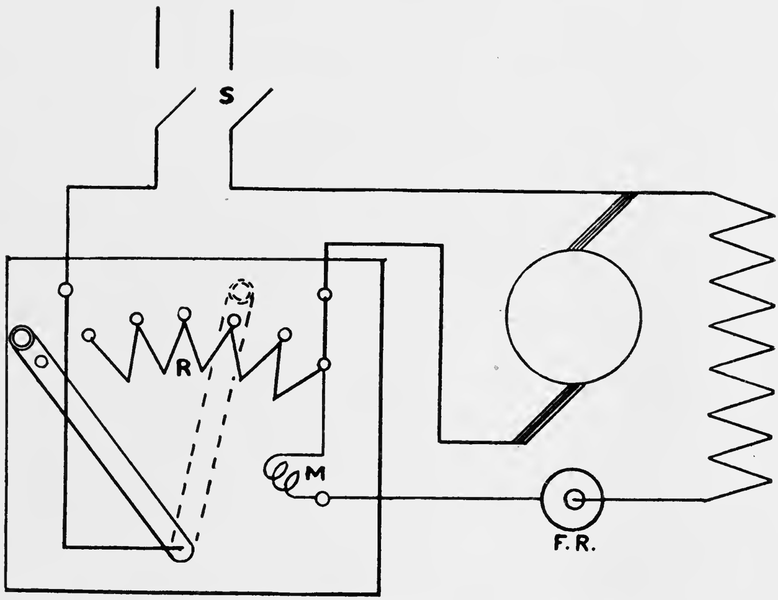


Fig. 53.—Ordinary shunt-motor starting box and connections.

Fig. 54.—Starting-box for shunt motor with no-voltage release. G. E. Co.

its original position, ready to be used again. Other forms of starting device will be treated later.

In Chapter II we had the formula $W = i\Phi$, where W = ergs

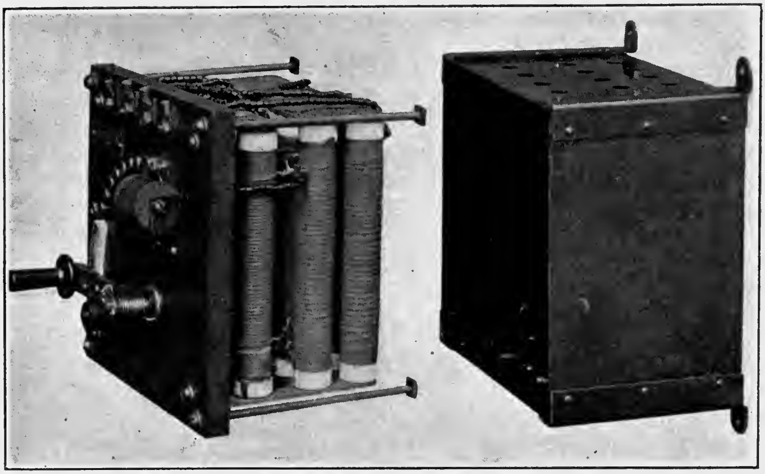


Fig. 55.—Starting-box, interior. G. E. Co.

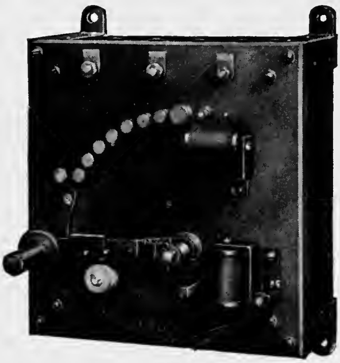


Fig. 56.—Starting-box with no-voltage and overhead release. G. E. Co.

performed when a wire, having current i absolute units, is moved by magnetic influence so as to cut Φ lines of force. This formula can be developed so as to give an expression for the torque T or twisting force of the armature of an electric motor as follows. The total flux cut per revolution by each armature inductor is the Φp of the fundamental equation of the motor, which takes the place of the Φ in the above formula. Similarly i must be replaced by $\frac{i_a N}{p'}$ where N is the number of armature surface-inductors, as before, and p' is the number of paths in parallel, i_a being the total armature current, I_a, in absolute units. The work in ergs per revolution of 360° or 2π radians (angular measure) $= 2\pi T$, when T is the force in dynes operating at the end of a radius of 1 centimeter. Hence

$$T = \frac{\Phi p N}{2\pi p'} i_a \text{ dynes.}$$

To express this torque in pounds developed at the end of a foot radius, the usual practical torque unit, the following changes are necessary.

$$\underset{\text{Lbs. and ft.}}{T} = \frac{\Phi p N}{p'} \times \overset{\text{Amps.}}{\frac{I_a}{10}} \times \frac{1}{2\pi \times \underset{\text{cm. per in.}}{2.54} \times \underset{\text{gms. per lb.}}{453.6} \times \underset{\text{dynes per gm.}}{980} \times \underset{\text{in. per ft.}}{12}},$$

or $T = \frac{\Phi p N}{10^8 p'} I_a \times 0.1175$ where I_a is in amps.

Now since power, P, is work per second, Wn, we have

$$P \text{ (in ergs per sec.)} = 2\pi n T = \frac{\Phi p N n}{p'} i_a \text{ absolute.}$$

To reduce to watts, or 10^7 ergs per second, and to amperes,

$$P(\text{in watts}) = \overset{= \text{volts.}}{\frac{\Phi p N n}{10^8 p'}} \times \overset{\times \text{ Amps.}}{i_a \times 10} = \frac{\Phi p N n}{10^7 p'} i_a = \overset{\text{Volts}}{\text{c.e.m.f.}} \times \overset{\text{Amps.}}{I_a}$$

which is simply another form of Lenz's law.

The interpretation of the equations of the motor will make clear the characteristics of the machine. In the first place in the equation $E_t = \text{c. e. m. f.} + I_a R_a$.

E_t and R_a are essentially constant. Consider now a load to be thrown on the motor, as happens when it is made to drive machinery. The decrease in speed due to the load decreases the

c. e. m. f., as is evident from the formula for the same, and the result is an increase in I_a. This means an increase in torqu This increase in current and torque is more rapid than the accompanying decrease in speed, and increases automatically, the greater the load put upon the motor. It is therefore unnecessary to feed into a motor by rheostat control or otherwise more or less current according to the power desired, for if the e. m. f. of the supply mains is kept constant, the motor will draw whatever current it needs to meet the load. In the direct-current motors indeed it is possible to overload the machine to such a point that the load current will overheat and destroy the armature. In this way a motor may be made to furnish many times its rated power, the current capacity of the windings alone determining the limit of power.

Another thing which the motor formulae make clear is the fact that a decrease in the field current of a shunt motor increases the speed. This is the most common method of speed control for such motors and is effected by means of a rheostat inserted in the field circuit, exactly similar in many cases to the rheostat used to control the voltage in shunt-wound generators. From formula $E_t = \frac{\Phi p N n}{10^8 p'} + I_a R_a$ it is evident that if a shunt motor be furnishing a given torque and its field current is decreased, Φ will be made smaller and the c. e. m. f. therefore also smaller. This will cause an increase in I_a and the machine will speed up. This increased value of n will operate to counteract the decrease in Φ, and a new balance will be obtained between the impressed volts E_t on the one hand and the c.e.m.f. plus armature drop on the other. If the torque remains constant throughout the operation, since P varies as nT, the new point of equilibrium will show an increase in developed power over the old, the decrease in Φ not being quite compensated for by the increase in n, and the new value of I_a being therefore greater than the original value. If, however, the torque demanded of the motor be so decreased wth increase of speed as to keep the power constant, then the increase in I_a will be only momentary, the new speed almost exactly compensating for the decrease in Φ so that the c. e. m. f. is kept constant.

From this discussion it will at once be evident that an increase in the load on a shunt motor is always accompanied by a slight decrease in speed unless special means are taken to prevent it. For when I_a increases, the impressed voltage remaining constant, the field current remains constant, and therefore the principal agent in effecting the necessary decrease in the second member of our equation is n. In actual operation, though the field remain constant, Φ is not absolutely unchanged with increase of I_a. The armature reaction, noticed under the characteristics of generators on page 50 lessens the field flux in motors as well, and so acts like a resistance in the field circuit. For this reason the speed does not fall off as much as it otherwise would with increase of load. In fact, it is possible in some machines to set the brushes in such a way that the speed will not decrease at all, or may even increase. This effect would be brought about by an extreme backward lead of the brushes. It is usually accompanied, however, by a decrease in efficiency and by danger of sparking, and is therefore not usually resorted to.

In the case of the series motor, where the armature and field current are necessarily the same, the increase of load on the machine brings with it an increase of field flux Φ, and hence a far greater decrease in n than in the case of the shunt motor. With this increase in Φ and I_a there comes also a greater increase in torque than in the shunt machine, for torque varies as $\Phi \times I$. It is the peculiar characteristic of a series motor to show great changes of speed under varying conditions of load, and at the low speeds to develop a very high torque. For this reason series motors are particularly adapted to purposes of traction. When a car of any sort is starting, the torque to overcome the static friction must be large and the speed low. After the inertia of the mass has been overcome, the little power required to maintain motion on a level track or road reduces both I_a and Φ, hence the great increase in speed, n. The shunt motor, on the other hand, is well suited to operate machinery of nearly every type, approximately constant speed under varying loads being the usually desired condition of operation.

A favorite method of obtaining the characteristic curves of motors is by means of the friction brake or other form of

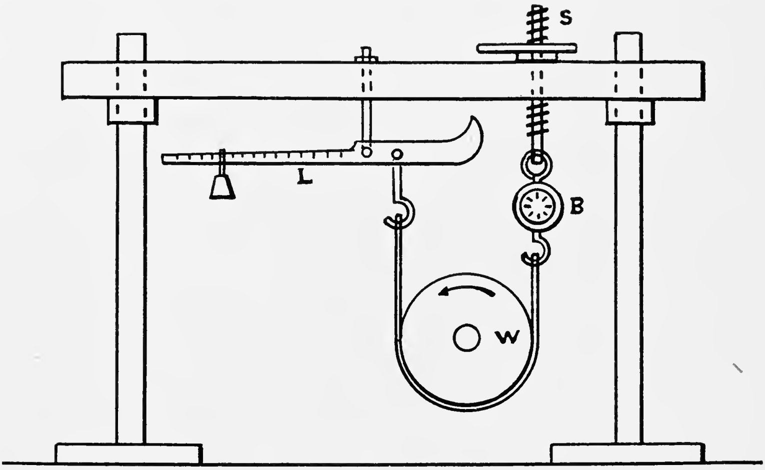


Fig. 57.—The friction brake.

dynamometer. Fig. 57 represents a convenient form of such an apparatus.

W is a piece of heavy cotton webbing placed about the pulley-wheel, as shown. B is a spring-balance for regulating the degree of tension by means of the hand-wheel and screw S. L is a

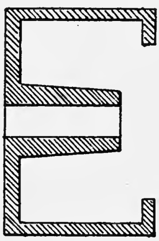


Fig. 58.—Cross-section of wheel for brake.

steel-yard or beam-balance. The difference in reading between L and B is the pull exerted by the motor at the rim of the wheel, and this number multiplied by the circumference is the work per revolution. In getting the circumference of the wheel the radius is taken to the middle of the strip of webbing. The wheel itself is preferably larger than the pulley-wheel usually furnished with the motor, and the surface should be flat, not crowned. It is also well to use a wheel of special form, whose cross-section is shown in Fig. 58. This is capable of holding water, which may be replaced from time to time during the test, keeping the wheel cool. This insures greater constancy of friction and prevents the heat developed by the brake from being conveyed through the shaft into the bearings. The formula for power developed by the motor is then

$$\text{Horse-power} = \frac{\text{Lbs.} \times \text{ft. circumference} \times \text{r.p.m.}}{33{,}000}.$$

This is the output. The input in watts may be obtained by an ammeter in the general circuit (field and armature) and a voltmeter across the terminals. Horse-power input is the watts divided by 746, and the per cent. efficiency is

$$\frac{\text{output}}{\text{input}} \times 100.$$

(b) Varieties of Field Excitation.

Fig. 59 shows the characteristic curves of a Bell Electric Company's shunt motor, rated at 3 horse-power, 115 volts, 25 amperes 1,200 revolutions per minute. Fig. 60 shows the characteristic of a General Electric Company's crane motor (series), rated at 5 horse-power, 220 volts, 25 amperes full load.

From the formula $E_t = \text{c. e. m. f.} + I_a R_a$ it is evident, that the smaller the resistance of the armature circuit, the more nearly constant will be the speed of a shunt motor under varying loads. For the smaller the changes in $I_a R_a$, the more nearly will c. e. m. f. $\left(= \frac{\Phi p N n}{10^8 p'}\right)$ approach a constant value. In the actual operation of nearly every motor, on the other hand, it must not be overlooked that the speed variation is considerably greater than appears from the manufacturer's curves. The reason is the IR drop is always present to a greater or less degree in the live wires leading to the machine from the source of supply. Unless the generator is compounded for this particu-

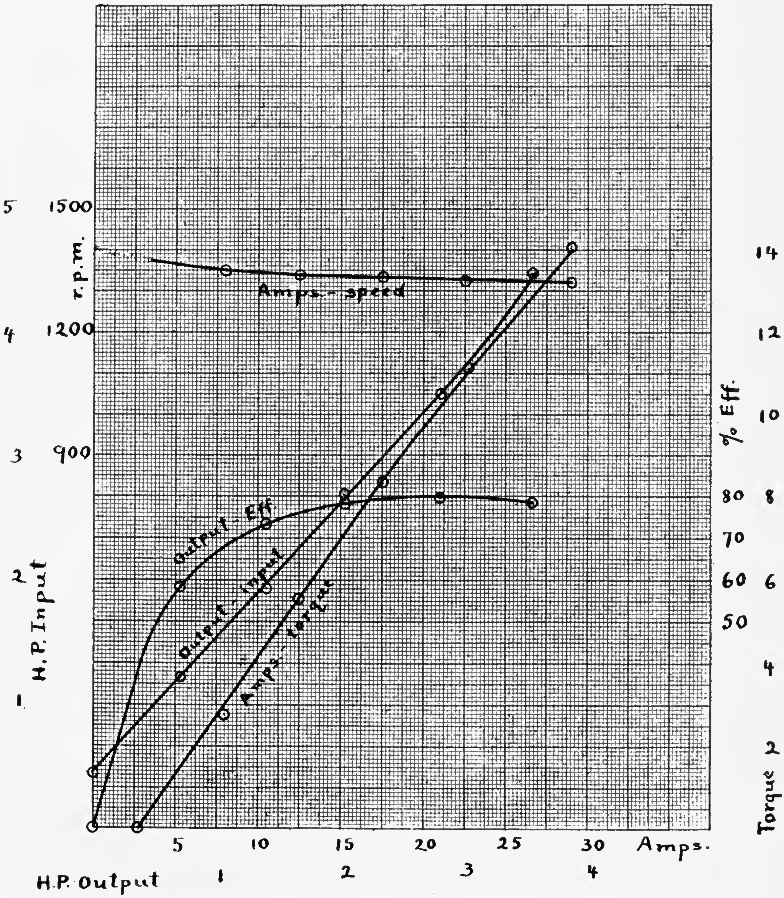


Fig. 59.—Curves of a shunt-motor. Bell Electric Motor Co. 3 H. P.

lar circuit or unless some other equally efficient means is adopted to maintain constant load-voltage, this IR drop lowers the voltage at the motor as the load increases, and has to be reckoned with in considering motor speeds.

Again, the speed of a motor, both shunt and series, is not the same after it has been operating for half an hour as at first. The heating of the field increases its resistance and so decreases

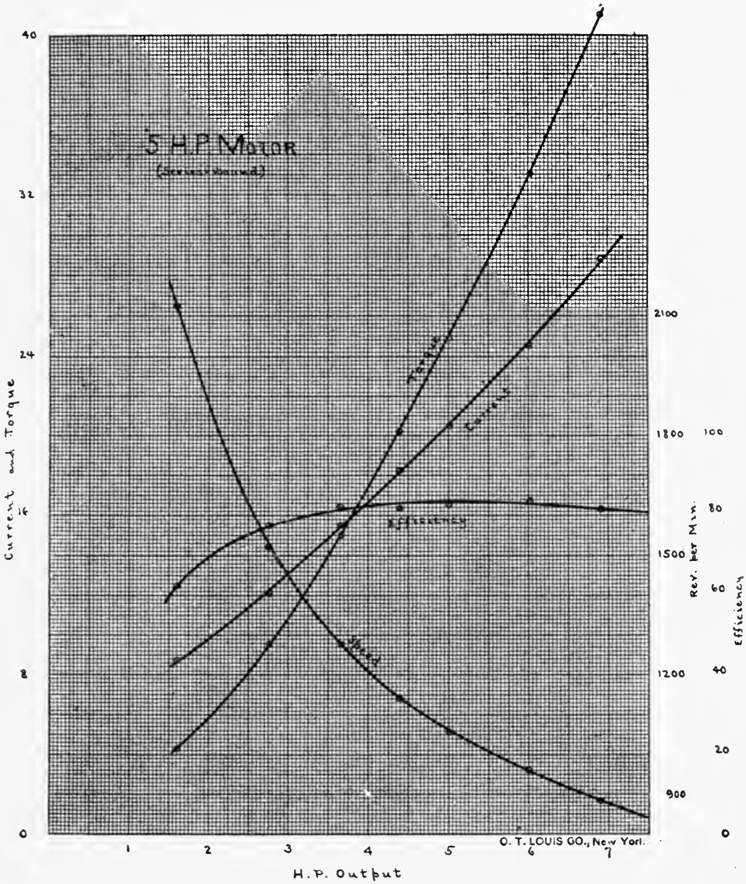


Fig. 60.—Curves of a series motor. G. E. Co. 5 H.P.

the flux. This results in a rise in speed which may be as high as 4 or 5 per cent.

Shunt motors may be compounded like generators, the characteristics of such machines resembling those of the shunt motor, but inclining toward those of the series motor in shape. An interpretation of the formula of the compound motor will make this clear, namely,

$$E_l = c.\ e.\ m.\ f. + I_a R_a + I_s R_s$$

where $I_s R_s$ is the IR drop in the series field winding. Since I_a and I_s are equal, the equation may be written

$$E = c.\ e.\ m.\ f. + I_a (R_a + R_s),$$

which shows that the series field is equivalent to an added resistance in the armature circuit. Hence the speed variation in such motors is larger than in the shunt motor. But not from this cause alone is this true. I_s in a compound wound motor goes to increasing the field flux, Φ, rendering a still greater decrease in n necessary to reduce the c. e. m. f. so as to balance the above equation than would be required in the case of the shunt motor. On the other hand, the increase in Φ with load increases the torque, so that a compound motor not only starts more slowly than the same machine would without the compound winding, but exerts a greater torque at starting. It is therefore suited for those cases where an essentially constant speed motor is desired, but one that is capable of meeting the requirements of a widely varying load. This is the case in the operation of passenger elevators. For derricks, on the other hand, and mine-hoists, where the speed variation is of minor importance, the series motor is more serviceable.

Given a compound generator, Fig. 61, to be operated as a compound motor, the series field connections must be reversed as in Fig. 62, else the series current will flow in a direction to oppose the shunt field.

If the generator of Fig. 61 should be operated as a motor, without reversing the series field terminals, it would be what is known as a differential motor, the series field acting so as to reduce the flux with increase of load. The result is a less falling off in speed than when operated as a shunt motor, that is, without the series field. In fact the automatic flux reduction by this means may be sufficient to increase the speed with increase of load. Operation of a motor under such conditions is a matter of great risk, as the speed may rise to a dangerous degree.

Although the differential machine shows a slightly lower efficiency than the others, yet it would be serviceable where absolutely constant speed is demanded. The differential motor is, however, little used.

From this discussion of the motor there ought not to be omitted a warning against loose shunt-field connections. When a motor

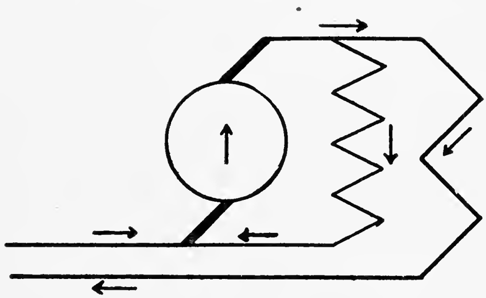


Fig. 61.—Compound generator.

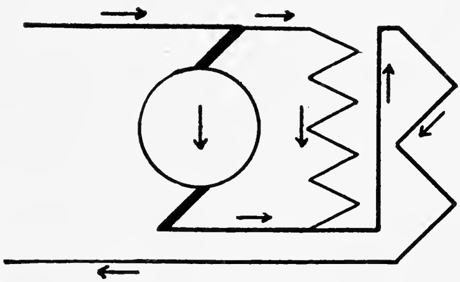


Fig. 62 —Compound motor.

is running free or only lightly loaded, the opening of the shunt field circuit results in a sudden decrease of the field flux almost to zero. The result is an inrush of current and an enormous increase in speed, so great and sudden in fact, that unless a fuse is blown or an automatic circuit-breaker opens in the line, the armature will fly to pieces simply by centrifugal force. Not too much care can therefore be taken to have all connecting points in the current path of the shunt field winding secure.

(c) Variable Speed Motors.

The control of speed of a shunt motor by means of resistance in the field circuit has been mentioned on page 71. The percentage decrease in field required to bring about a given increase in speed depends on the magnetization curve of the machine combined with armature reaction. This latter becomes greater and greater, distorting the field flux more and more, the weaker the flux becomes. Fig. 63 represents the distribution of flux in a motor field (a) with strong field excitation and (b) with reduced excitation for increase of speed, both being under condition of full load on the motor.

Such field distortion naturally leads to sparking (see page 63)

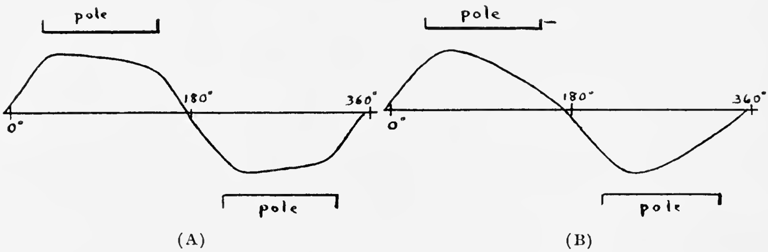


Fig. 63.

even when the brushes are shifted to the new neutral axis. Sparking sets the limit of speed increase by this method.

The ordinary type of shunt motor with simplex-wound armature can stand a speed increase of only about 30 per cent., for which a field decrease of about 50 per cent. is required. Numerous means have been devised, however, for overcoming sparking, so that now a speed range of from 1 to 6 is successfully obtained in shunt motors. Underlying these various devices of different inventors and manufacturers there are but two fundamental principles to be observed. The one is the reduction of the self-induction of the armature circuit to a minimum, the other is the prevention of the distorting effect of armature reaction on the field flux.

Self-induction in an electric circuit varies as the square of the number of turns. This will be evident if we consider two formulae of Chapter II, namely,

$$(1).\quad \Phi = \frac{4\pi NI}{\text{reluctance}}. \qquad\qquad (2).\quad e = \frac{d\Phi}{dt}.$$

The flux Φ in this case is not the field flux, but a flux due to the current in those armature coils in which commutation is taking place. They are the coils short-circuited by the brush. It is the dying out and rebuilding in the reverse direction of this flux which causes the inductive e. m. f., and hence the spark at commutation.

In self-induction, where the same turns of wire produce the flux as cut the flux, a doubling of N means a quadrupling of *e*, or the e. m. f. of self-induction varies as N^2.

If therefore each armature winding-element be made to have half the number of turns and the number of winding-elements be doubled, the self-induction will be greatly lessened. This arrangement necessitates that the commutator be made to have twice the number of bars, so as to accommodate the increased number of winding-elements.

Another thing that aids in decreasing self-induction is to have the current in each armature inductor comparatively small. This can be brought about by making the armature winding duplex or triplex, which causes the current to be shared by two or three windings. This again increases the number of winding-elements and of commutator bars. It also requires a wider brush, two and three bars being covered by the brush face, according to the winding. To be sure, both of these features of the winding call for a larger armature core than usual, and also a larger commutator.

The increased width of brush necessitated by the above-mentioned features, lengthens the period during which the coil is short-circuited by the brush, that is, the period of current reversal in the coil—another aid in reducing the self-induction, as appears from $e = \frac{d\Phi}{dt}$.

The increased size of armature calls for a larger size of field than common, hence the gain in convenience of speed control is in a measure offset by unwieldiness and expense of machine. In general practice, almost any ordinary shunt or compound wound motor in which the brushes are made to overlap two or three commutator bars will be found capable of a 1 to 2 speed range, if not more, by means of field rheostat control. Greater speed ranges than this, whatever other means may be used to prevent sparking, call for motor frames as follows:—

Power of motor.	Size of frame.
3 horse-power	5 horse-power
5 horse-power	7 1/5 horse-power
10 horse-power	15 horse-power

The Bullock Mfg. Co. resorts to lengthening the armature as well as increasing the diameter, whence the unusual size.

As regards the means of preventing the distorting effect of armature reaction on a weak field, several manufacturers resort to a special shape of pole-piece. The Stow motor, instead of changing the field current, has movable iron plungers, forming the centers of the field cores and operated by gear-wheels. An increased air gap increases reluctance and lessens flux. A speed-range of 1 to 4 is obtainable in these machines, but the gearing is unwieldy and expensive.

In order to avoid the extreme distortion caused in a weak field by armature reaction, the Fort Wayne motor makes use of a divided field core. See Fig. 64. By this means the one-half

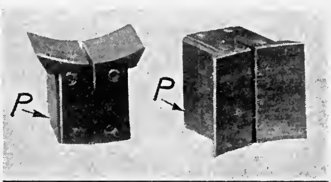


Fig. 64.—Pole piece of Fort Wayne motor.

of the field core is kept fairly saturated so that the flux from the other half may not so readily be crowded into it by armature reaction. The flux curve, then, is somewhat as shown in Fig. 65 under weak field.

The newest type of Storey motor goes a step further in this direction, and allows of no direct magnetic connection between the two halves of field core, the encircling binding-ring being made of brass.

In Fig. 38 (A) it was shown how the current in part of the armature inductors creates a cross magnetization, distorting the field flux. The attempt has been made to counteract this arma-

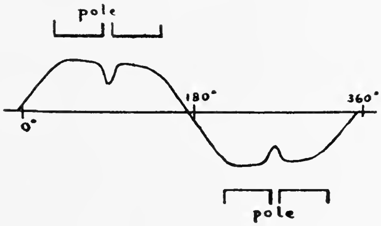


Fig. 65.

ture reaction by means of a compensating winding imbedded in the pole faces and connected in series with the armature so as to carry the armature current, only in a reverse direction. (Fig. 66.)

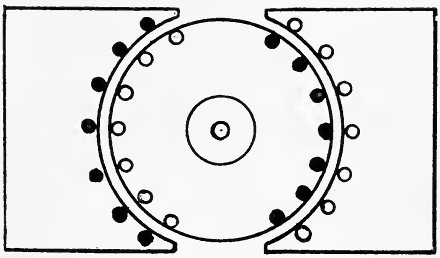
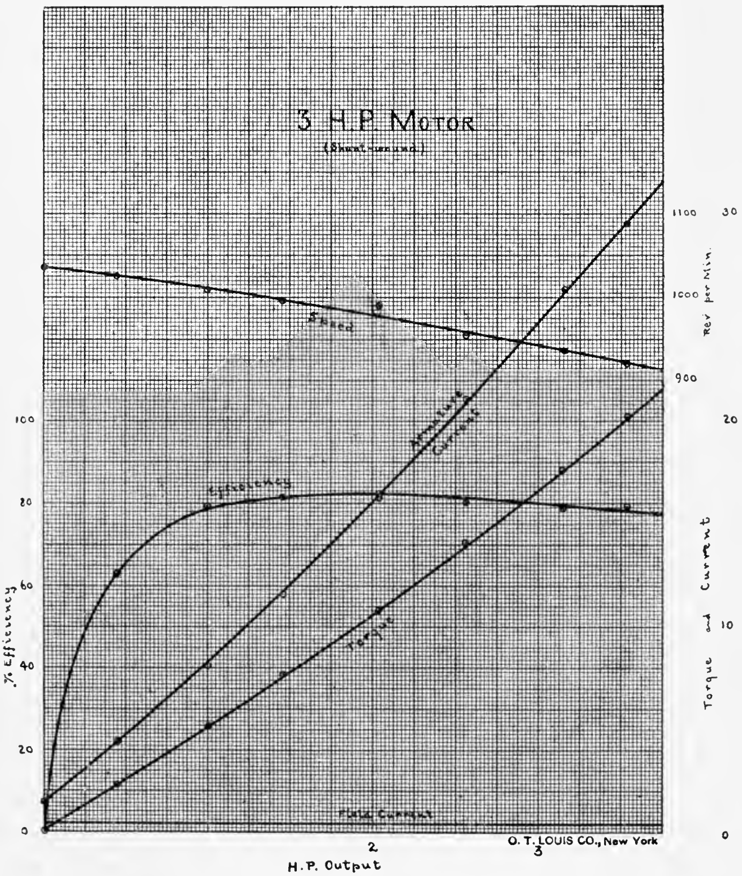


Fig. 66.—Compensating winding.

This corrective device was not found sufficient to prevent sparking with weak fields and furthermore proved expensive in manufacture. It also interfered with cooling.

The most recent and by far the most successful device for counteracting the effects of armature reaction is found in the interpole motor, for whose invention credit must be given to

Mr. Pfatischer of the Electro Dynamic Co. Fig. 68 shows such a motor of this company and Fig 69 the same machine with armature and end-plate removed. The interpoles carry a winding of a few turns connected in series with the armature circuit.



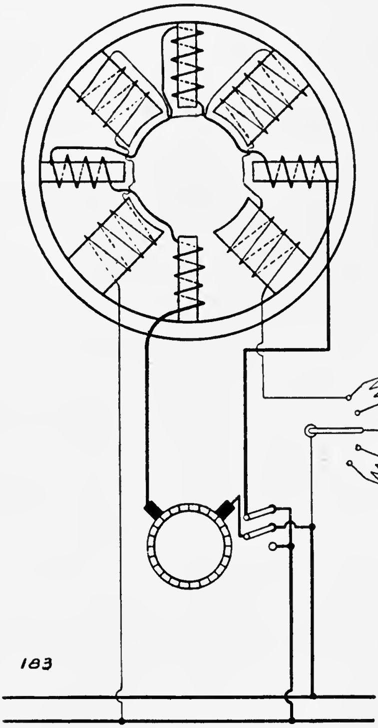
Figs. 67.—Curves of an interpolar motor, at high speed. Electro Dynamic Co.

Their function is to inject into the short-circuited armature inductors at the instant of commutation just the requisite flux for reversing the current. The excitation of the interpoles, being

Fig. 68.—Interpole motor—commutor end. Ball bearings.

Fig. 69.—Interpole motor. Complete field frame. Electro Dynamic Co.

accomplished by the load-current, varies with the load, as it should. The flux for reversal, being thus provided exactly where it is required, the shunt fields may be made as weak as is desirable to secure proper speed and torque, without the evil effects of armature reaction. The brushes, furthermore, are set per-



Wiring Diagram, showing electrical connections between the armature, field, and "Inter-poles."

Fig. 70.

manently on the line of geometric symmetry between the poles, thus enabling the machine to be operated in either direction. When properly adjusted, it is found that the angle of lag usually given to the brushes of shunt motors is unnecessary. This motor also takes advantage of the large armature and commutator to be found in most adjustable speed shunt motors, as previously described, thus securing a range of speed from 1 to 5 or even 1 to 6 in either direction, without sparking.

In connection with this motor it should be noted that a very slight shifting of the brushes from the correct position causes it to behave in a curious way. The interpole then acts somewhat like a differential series field, causing the machine to speed up till the c. e. m. f. is above the line voltage, and for a moment the motor acts as a generator, boosting the voltage of the whole system a point or two. This immediately causes a falling off in speed, when the same thing is repeated. This is not a frequent phenomenon, however, where these motors are installed, and is guarded against, after the brushes have been once adjusted, by fixing them in position.

All means of speed control thus far considered have been for increasing the r. p. m. For the reverse process, when the full field current is on, there is no convenient method adapted to constant speed motors. A rheostat in series with the armature, although it would reduce the speed, is to be avoided for the reason that variable load makes the IR drop over the rheostat variable, which is the same thing as applying a varying voltage to the armature, a decreasing voltage with increase of load. The speed current curve then declines toward zero speed.

An entirely different type of multi-speed motors to those thus far considered is one having two distinct windings on the armature and two commutators. By having the numbers of inductors in these windings related as 2 to 3, the following relative speeds may be obtained:

Connection.	Speed.
2 and 3 opposed	highest speed, 5 × a constant
2 alone	3 × a constant
3 alone	2 × a constant
2 and 3 in series	lowest speed, 1 × a constant

A similar system to this and one which has been developed with more success commercially is that of operating motors on multi-voltage lines. The field is excited on the highest voltage, and different voltages are applied to the armature, according to the speed desired. The various voltages are obtained by dynamos operating in series. Three such systems are in existence, and are represented in Figs. 71, 72 and 73.

Intermediate speeds are obtainable by field control. All these systems differ from those of the single voltage field control

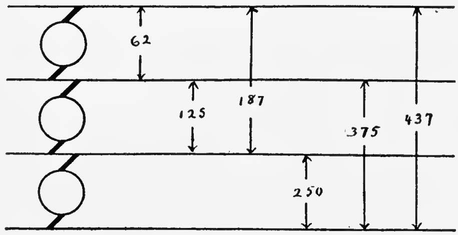


Fig. 71.—Ward Leonard. Speed ratios, 1 : 2 : 3 : 4 : 6 : 7.

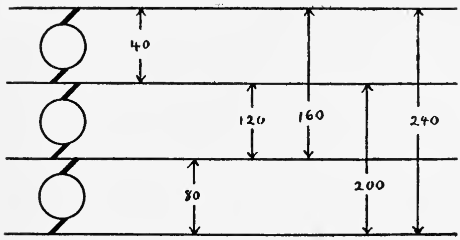


Fig. 72.—Crocker Wheeler. Speed ratios, 1 : 2 : 3 : 4 : 5 : 6.

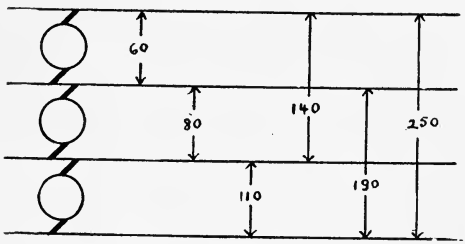


Fig. 73.—Bullock. Speed ratios, 3 : 4 : 5.5 : 7 : 9 5 : 12.5.

method in the fact that with added voltage there is an added input and added horse-power developed. In other words, these latter systems supply constant torque with various speeds, in distinction to constant horse-power with various speeds, which characterizes the interpolar motor and its predecessors in the market. And when it is considered that the electric motor is a machine which

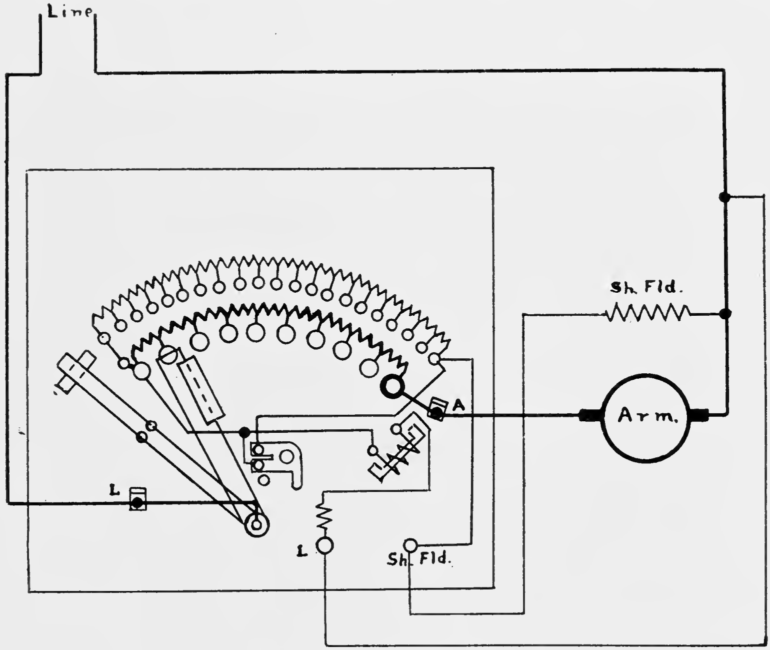


Fig. 74.

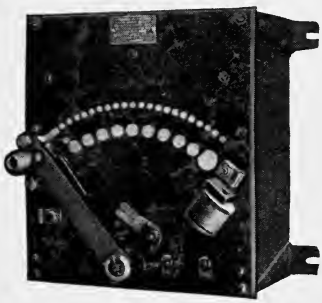


Fig. 75.

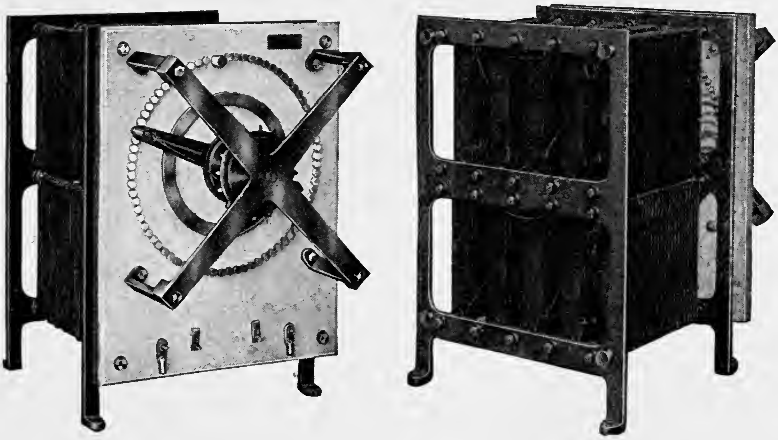
in any event automatically develops torque and horse-power according to the load put upon it, the fact that the interpolar

Fig. 76.—Ward Leonard field rheostat.

shunt motor operated on a single voltage is rapidly superceding all other direct-current devices can be easily accounted for.

(d) Starting-boxes and Controllers.

Together with the adjustable speed motor there has come in a new form of starting-box with a self-contained field rheostat. Fig. 74 shows the internal connection, and Fig 75 the external appearance of the box. The handle is double. The movement for starting is the same as in the ordinary box. At the end of



Front view. Back view.

Fig. 77.—Field rheostat for generators. G. E. Co.

the starting stroke the handle divides, one blade being held by the retaining magnet, the other being movable back across the box-face, throwing increasing resistance into the shunt-field circuit by means of the upper row of studs.

The usual form of field rheostat, used with the ordinary type of starting-box, is shown in Fig. 76. Its resistance coils or strips are embedded in porcelain. The type of rheostat more particularly used for voltage control in generators is shown in Fig. 77.

In regard to starting-boxes for shunt and compound motors, it should be noted that the resistance coils for the armature current are capable of carrying that current only for a short time without overheating. The box should therefore never be used as a speed-reducing rheostat, unless attached to a motor much smaller than that for which it was designed. Under ordinary conditions the starting-box for shunt motors is designed to be used 15 times an hour without overheating and it is calculated that 15 seconds may be consumed in the operation of starting.

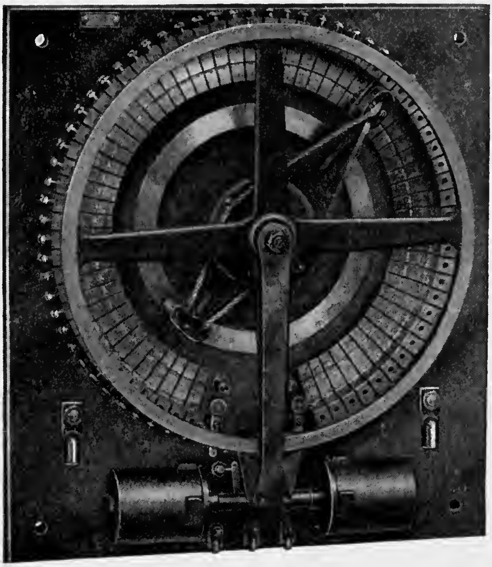


Fig. 78.—General Electric Co. Ratchet-driven remote control rheostat.

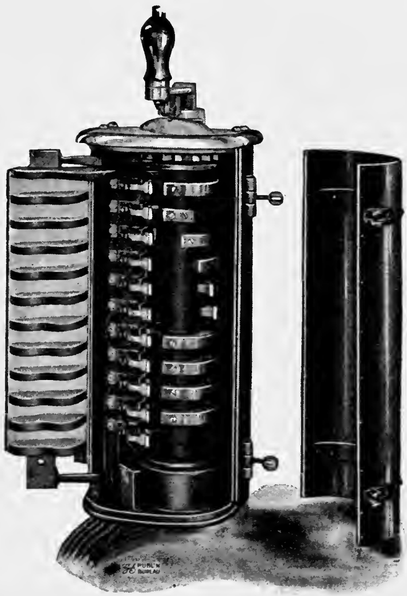
Small motors and motors not starting under load require much less time than this.

It may be laid down as a general rule that a motor starting free should begin to rotate when the starting handle is on the first contact point of the box. Under load the handle may be moved to the second or even the third before the armature begins to rotate; but if the machine does not then start, it is a sign of too heavy a load at starting or of some other trouble. Some boxes are provided with an overload release, which is in effect nothing more than an automatic cut-out or circuit-breaker.

For stopping a shunt or compound motor, the handle of the box should never be moved back across the studs, as this will burn and roughen them. The supply switch must be opened instead, leaving the handle to return automatically to its first posiion.

For the series motor the starting device is simply a rheo-

Starting rheostat for series motor.



G. E. Co. reversible controller for series motor.

Fig. 79.

stat in series with the machine. Because of the heavy current used in such machines, large starting torque being usually sought, the close-lying knobs and light coils of the shunt starting-box are unsuited. Fig. 79 represents a series motor controller and rheostat. The contact fingers are of heavy copper and spring-hinged. They are also separated from one another by thick insulating partitions, usually of asbestos. An electro-magnet provides flux for blowing out the arcs at contact points.

(e) Motor Uses.

Because of the great convenience and other advantages of electric driving apparatus, most makers of machine tools and other factory appliances to-day equip them with motors and provide places on the frames for installing the same. In their new and comprehensive work on electric motors, Messrs. Crocker and Arendt enumerate many points in favor of separate electric drive for the machines of manufacturing plants as against the older system of overhead shafting and pulleys. Some of these are as follows:

(1) The loss of power incident to shafting and belts is prevented.

(2) Better lighting and greater cleanliness are obtainable.

(3) Floor space may be utilized to better advantage, it being possible to place a machine anywhere and to face it in any direction.

(4) With motors of wide speed-range, cone pulleys and interchangeable gear-wheels become, to a large extent, unnecessary.

(5) The ease and quickness of speed adjustment not only saves the time of operatives in the shops, but by encouraging a greater care as to the proper speed to be used, insures a more perfect product. This is one of the greatest advantages. See Fig. 80.

(6) Side-walls and roof-beams may be of lighter construction where shafting does not have to be supported.

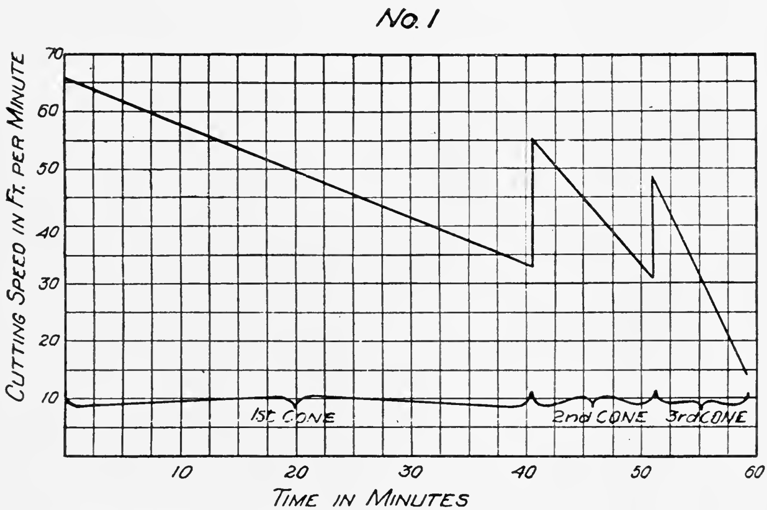
(7) In cases of shut-downs, part of a plant or even isolated and widely separated machines may be operated without the loss of power incident to lines of shafting and pulleys.

(8) Individual motors draw power in close proportion to the work they are doing.

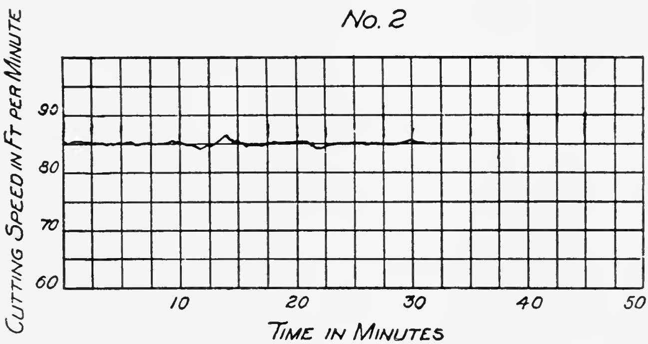
As to whether original cost outweighs these advantages is a matter that must be decided for each special case.

(f) Traction Motors.

In the operation of series motors for traction purposes, it is the custom to use two or four machines to a car, and to make the one machine or pair serve as rheostat to the other machine or pair at the time of starting. When running at full speed, the



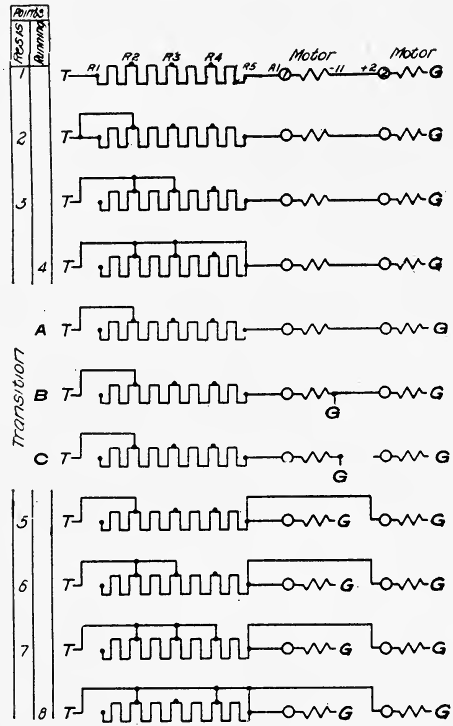
CUTTING SPEEDS AND TIME REQUIRED TO FACE A 72-INCH CAST IRON DISK USING THREE STEPS ON THE CONE PULLEY.



CUTTING SPEEDS AND TIME REQUIRED TO FACE A 72-INCH CAST IRON DISK WITH LATHE DRIVEN BY MOTOR WITH FIELD CONTROL.

Fig. 80. By courtesy of the G. E. Co.

machines are operated in parallel. Besides, a rheostat in series with each machine provides the intermediate steps. The transition from series to parallel connection is an operation of some degree of complication. Two types of series-parallel hand controllers are in most general use. Type K shunts and short-circuits one of the motors when changing from series to parallel connection. Type L controller opens the power circuit in making the change. The series of steps in the first type is illustrated in Fig. 81. It will

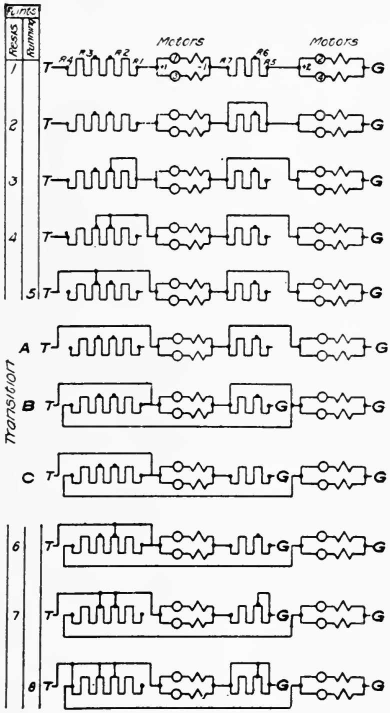


CONNECTIONS FOR SMALL CONTROLLERS

Fig. 81.

be observed that not every point is a running position. The rheostat is not heavy enough to stand the operating current for any length of time, and some points are passed over without being indicated either in the motion or by marks on the top of the controller box.

These controllers and the motors operate on voltages ranging from 500 to 600 and the horse-power of the motors ranges from 25 to 50. Above this size the multiple unit system of control is preferred. This system, used in electric trains, consists of a master controller drawing but a small current and operated in any car of the train and the larger motor controllers carried



CONNECTIONS FOR LARGE CONTROLLERS

Fig. 82.

with the resistances under the car and operated either by solenoid coils or by compressed air, in unison with the movements of the master controller. In changing from series to parallel connection, the Sprague General Electric automatic control system provides means of keeping both motors in operation and preserving their torque throughout the change. (The same is true of the new larger type K controllers. See Fig. 82). Furthermore it sets a maximum limit relay to the rate of motion of the controllers and so to the acceleration of the train. For fuller acounts of these interesting controlling devices, the reader is referred to works on electrical railway engineering, such as Sheldon and Haussman Electrical Railways, published by Van-Nostrand Co., 1911.

(g) The Motor-Dynamo.

This is the proper point at which to introduce the motor-dyna-

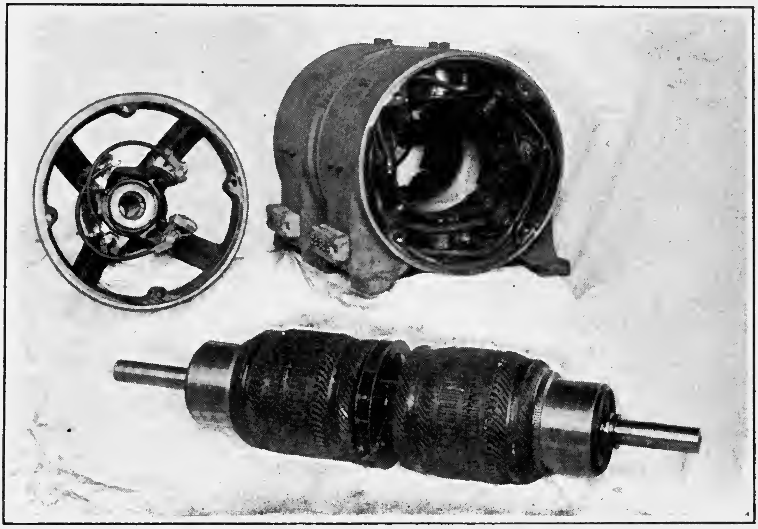


Fig. 83.—Motor-dynamo. G. E. Co.

mo, a machine having two distinct armature windings on the same core or separate cores with a commutator at either end. It may be used to step direct-current voltages up or down by a given ratio, according to the relative number of inductors in the two windings. The chief use of this instrument is as a balancer in the Edison three-wire system. In such case the two windings and voltages are alike. The modern type of this machine is double in field and armature. (Fig. 83.)

The balancer is employed when it is desired to run a three-wire system from a single 220-volt generator. Fig. 84 will make the operation clear. As long as the system is perfectly balanced,

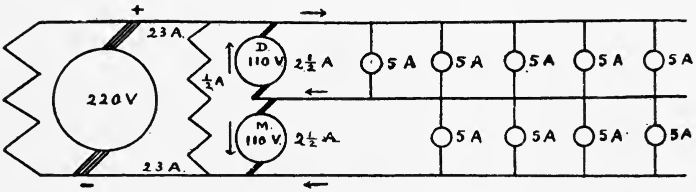


Fig. 84.—Three-wire system with balancer.

the balancer has nothing to do. But in the case in the figure, the return of 5 amperes on the middle wire divides, about 2½ amperes operating the balancer as a motor by means of one of the armature windings and causing the other winding to generate the extra 2½ amperes required in the positive wire of the circuit.

(h) Losses of Power in Generators and Motors.

In direct-current machines the losses are usually divided as in the following table.

Copper losses:
- (a) Watts lost in shunt field, $I_f^2R_f$.
- (b) Watts lost in series field, $I_s^2R_s$.
- (c) Watts lost in armature, $I_a^2R_a$.

Stray power losses:
- (d) Eddy current losses in armature iron and pole-faces, varying approximately as the square of the speed.
- (e) Hysteresis losses in armature core, varying as speed and as $B^{1.6}$.
- (f) Bearing friction, brush friction and windage varying approximately as the speed.

A reference to page 11, Chapter II, is all that is necessary to make the copper losses clear. They vary with the square of the current and hence depend upon the load. Eddy-currents occur whenever solid masses of conducting material move rapidly through an un-uniform magnetic field. The armature-core, though laminated, is not wholly free from eddy-currents. Again, the flux in the air-gap between field and armature is really of the shape shown in Fig. 85.

The shifting of these tufts over the pole-face engenders in it an e. m. f. and hence electric currents in the form of little whirls. A similar thing occurs in the armature conductors themselves, especially if they have considerable superficial area. Since e. m. f. and hence current varies as rate of cutting the flux, and watts vary as the square of the current, these losses vary as the square of the speed.

Hysteresis results from the reversals of magnetism in the

Fig. 85.

armature core. Once in every revolution of a bi-polar machine, the armature iron goes through a complete magnetic cycle. The watts lost depend upon the degree of saturation and the frequency. The load carried by the machine has little influence on the eddy current and hysteresis losses, the only effect of the armature current in this direction being its reaction on the field flux.

With this exception and the fact that during operation the tension on the belt may increase the bearing friction, all the stray power losses of the dynamo machine are the same when the machine is running free as when it is loaded, provided the field excitation and the speed are the same as when under load. The stray power test of efficiency consists in determining the dynamo losses, when the machine is thus running light. Then for generators

$$\text{Per cent. efficiency} = \frac{\text{output}}{\text{output} + \text{losses}} \times 100.$$

and for motors

$$\text{Per cent. efficiency} = \frac{\text{imput} - \text{losses}}{\text{input}} \times 100.$$

In any machine the losses are the same, whether operating as a generator or as a motor.

The citation of an actual case will make this clear. Connections for the test are shown in Fig. 86. Suppose a certain motor, when loaded and operating on a circuit of 115 volts, to draw 31 amperes total current, the speed being 1,200 revolutions per

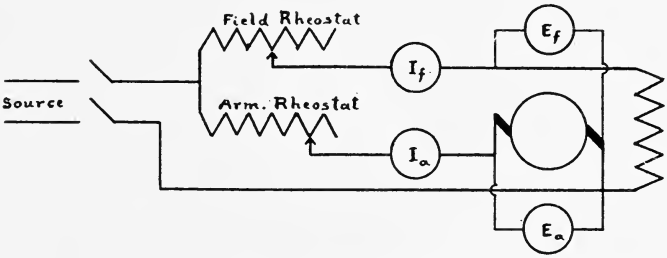


Fig. 86.—Connections for stray-power test.

minute. If we know the field current at this time, say 1 ampere, the working conditions of field and speed can be readily reproduced and the stray power losses determined as follows: Operate the motor free from load, and by means of the field rheostat and ammeter reproduce the field current of 1 ampere as closely as possible. Next by means of a rheostat in the armature circuit cut down the speed to the load speed value, namely, 1,200 revolutions per minute, and read the amperes furnished to the armature and the voltage between the brushes. Suppose these to be 2 amperes and 75 volts. The watts furnished to the armature are then $= 2 \times 75 = 150$. Of these there are consumed in the armature resistance $I_a^2R_a = 2^2 \times 0.5 = 2$ watts, leaving 148 watts This is known as stray power, because together with the $I_f^2R_f$ of

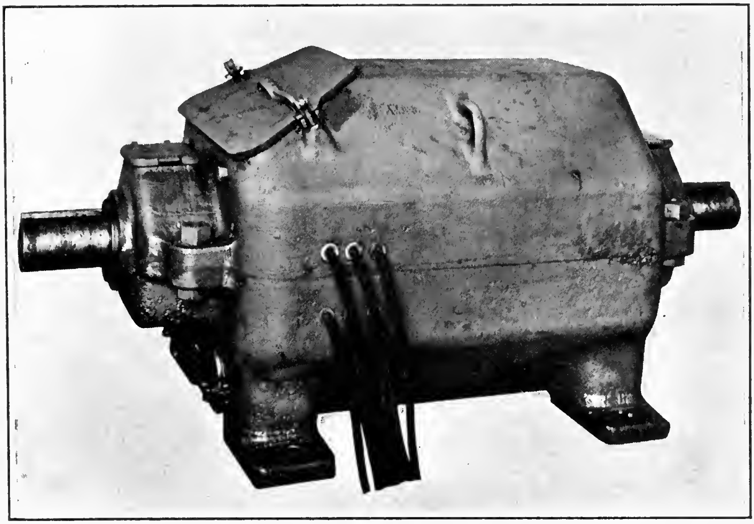


Fig. 87.—Mill type motor. G. E. Co.

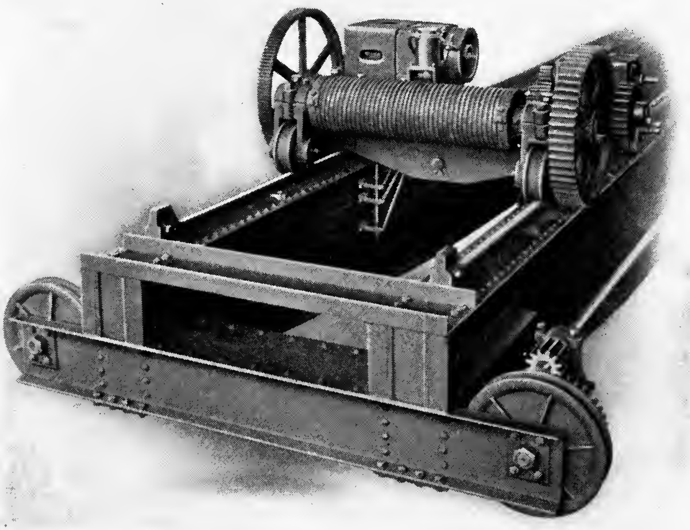


Fig. 88.—Motor-operated crane. Crocker-Wheeler Co.

the field it represents the power used to drive the machine at load speed doing no work whatsoever but to overcome the opposing forces of the machine itself. The total losses of the machine, then, when loaded to the extent named, are this stray power loss

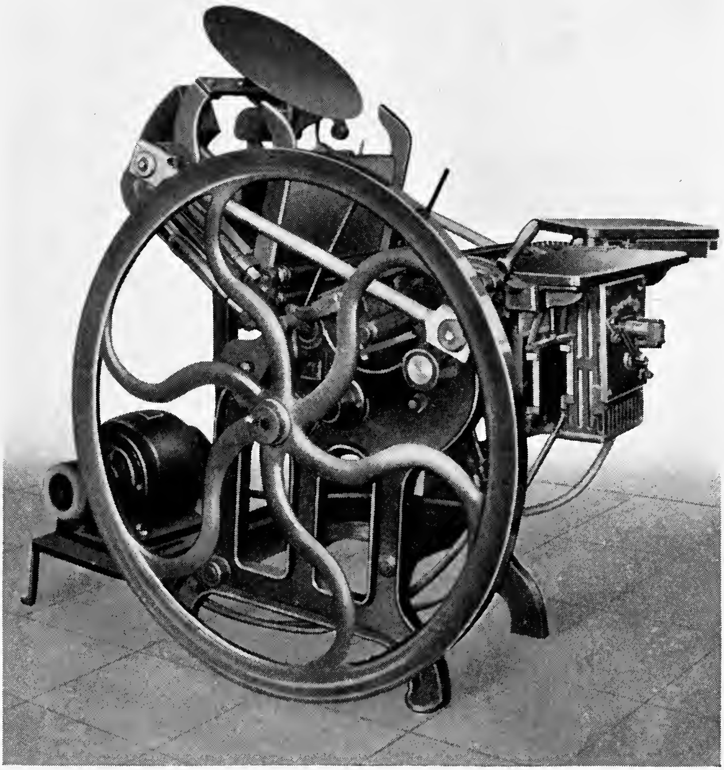


Fig. 89.—Motor-operated press.

plus the copper losses of field $I_f^2R_f$ and armature $I_a^2R_a$. These latter are, namely, I_fE_f, or $1 \times 115 = 115$ watts in the field and $30^2 \times 0.5 = 450$ watts in the armature. The total loss under this condition of load is therefore $115 + 450 + 148 = 713$ watts.

Now the input was I E $= 31 \times 115 = 3{,}565$ watts. The output must therefore be input minus losses, or $3{,}565 - 713 = 2{,}852$ watts, and the efficiency of the motor for this load and field excitation must be $\frac{2{,}852}{3{,}565} \times 100 = 80$ (per cent.).

The stray power losses determined in this way on a shunt motor are fairly constant throughout a considerable range of speeds and loads. The test may also be made on a series or a

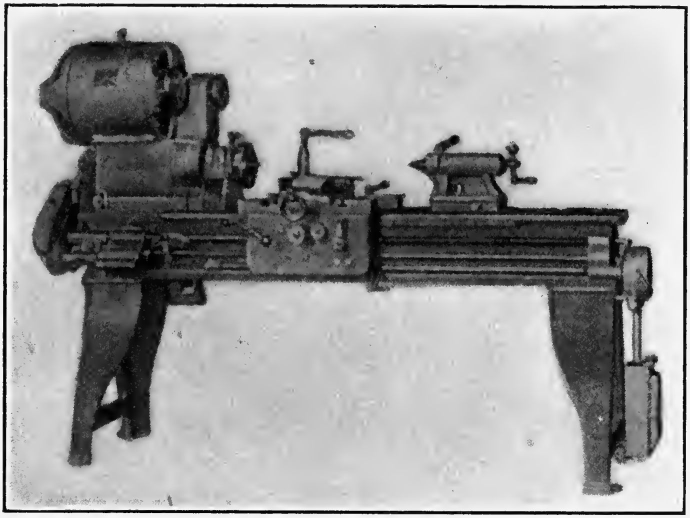


Fig. 90.—Motor-operated lathe. Reliance Electric & Engineering Co.

compound motor, but rheostats of large carrying capacity, such as banks of incandescent lamps or a water-barrel rheostat, must be used. In testing a shunt dynamo machine, however, this method is most convenient, since it draws but little power even for very large machines. The readings of voltage, field current, load current, and speed, must previously have been taken under conditions of actual operation. This applies equally to testing the generator and the motor.

The stray-power method of obtaining efficiency gives results a little too high, owing to the fact that all defects incident to full load current in the armature are lacking. The error is however slight, and the results are likely to be more accurate than might be determined by a clumsy or imperfect friction brake. In cases of too great discrepancy because of small load current, a machine may be tested by what is known as

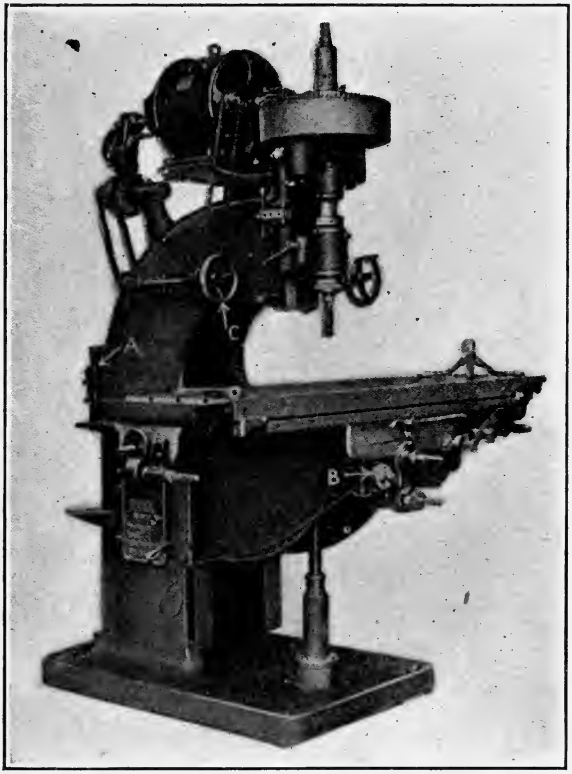


Fig. 91.—Motor-operated milling machine. Reliance Electric & Engineering Co.

the pumping-back test. In this there are two machines exactly alike coupled in series, one furnishing current to the other. Preserving the load current in this way through the armatures, the test proceeds similarly to the stray power test.

Figs. 87, 88, 89, 90 and 91 show a number of motor applications.

CHAPTER VI.

THE ALTERNATING CURRENT AND ITS MEASUREMENT.

(a) The A. C. Wave.

An alternating current is one which periodically reverses its direction of flow. The alternating currents of commerce are restricted to a certain number of reversals per second and approximate a particular ideal wave-shape, known as a sinusoidal curve. The following will make this clear:

The Sinusoidal Curve.—Consider the point P (Fig. 92) to be moving uniformly around the circumference of a circle, or along the path *a b c d a*. The projection of this motion on a vertical

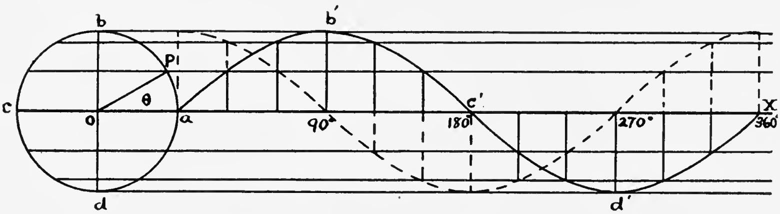


Fig. 92.—The sinusoidal curve.

diameter through *o* becomes the motion *o b d o*. This latter is known as simple harmonic motion, and the circle corresponding is called the circle of reference. As the radius-vector joining *o* and P sweeps around the circle, the angular displacement (denoted by θ) of P from *a* passes through all values from zero to 360°. The corresponding linear displacement from *o* of the projection of P on the vertical diameter is equal at any instant to the radius $(r) \times \sin\theta$, and is known as a harmonically varying quantity. If we draw a horizontal line *ax* divided to represent degrees, and from this up and down lay off the values of the corresponding linear displacements and join these points, we shall have a so-called sinusoidal curve, or curve of sines; viz., *a b′ c′ d′ x*. A curve of cosines would have the same shape, and would differ only in position, being 90° removed along the axis *ax*. $\cos\theta = \sin(\theta + 90)$. The dotted line represents the curve of cosines.

In order to explain why the shape of the alternating-current wave approximates to such a curve, it is necessary to show that the rate of change of a harmonically varying quantity, like the sine of the varying angle θ, is another harmonically varying quantity, such as the cos θ. This is expressed at once by the differential calcus as $\frac{d \sin\theta}{dt} = \cos\theta$. It can be observed also in the curves. The increase in the sine values is greatest at a and gradually becomes less and less till at b' variation is zero. This variation is expressed by the first quarter of the declining dotted curve, which crosses the axis at the 90° point. From b' to c' the sine value decreases, at first slowly and finally with greatest rapidity at c'. This rate of change is expressed by the second

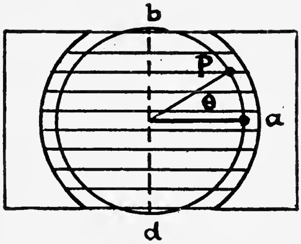


Fig. 93.

quarter of the dotted curve, whose greatest negative value is opposite c'. And so on.

Now let the horiontal lines in Fig. 93 represent a uniform magnetic field of a two-pole generator, and let P be the end view of an inductor moving around with the rotating armature. The rate of cutting these lines of force is the e. m. f. generated between the terminals of the inductor in absolute units (see p. 5, Chap. II).

From a comparison of this figure with Fig. 92, it will be seen that this rate of cutting is the *rate of change* of the sine of the varying angle θ. This is, as has been shown, a harmonically varying quantity. Hence the generated e. m. f., which in the absence of a commentator is the alternating-current e. m. f., can be represented by the curve of cosines,—or equally well, as to shape, by the curve of sines.

In fact, if *a* be the starting point as in Fig 93, we start with the maximum value of the e. m. f. generated. A more appropriate point from which to measure the angles of rotation would be where the e. m. f. is at its lowest value or zero, the lines of force being cut with least rapidity at this point. The curve would thus be removed 90 degrees in advance of the cosine curve, and would be the true sine curve. If the maximum value attained by the e. m. f. during the cycle be expressed by the radius, or by sin 90 degrees, then the value of e. m. f. at any moment of time t, dating from the passage of this origin by the coil would be the maximum value of the e. m. f. $\times$ sin θ. Denoting angular velocity by ω, any angle θ so measeared would be ωt.

$$\text{Hence } e_{\text{instan.}} = E_{\text{max}} \sin \omega t.$$

This is made more clear by the so-called clock diagram. In Fig. 94 let the length of radius vector o E represent E_{max}.

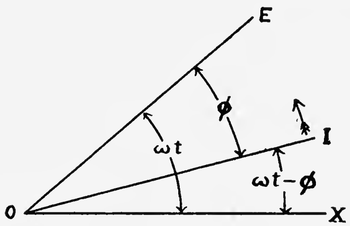


Fig. 94.—Clock diagram.

The current may be similarly expressed. Because, however, of self-induction, which is almost always present in alternating-current circuits, the current curve seldom coincides with the e. m. f. curve, as will be explained later, and

$$i_{\text{instan.}} = I_{\text{max}} \sin (\omega t - \Phi)$$

where Φ is the angle by which the current $i_{\text{instan.}}$ lags behind the voltage. A lagging current would be indicated by Fig. 95, the e. m. f. reaching its maximum value while the current is still on the increase. The angle Φ expresses the difference in phase between the two.

The number of cycles (∽) per second is known as the frequency. There are twice as many alternations as there are cycles. In a two-pole generator, there is one cycle per revolution. The

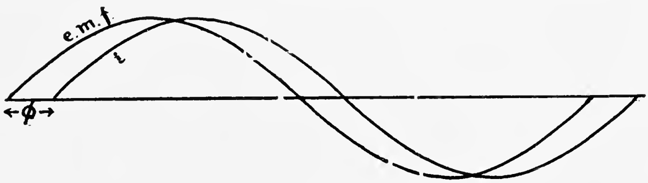


Fig. 95.—Lagging current.

frequency may therefore be found for any machine by multiplying revolutions per second by the number of pairs of field-poles.

(b) Mean, Average and Effective Values.

An alternating current of any definite number of amperes means a current that will have the same heating effect as that number of direct-current amperes. The hot-wire ammeter was one of the first forms of meter used for measuring alternating currents. The formula for the calories (H) developed by any current is

$$H = 0.24\ I^2Rt.$$

Thus it comes about that the effective amperes alternating-current are not the maximum amperes expressed by the peak of the wave, nor the mean between this maximum and zero, nor even the average value of all the instantaneous amperes of a complete cycle, but rather the square root of the average square of the instantaneous amperes.

In the direct-current ammeter with fixed permanent magnet and movable coil, the usual type, the pointer attached to the coil moves across a scale of even divisions. Such an instrument would not register alternating-current, except by a possible trembling motion of the pointer. In the alternating-current instrument, the magnet is replaced by a coil, the movable coil turning in the flux set up by this fixed coil. As the current alternates simultaneously in the two coils, the deflection is in one direction only. But this deflection is now necessarily proportional to the square of the current, and the scale divisions are uneven. The pointer does not oscillate, but because of the inertia of the moving element it takes up a definite position. In this instrument too, therefore, as well as in the hot-wire ammeter, the deflection is that caused by the average square of all the instantaneous current values of the complete cycle and the amperes marked on this scale are the square root of this mean or average square. Thus it is that this value rather than any other value comes to be regarded as the direct-current equivalent or the effective alternating-current amperes. The same is true of alternating-current volts.

Now the average value of the sines for a complete cycle of 360 degrees equals the average value of the cosines, and also

$$\text{Average } \sin^2 \omega t = \text{average } \cos^2 \omega t.$$

But $\sin^2 \omega t + \cos^2 \omega t = 1$ for all values of ωt.

Hence average $\sin^2 \omega t = \frac{1}{2}$, and $\sqrt{\text{average } \sin^2 \omega t} = 1/\sqrt{2}$.

Since $e_{\text{instan.}} = E_{\text{max}} \sin \omega t$,

$$\text{average } e^2_{\text{instan.}} = E^2_{\text{max}} \times \text{average } \sin^2 \omega t = \tfrac{1}{2} E^2_{\text{max}},$$

and $E_{\text{effective}} = \sqrt{\text{av. } e^2_{\text{instan.}}} = \dfrac{E_{\text{max}}}{\sqrt{2}} = 0.707\ E_{\text{max}}.$

The same may be deduced practically from the following table:

Angle	Sine	Sine squared
0	0.000	0.00
30	0.500	0.25
60	0.866	0.75
90	1.000	1.00
120	0.866	0.75
150	0.500	0.25
	6)3.732	6)3.00
	Average sin = 0.622	Av. $\sin^2 \omega t$ = 0.5
		$\sqrt{0.5}$ = 0.707

(c) Inductance or Self-Induction.

Because of the magnetic flux which surrounds a current-bearing wire, any change of current is accompanied by a change of flux. By Lenz's law, this change of flux due to change of current in the wire tends to set up an e. m. f. in a direction such as to oppose the change of current. Thus an electric current has a property very similar to the inertia of a moving mass. Like inertia, this is a property of the type, shape, and dimensions of the circuit and is independent of the current in it. A helix has more self-induction than a straight wire, and a helix containing an iron core has more than one without.

Inductance (L) is measured in henries. A henry is such an inductance as will cause a counter e. m. f. of one volt, when the current changes at the rate of one ampere per second. This c. e. m. f. is of the nature of an ohmic resistance, is measured in ohms and is called reactance. Since angular speed per second in the cycle is denoted by ω, or $2\pi f$, the value of this reactance is $2\pi f$ L, where f is the frequency.

The calculus expresses this as follows: The rate of change of current is $\frac{di}{dt}$; and since i (instantaneous) $= I_{max} \sin \omega t$, $\frac{di}{dt} = \omega I_{max} \cos \omega t = \omega I_{max} \sin (\omega t + 90°)$. This is counter e. m. f., and the effective value thereof is ωI_{eff} (or $2\pi f I_{eff}$) for each henry of the circuit and is 90 degrees removed from the current causing it. This being a c. e. m. f., the effective volts applied to overcome it and cause the current to flow must be 180 degrees removed in phase, or 90 degrees from the current on the opposite side. By clock diagram we have Fig. 96. IR is plotted in the direction of the current, they being both in the same phase. $2\pi f$LI is plotted 90 degrees in advance of the current, being the impressed volts which at this frequency f is required to force current I through the circuit of L henries inductance (that is, through $2\pi f$L ohms reactance). The resultant of these two e. m. f.'s gives the effective e. m. f. for this circuit, namely OE, whose direction shows the phase relation between current and voltage in this case.

All this can be made clear diagrammatically as follows: In Fig. 97 the current curve *abcd* changes most rapidly at *a* and *c*,

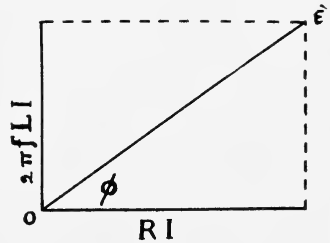


Fig. 96.

hence the c. e. m. f. curve is greatest at these two points, being negative where the current is positive, and is represented by the curve *efgh*. To oppose this c. e. m. f., the impressed volts which cause the current to flow must be represented by the cruve *kflh*, which precedes the current curve *abcd* by 90 degrees.

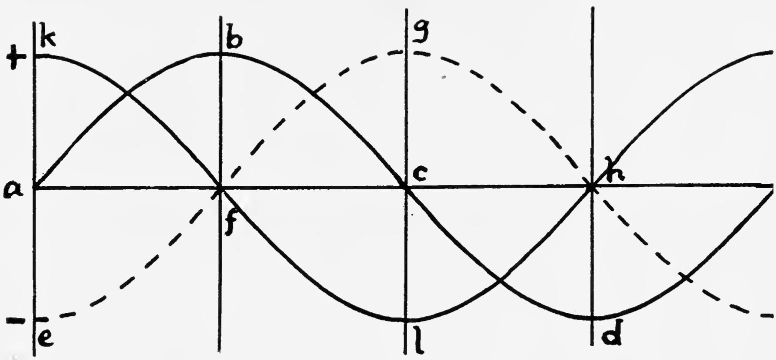


Fig. 97.

The vector sum of resistance and reactance is called impedance. The reciprocal of impedance is called admittance, similarly as the reciprocal of resistance in direct-current is called conductance. Impedance, like reactance is measured in ohms.

(d) Capacity in Circuit.

When an alternating e. m. f. is applied to the terminals of a condenser, the latter is charged and discharged in rapid succession, each plate receiving alternately a + and — charge. The effect is the same as if the alternating-current went through the condenser, which offers a resistance effect to the flow of current,—also a form of reactance. But whereas inductance causes a lagging current, a condenser, or capacity, in the circuit causes the current to precede or lead the e. m. f. in phase.

The calculus explains this as follows: If K is capacity in farads, E pressure in volts, and Q quantity of electricity in coulombs or ampere-seconds, then

$$Q = K\,E$$

It must be remembered that a farad is that capacity which will receive a charging current of one ampere when the e. m. f. is changing at the rate of one volt per second.

The condenser current i_k at each instant is proportional to the rate of change of pressure, or

$$i_k = K\,\frac{de}{dt}.$$

But $e_{instan.} = E_{max} \sin \omega t$,

and $\frac{de}{dt} = \omega\, E_{max} \cos \omega t$.

Hence $\frac{i_k}{\omega K} = E_{max} \cos \omega t = E_{max} \sin (\omega t + 90°) = e_k$ where e_k is the instantaneous pressure in phase with the condenser current. Hence the effective value of I_k divided by ωK (or by $2\pi f K$) is the value of the effective e. m. f. causing this current I_k and is 90° behind I in phase.

In Fig. 97 let *efgh* represent the e. m. f. wave. At *e* the e. m. f. is changing least rapidly, and so the current flowing into the condenser is least, giving *a* as the current point. At *f* the e. m. f. is changing most rapidly, hence current value is highest, or at *b*. From *f* to *g* the e. m. f. is still increasing, but less rapidly, hence the current, although still positive, decreases, and so on.

In the vector diagram, $\frac{I}{2\pi f K}$ would be plotted therefore 180 degrees removed from $2\pi f LI$, or in the opposite direction. Hence in the vector diagram Fig. 96, it should be laid off downward. The complete effect of resistance, inductance and capacity in a circuit would be represented vectorially as in Fig. 98.

$\frac{1}{2\pi f K}$, the reactance due to capacity and $2\pi f L$, the reactance due to self-induction, must be added algebraically. In this case $2\pi f L$ is the larger. The vector sum of these reactances

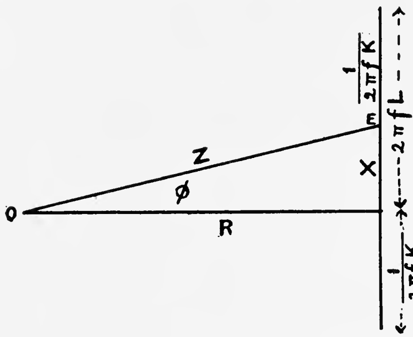


Fig. 98.

(X) and the resistance (R) of the circuit is represented by the hypothenuse of the triangle and is the impedance (Z) of the circuit. Hence $Z = \sqrt{R^2 + \left(2\pi f L - \frac{1}{2\pi f K}\right)^2}$.

It is seldom possible to have resistance in an alternating-current circuit without inductance and vice-versa. Let there be, however, an ideal circuit composed of pure resistance, pure inductance and pure capacity, connected in series, and let the drop over each part of the circuit be obtained separately by a voltmeter, the current in the circuit being maintained constant, then the vector-sum of the resistance drop and reactance drop will be the impedance crop, or difference of potential across the circuit as in Fig. 99.

(e) Power in A. C. Circuits.

From the fact that the voltage and current are seldom in phase in alternating-current circuits, it is at once apparent that the volt amperes is usually larger than the watts. The ratio of these two quantities is known as the power factor, and is the cosine of the angle ϕ on the vector diagrams Figs. 96 and 99.

Treating Fig. 99 as a clock diagram, counter-clockwise rotation being regarded as positive, let the volts be ploted in the direction OE. The current will then be in the direction OI, lagging behind the volts by the angle ϕ, due to impedance. This direction will correspond to that of the resistance drop, since

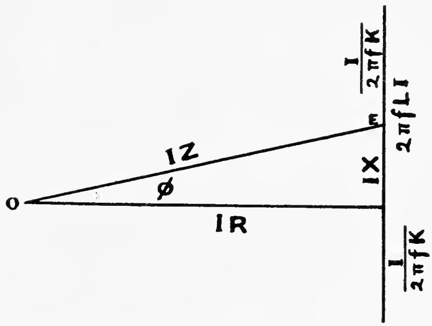


Fig. 99.

pure resistance causes no change of phase. The component of OE in the direction OI is then OE cos ϕ and

$$\frac{\text{watts}}{\text{volts} \times \text{amps.}} = \cos\phi = \text{power factor.}$$

We thus see that the impressed volts in an alternating-current circuit are made up of two components, one overcoming the resistance and the other the reactance. It is sometimes of advantage to interchange OE and OI on the diagram, considering clockwise rotation as positive. Then one may speak of two components of current, the power component, which is in the direction of IR, and the wattless component at right angles to it.

The formula may be deduced mathematically, as follows:

$$e = E \sin \omega t$$
$$i = I \sin (\omega t - \phi)$$
$$ei = EI \sin \omega t \sin (\omega t - \phi)$$
$$\sin (\omega t - \phi) = \sin \omega t \cos \phi - \cos \omega t \sin \phi$$
$$ei = EI \sin^2 \omega t \cos \phi - EI \cos \omega t \sin \omega t \sin \phi.$$

Average $ei = EI \cos \phi \text{ av. } \sin^2 \omega t - EI \sin \phi \text{ av. } (\cos \omega t \sin \omega t)$.

But av. $\sin^2 \omega t = \frac{1}{2}$ and av. $\sin \omega t \cos \omega t = 0$

hence, $\text{av. } ei = \text{watts} = \frac{EI}{2} \cos \phi$

which is the same as $\frac{E}{\sqrt{2}} \frac{I}{\sqrt{2}} \cos \phi$ or $E_{eff.} I_{eff.} \cos \phi$.

This $\cos \phi$ is again the power factor, or that quantity by which the effective volt amperes must be multiplied to obtain effective watts.

Since watts is a rate of working, it may be represented by an area formed by the products of volts by amperes at each successive instant of time. Those areas which lie above the line, being due to the product of quantities of like sign, are positive and denote power furnished by the circuit. Those which lie below the line are negative and represent power withdrawn by or used up in the circuit. See Figs. 100, 101 and 102.

(f) Alternating Current Measuring Instruments.

It will be remembered that the most common type of direct-current ammeter or voltmeter consists essentially of a movable coil operating in the field created by a permanent magnet. Obviously with an alternating current in the coil no steady position of the needle could be maintained. In fact, unless the alternations were very slow or the movable parts very free from inertia, the needle would only tremble slightly back and forth or would refuse to move at all. This difficulty is avoided by eliminating iron from the instrument and allowing a stationary coil bearing the current to furnish an alternating, that is, continually reversing, magnetic field. The movable coil is supplied from the same source and the current in it alternates at the same rate and

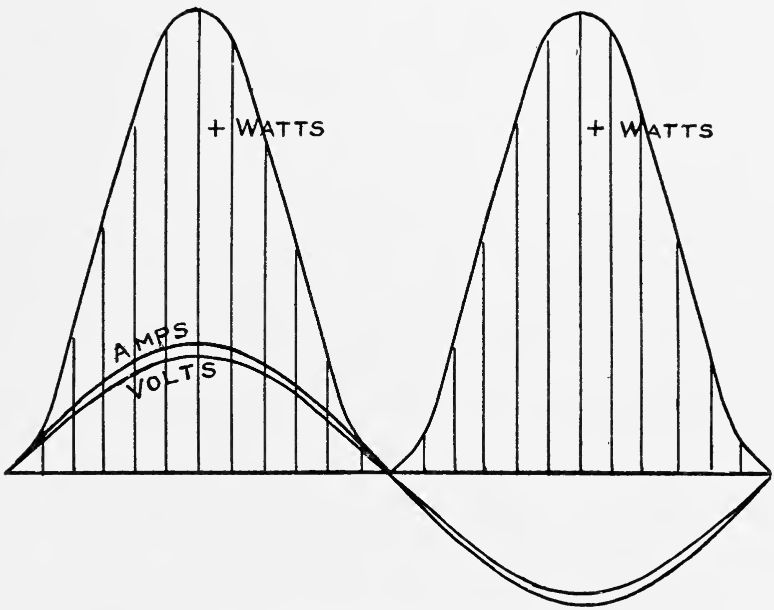


Fig. 100.—Power in a non-inductive circuit.

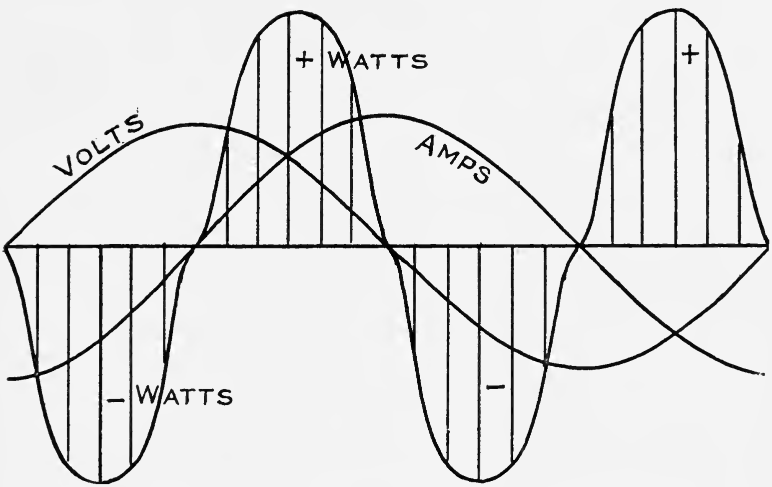


Fig. 101.—Current lagging 90°. Algebraic sum = zero. So-called wattless current.

in synchronism with the magnetic field. This creates a unidirectional torque on the movable coil.

In the case of the wattmeter as well there are two coils, one movable and the other stationary. The one, however, is in series with the circuit, is of low resistance, and bears the current (amperes). The other is of high resistance and voltmeter-like is tapped across the circuit. The combined effect, therefore, is at each instant proportioned to the product of the volts by the

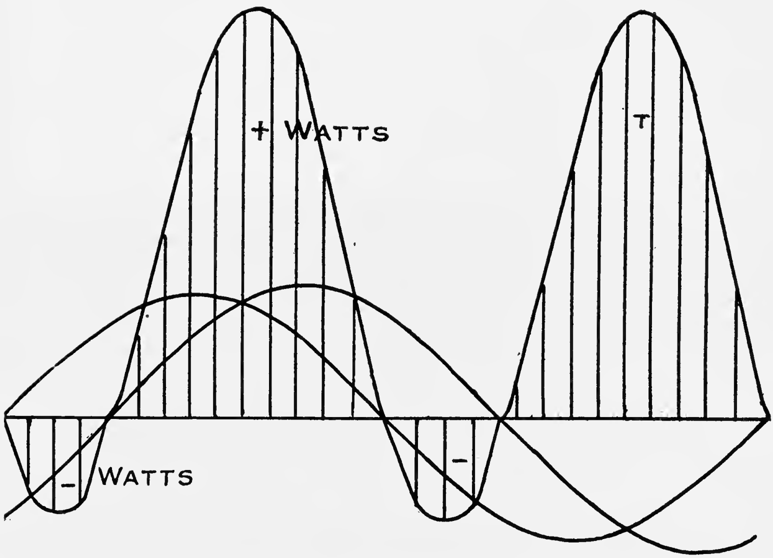


Fig. 102.—Usual lagging current. Power-factor less than 1.

amperes. With such instruments there is necessarily a power-factor of the wattmeter itself which varies with the character of the circuit. It is, however, usually small.

An instrument having an extremely light movable part has in recent years been perfected, known as the oscillograph. In this instrument, by means of a mirror oscillating with the current, a photographic record may be taken of the current curve, and simultaneously on the same film by means of other mirrors, each on its own motive device, the e. m. f. wave or any other desired may be photographed. Fig. 103 is a reproduction of such a photograph.

(g) Voltage in A. C. Circuits in Series.

It is possible to have a non-inductive circuit, that is a pure resistance, but the reverse, a pure inductance without resist-

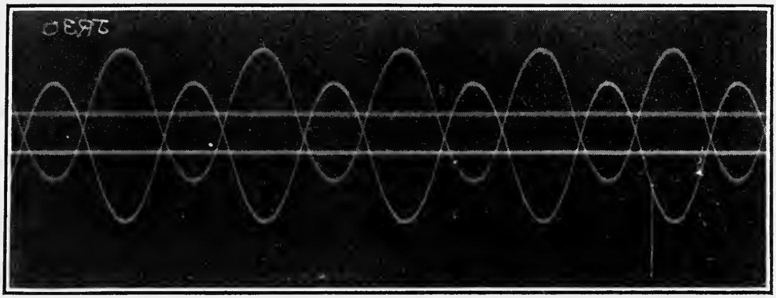


Fig. 103.—Sinusoidal curves. Courtesy of G. E. Co.

ance is of course impossible. The theoretical diagrams, therefore, thus far given have to be modified in practice. Let the circuit represented in Fig. 104 consist in part of a pure resistance and in part of an impure inductive circuit or an imped-

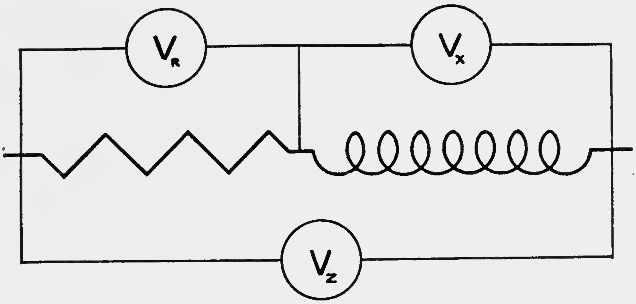


Fig. 104.—Series circuit.

ance, and let the voltmeters show the drops across the different parts of the circuit when current is flowing. If then the three voltmeter readings be laid off in vector diagram, Fig. 105, it will be found that the angle at *c* is not a right angle.

The distance of *cd* ought theoretically to represent the resistance drop of the inductive circuit and is indeed of the nature of a resistance drop, but is considerably greater when obtained

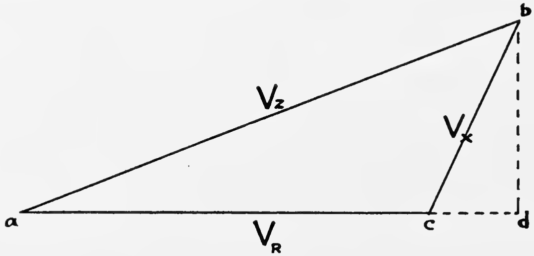


Fig. 105.

by alternating-current than by direct-current, owing to hysteresis and eddy currents in the inductive apparatus.

(h) Current in A. C. Circuits in Parallel.

When alternating circuits are arranged parallel, the total voltage must of course be the same as that over each part.

When alternating-current circuits are in parallel the total current is the geometric sum of the current in the branches. Fig.

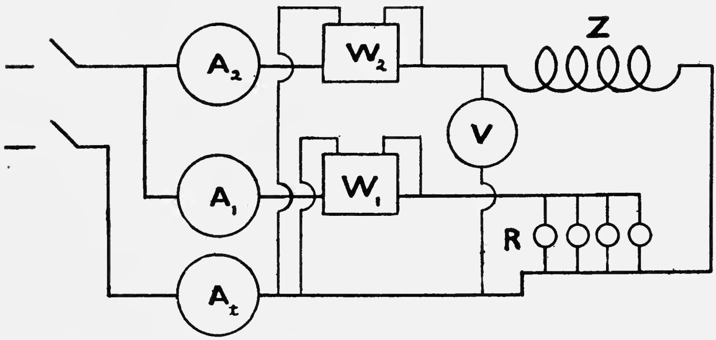


Fig. 106.—Parallel circuit.

106 represents two such circuits, the one containing pure resistance R, the other an impedance Z.

Let the horizontal line in Fig. 107 represent the current I_1, shown by ammeter A_1, the current and e. m. f. of this circuit being in phase. The phase angle between I_1 and I_2 can be found

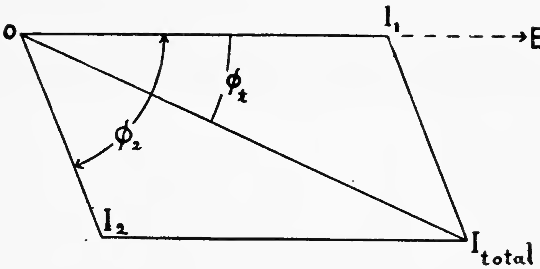


Fig. 107.

by the formula $\frac{W2}{EI_2} = \cos \phi$. Complete the parallelogram and the diagonal will be the value of I_{total} read by ammeter A_t.

(i) Two-Phase and Three-Phase.

It was seen on page 14 that by means of rings tapped on to the armature winding of a direct-current generator at points separated by the polar span, an alternating e. m. f. could be ob-

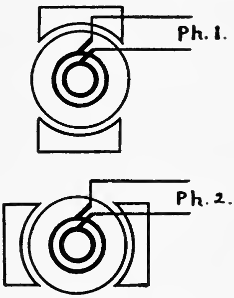


Fig. 108.—Two phase.

tained. This would be single phase alternating-current. If now two more rings were similarly tapped onto the armature winding at points in quadrature to these, or at a phase difference of 90 degrees, the two-phase current or e. m. f. lead off on the four wires would be as represented in Fig. 109.

The same result could be obtained by means of two single phase two-pole generators whose shafts are coupled in a position represented by Fig. 108. The relative position of the poles in

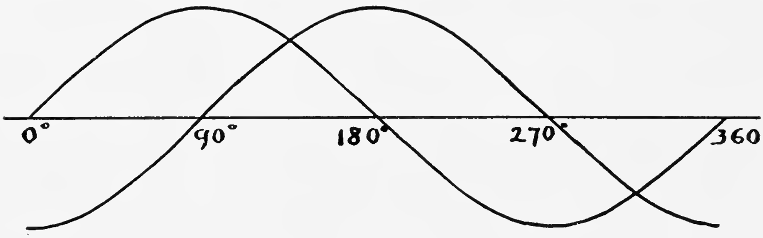


Fig. 109.—Two phase.

quadrature is to indicate the relation in space of the two e. m. f. curves. The clock diagram corresponding to Fig. 109 as to voltage and with a lagging current is Fig. 110. When the currents in the two phases are equal and ϕ is the same for each, the system is said to be balanced. In such a case as this, three wires may be used instead of four. The current in the joint or middle wire is then 1.41 times that in either outside wire, that being

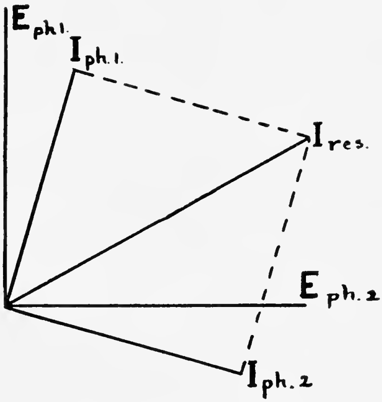


Fig. 110.—Two-phase clack diagram.

the ratio of either side of the square to the diagonal. Hence in a two-phase alternator the current capacity of the armature winding is 41 per cent. more than if the same machine were wound for one phase, heating and energy losses being the same in the two cases.

If the direct-current armature and commutator above referred

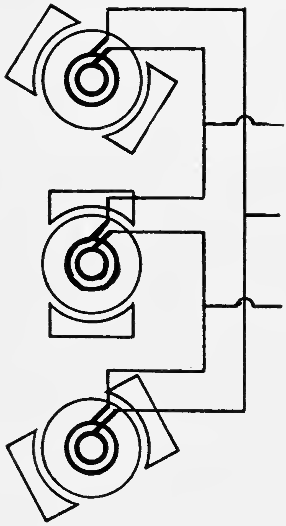


Fig. 111.—Three-phase Δ.

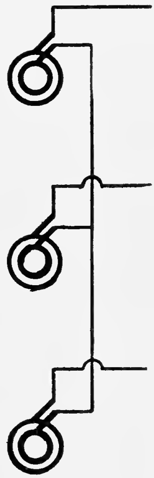


Fig. 112.—Three-phase Y.

to were tapped at three points 120° apart, a three-phase current and voltage could be obtained. The figures for three-phase corresponding to Fig. 108 and Fig. 109 are Figs. 111, 112 and 113. In Fig. 111 represents what is known as the delta (Δ) method of

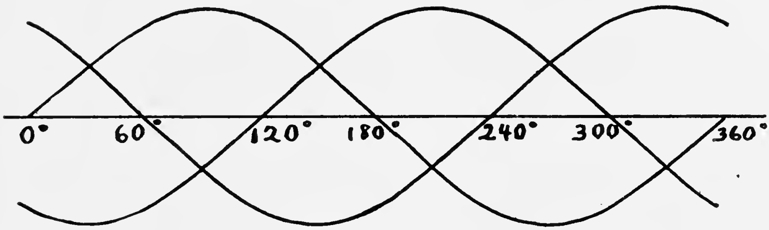


Fig. 113.—Three-phase.

connecting and Fig. 112 represents what is known as the star or Y method of connecting the three distinct armature coils or windings, as in Figs. 114 and 115.

In the Δ system the voltage between any two line wires is that generated in the armature coil from which they spring. The current in each line wire, however, is the vector sum of the

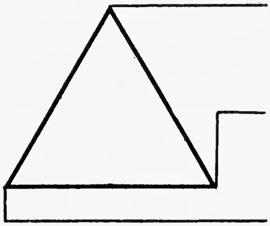


Fig. 114.

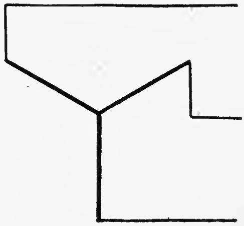


Fig. 115.

currents in the adjacent armature coils. If the system is a balanced one, the line current in each wire will be $\sqrt{3}$ times the current in one armature winding, as appears from Fig. 116.

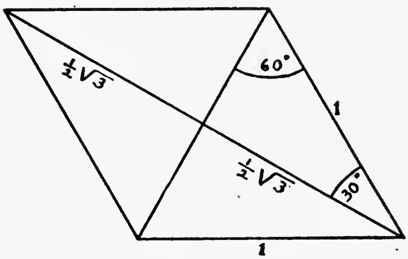


Fig. 116.—Δ-current.

In the Y system, the current in any line wire is the same as that in the armature winding from which it leads. The voltage, on the other hand, between any two line wires is $\sqrt{3}$ times the

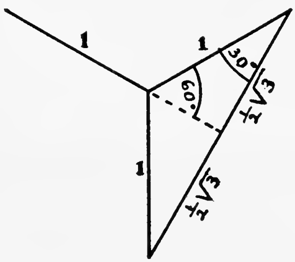


Fig. 117.—Y-voltage.

voltage generated in one armature winding, as appears from Fig. 117.

CHAPTER VIII.

ALTERNATING CURRENT MACHINERY.

(a) A. C. Generators.

In polyphase current alternators, except in very small machines, the continuous winding corresponding to the tapped direct-current armature above referred to is not used. Machines for the gen-

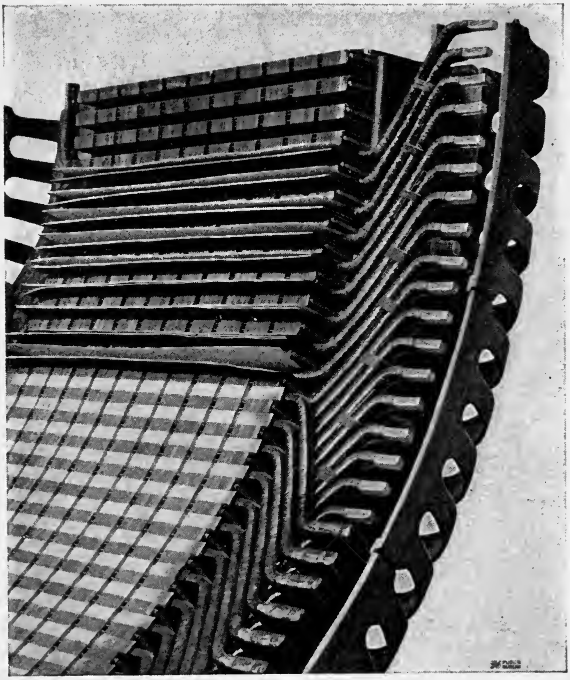


Fig. 118.—G. E. Co. alternator armature-(stator)winding.

eration of the commercial alternating-current employ instead separate windings as suggested by Figs. 108, 111 and 112. It is furthermore usual to place these armature windings on the inner side of the stationary frame of the machine and to employ a rotating field. The small exciting direct-current is conveyed to this field by means of rings. The armature current then is drawn direct from the windings, without any brush contacts. See Figs. 118, 119, 120 and 121.

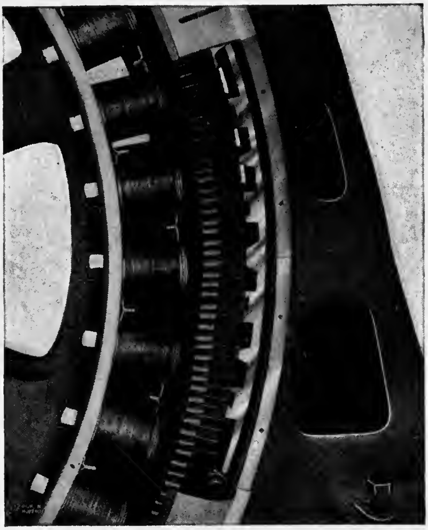


Fig. 119.—G. E. Co. alternator, showing core laminations, frame and field poles.

The exciting current for the fields of large generators is usually derived from a separate small generator. In power plants one such field generator may be used to supply several machines. For isolated alternating-current generators the field exciter is sometimes direct coupled to the shaft of the alternator. In smaller machines with stationary field, a commutator may be provided for field excitation.

(b) Voltage Regulation of the Alternator.

Alternators, like direct-current generators, have the magnetization curve similarly determined, and also the external characteristic curve. The latter depends greatly on the character of the load, whether it be inductive or non-inductive.

The voltage regulation of an alternator, as also of a direct-current generator, is technically expressed by the equation

$$\text{regulation} = \frac{\text{voltage at no load} - \text{full load volts}}{\text{full load volts}},$$

and gives the per cent. rise in voltage resulting from a sudden reduction of the load to zero.

In very large machines, such as those in central power stations,

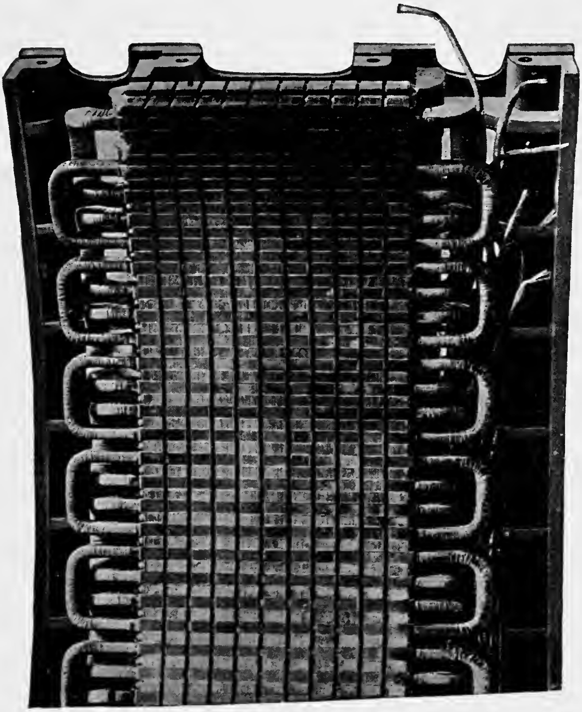


Fig. 120.—G. E. Co. three-phase stator-winding of alternator.

this ratio is difficult to determine by direct readings, it being usually impossible to load such machines to their full capacity, because of the difficulty in supplying resistance suitable for receiving the full-load current. The regulation has therefore to be arrived at by an indirect experimental test. The problem will be made clear by the following consideration.

The armature circuit of the alternator, like any other circuit, contains resistance and inductance. The drop over each of these,

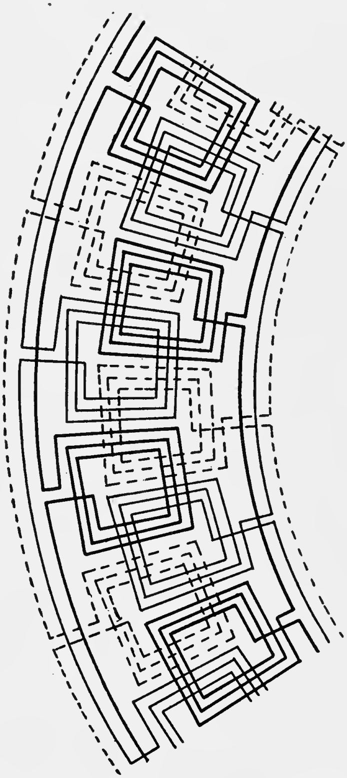


Fig. 121.—Portion of stationary-armature winding of a three-phase alternator.

under condition of any given load, is represented in Fig. 122 by IR_a and IX_a respectively, the load being a non-inductive one.

Figs 123 and 124 show two different cases with inductive load. The first case is such that the impedance of the armature circuit increases the phase angle between generated volts and current. In the second case the armature impedance decreases this angle.

R_a can be determined by the methods used in direct-current generators. One method of arriving at the reactance of the armature circuit is the following: With the field circuit of the alternator open, the armature terminals are short-circuited through an ammeter and the field is cautiously excited until the ammeter reads full-load current. The voltage now generated is

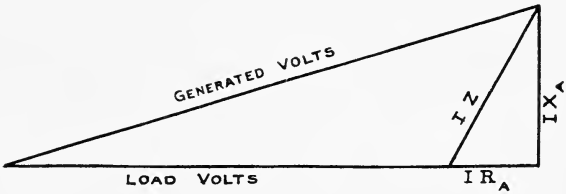


Fig. 122.—Voltage regulation with resistance load.

all used up in sending this current through the armature circuit. By opening the short-circuiting switch and keeping the speed and field excitation constant, the voltage generated under these conditions may be read on a voltmeter.

This voltage includes the drop at full load due to armature

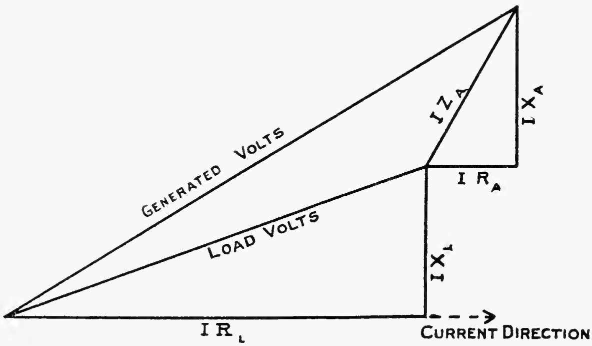


Fig. 123.—Voltage regulation with inductive load.

resistance and reactance and also includes the effect of armature reaction on the field flux. Because the first of these three factors is very small and because the third has an effect on the power factor of the machine similar to reactance, the voltage thus obtained is called the drop due to synchronous reactance and may be considered the IX_a of the preceding diagrams.

The method here given, known as the electro-motive-force method of determining voltage regulation, is not an accurate one, owing to the fact that the field being necessarily weak, the armature reaction is excessive. In a polyphase machine, however, the result is likely to be nearer the true value than in a single-phase

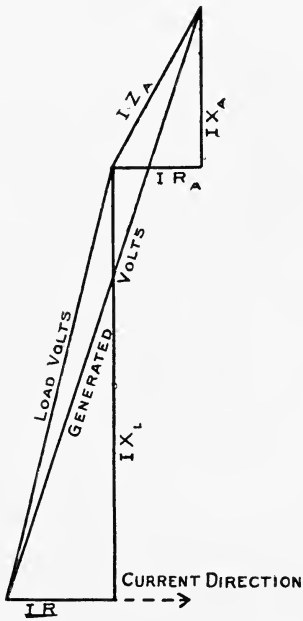


Fig. 124.

generator. For a more elaborate treatise on this subject than is allowed by the scope of this book the reader is referred to Thomälen's "Electrical Engineering."

(c) The Inductor Alternator.

The inductor alternator differs from all other types of electric generator in that the windings, both field and armature, are stationary, and the iron alone revolves. The armature is wound on the frame, as in other alternators, and the field cores constitute the rotating part. This machine, therefore, is very rugged in construction. Its alternating-current wave is almost a pure sine curve, and in power-factor and efficiency it compares favorably with the ordinary type of alternating-current generator. It

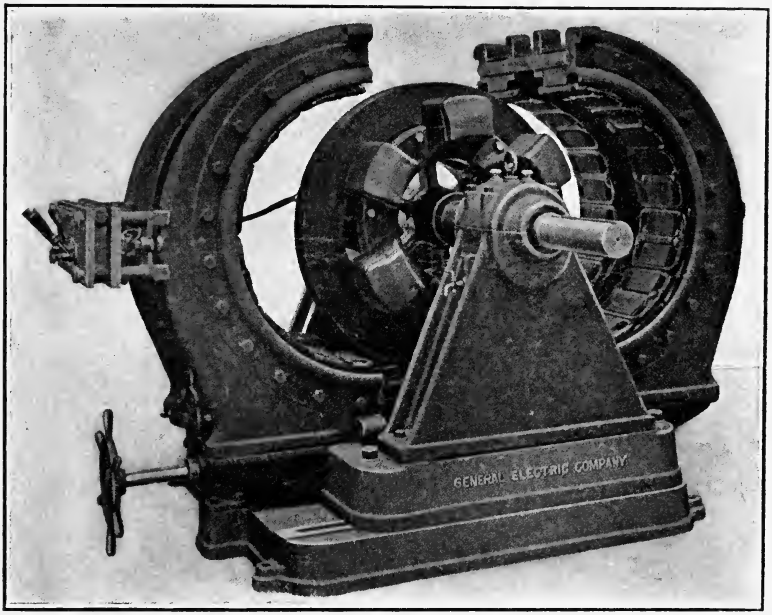


Fig. 125.—Inductor alternator with vertically split armature.

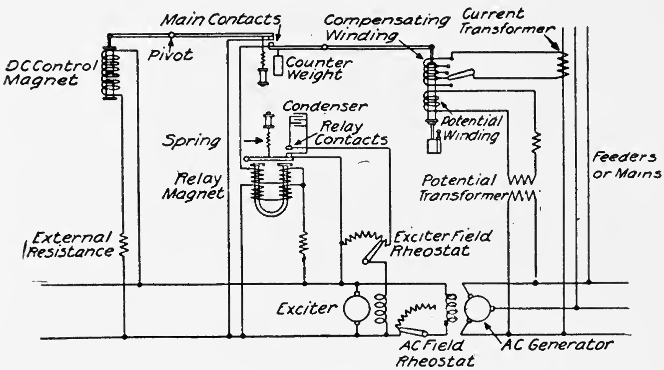
is especially well adapted for a widely varying load at low voltage, as is demanded for electric welding, etc. See Fig. 125.

(d) The Compounding of Alternators.

A series winding is sometimes added to the field of an alternator for the purpose of maintaining a constant or an increasing voltage with increase of load. Formerly, one method largely employed consisted in shunting off a portion of the main armature current and passing it through a rectifier. This was simply a commutator having as many segments as there were field poles and mounted on the shaft of the machine. The brushes took off a pulsating current which supplied the series field and varied with the main armature current.

The modern method is to vary automatically the voltage impressed on the field of the alternator by its direct-current exciter. The automatic device controlling this operation is termed the Tirrell regulator, and the connections are shown in Fig. 126. Briefly its operation is as follows:

When the exciter voltage falls too low, the direct-current control-magnet on the left is weakened. When the alternating-current generator voltage falls, the solenoid magnet to the right is



ELEMENTARY DIAGRAM OF TA. FORM A REGULATOR

Fig. 126. G. E. Co.

weakened. Either or both of these operations close the main contacts, according to the adjustments of the counterweight. This neutralizes the relay magnet, closing the relay contacts, and so short-circuits the exciter field rheostat and raises the exciter voltage. This increase of voltage re-opens the main contacts. "The operation is continued at a high rate of vibration, due to the sensitiveness of the control-magnets, and maintains not constant but a steady exciter voltage." A compensating winding on the alternating-current control magnet is connected to a current transformer in the main line and causes an increase of voltage with increase of load, thus taking care of the line-drop.

(e) The Synchronous Motor.

In treating of the direct-current motor, it was shown that rotation is produced by the action of the field flux on the current-bearing armature conductors. In order that this thrust may produce continuous rotation, a commutator is required to change the direction of the current in each conductor twice in each cycle, that is, to produce in the conductor an alternating current whose direction changes simultaneously with the passage of the conductor from pole to pole. If therefore the field continues to be

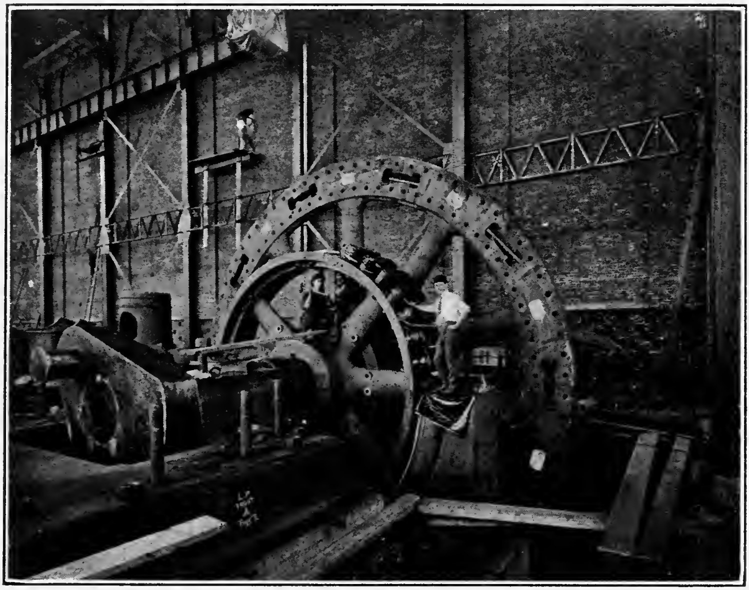


Fig. 127.—A large alternator in process of construction.

excited with a direct current, and the commutator of such a motor be replaced by rings, and an alternating current of the proper frequency be fed into the rotating armature, the motor will continue to run at a constant speed in synchronism with the alternating current. To operate such a motor on the alternating current, it must obviously first be brought up to speed and also into the correct phase relation with the given current. Should it be slowed down so as to fall out of step with the given alternating current source of supply, it will immediately stop.

Fig. 128 shows a device used in starting such motars. It con-

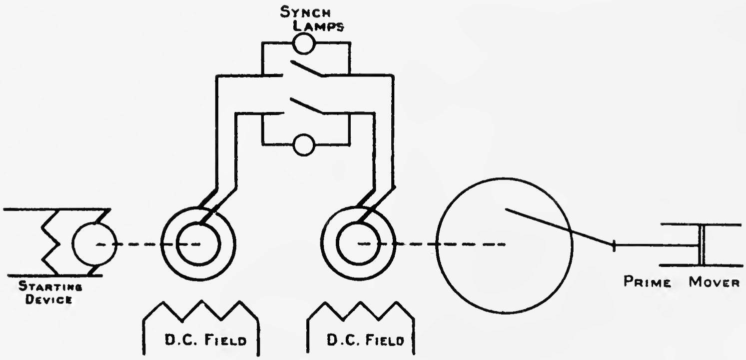
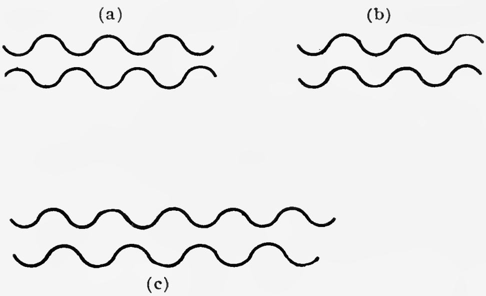


Fig. 128.—Connections for syhchronous motor.

sists of lamps bridged across the switch between the motor and its generator. These lamps prevent the flow of an excessive current and serve to indicate the relative frequency and the phase



relation of the two machines. Let the generator be driven by its engine or other prime mover at a definite and constant speed, and let the motor be started by some device, say a small direct-current motor, whose speed can be regulated. Each machine will now be generating an alternating-current e. m. f. If these e. m. f.'s are opposed to each other in direction through the lamps, it is evident that no current will flow between the machines, and the lamps will be dark. The e. m. f.'s are opposed to each other in phase (see (a)). If on the other hand, the e. m. f.'s are so related as to send the current in the same direction through the lamps, they correspond in phase as regards this circuit (see (b)), and the result will be an increased voltage across the lamps causing them to glow. If either machine has a different frequency from the other, there will result alternate reinforcement and interference, and the lamps will flicker as in (c).

The method is to regulate the speed of the motor so that the flickering becomes very slow, and then to close the switch in the middle of a dark period. This may be varied by having the lamps cross-connected. The switch should then be closed in the

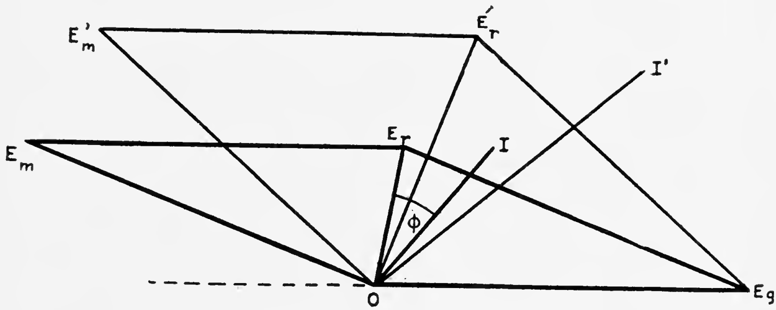


Fig. 129.—Vectordiagram of synchronous motor.

middle of a bright period. If now the starting device be mechanically disconnected or its driving circuit opened, the synchronous motor will continue to operate on the alternating-current fed into it. This will be clearer if the e. m. f. generated by the motor in starting be considered its natural counter e. m. f., as in the direct-current motor, which is opposed in direction to the impressed e. m. f. of the driving circuit.

It will be remembered that the direct-current motor draws current in proportion to the load put upon it, because of the retardation in speed caused by the load. In the synchronous motor, being a constant speed machine, this cannot be the case. The operation of this motor is to be explained by the vector diagram, Fig. 129.

Let the e. m. f. of the generator E_g be considered positive and so plotted toward the right from the origin O. The counter e. m. f the motor E_m will then extend toward the left. But although at the instant of connection to the circuit the motor may be in direct opposition to the generator, when its starting device is cut off, it instantly falls somewhat behind the 180° phase; that is, its vector will take the direction OE_m. These e. m. f.'s are in a series circuit. Following the usual method of combining e. m. f.'s in series by completing the parallelogram, we have the resultant e. m. f. OE_r, which sends the driving current through the motor armature. Because of the impedance of the motor circuit, this is a lagging current, or OI, the $\cos\Phi$ depending solely on the character of the motor circuit and being therefore a constant.

Now suppose the load on the motor to be increased. This

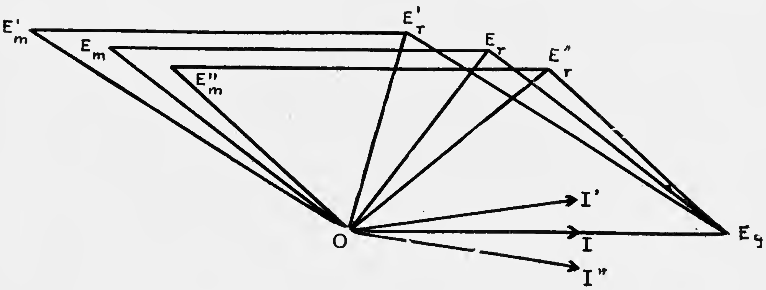


Fig. 130.—Vector diagram of synchronous motor.

tends to cause a slackening of speed, but what really happens is that E_m swings into a new relation with E_g, namely E_m', giving a new resultant E_r', and current I′. The impedance of the circuit being essentially constant, I increases with the increase in E_r.

It will be remembered that the speed of a D. C. shunt motor may be increased by resistance in the field circuit. A change in the field current of the synchronous motor serves only to shift the phase relation between E_g and E_m. In Fig. 130 the vectors OE_g and OI correspond in direction, and the power factor of the driving current is unity. Should E_m be increased, by an increase in the motor field current, to E_m', then E_r and I would have new positions, namely E_r', and I'. Likewise should E_m be decreased to E_m'', then E_r and I would become E_r'' and I''. The lower values of E_m therefore cause the current from the generator to be a lagging current and the higher values of E_m cause the synchronous motor to have the effect of a capacity, giving the generated current a position of lead.

For any given power input into the motor, there is one value of motor field at which the driving current is a minimum, a change either way causing an increase in the current for the same amount of power delivered to the motor. This gives rise to the so-called V curves plotted between motor current and motor e. m. f.

A synchronous motor with over-excited field may be used to improve the power factor of a transmission line.

An inspection of Fig. 129 will make it evident that the synchronous motor is limited in the load it can carry without pulling out of step. E_m can shift phase with respect to E_g until the angle between E_m and motor current I is 90°. This means a current of zero power factor, and the motor will stop when this angular relation is reached. The stopping of the synchronous motor is sudden, when it has pulled out of phase. The actual operative range of the synchronous motor is over a smaller angle than that indicated by this 90° limit, because of internal losses in the machine. The stopping of the motor under these conditions is the same as would happen in a direct-current machine, if commutation were to occur not on an axis at right angles to the field flux but 90° removed from this point.

(f) The Operation of A. C. Generators in Parallel.

Instead of generator and synchronous motor, consider the two machines just under discussion to be two alternating-current generators. Let one generator be furnishing current to a circuit. The other generator can be brought up to speed and voltage, synchronized and connected to the bus bars in the same manner as the synchronous motor. When once so running and connected, two alternators tend to remain in step. For let one of them be supposed to drop behind, it immediately becomes a synchronous motor, the resultant e. m. f., E_r of Fig. 129, sending a current through its armature. This relieves the load on its driving engine and tends at the same time to retard the other machine, so that the two swing again into step. This very action, however, has proved to be a source of great trouble when the governors of the engines are of quick action. For in that case it is found that the heavily loaded machine is immediately supplied with more power, the driven one with less, which interferes with their natural tendency to fall again into step. Heavy fly-wheels also interfere with this tendency to remain in synchronism by carrying the retarded or aided machine beyond its proper position and so leading to the phenomenon known as "hunting."

It will be recalled that when direct-current generators are operated in parallel, the distribution of the load between the two machines is regulated by their field rheostats, controlling their relative e. m. f's. This is not the case with alternators. An increase of voltage of either generator gives rise to a shift in the phase relation of the two machines and a useless cross-current between them. There is therefore one position of the field rheostat for each alternator operating in parallel with others such that the sum of all the currents shall just equal the total output of the station. A change in either direction from this position indicates an uneconomical adjustment and a loss of power.

The means of controlling the output of the various alternators in parallel connection is to be sought therefore in the power supplied to the prime movers, as, for instance, the steam supplied to the engines. By regulating this, the load on the various generators can be controlled.

For synchronizing generators in power stations, preparatory to throwing a machine into service, a device with a hand and dial known as a synchroscope is generally employed in place of the less reliable lamps. The direction of rotation of the hand indicates whether the machine to be connected is running too fast or too slow. A stationary hand indicates perfect synchronism and a hand stationary in a vertical position indicates perfect synchronism and equality of phase. See Fig. 131.

As regards the motive power of alternating-current generators

Fig. 131.—Synchronism indicator. G. E. Co.

operating in parallel, reciprocating steam engines are still found in many large plants. But because of the irregularities in the period of rotation of any reciprocating engine due to the very

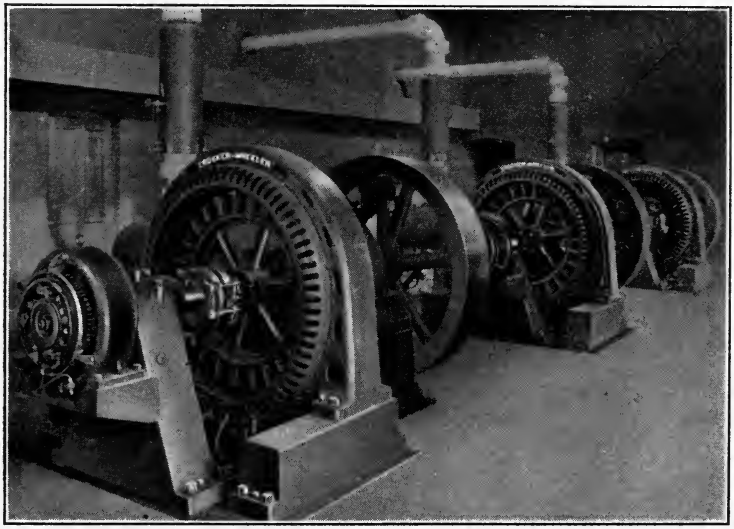


Fig. 132.—Crocker-Wheeler Co. a.c. generators driven by reciprocating steam engines.

nature of its construction, turbines, both steam and water, seem

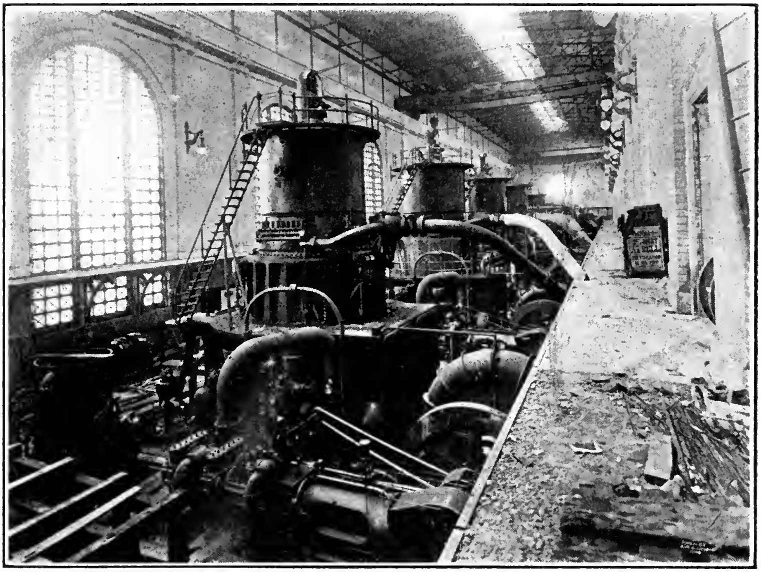


Fig. 133.—G. E. Co. 8,000 k.w. a.c. generators with vertical shaft operated by Curtis steam turbines.

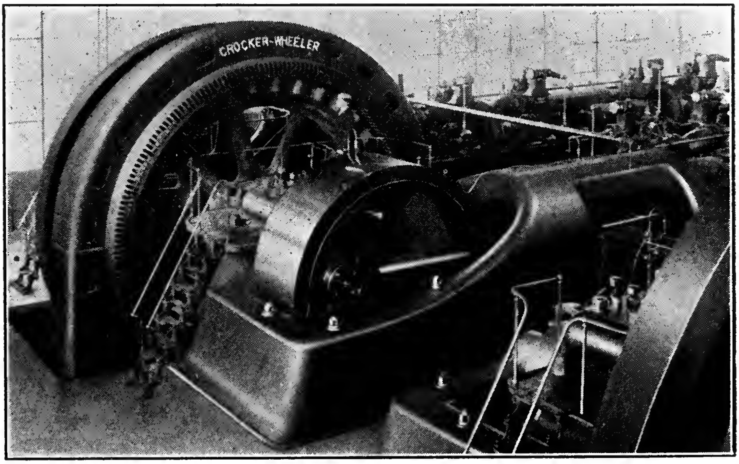


Fig. 134.—Crocker-Wheeler Co. 4,000 k.v.a. generators operated by gas engines.

now to be preferred as prime-movers for alternators. Especially water-power drive has been rendered very perfect to-day by the invention of an oil-pressure governor. The oil is kept under pressure by a pump, either controlled or directly operated by the turbines. A change in speed of any generator and turbine results in a change of oil-pressure. By a system of pistons and com-

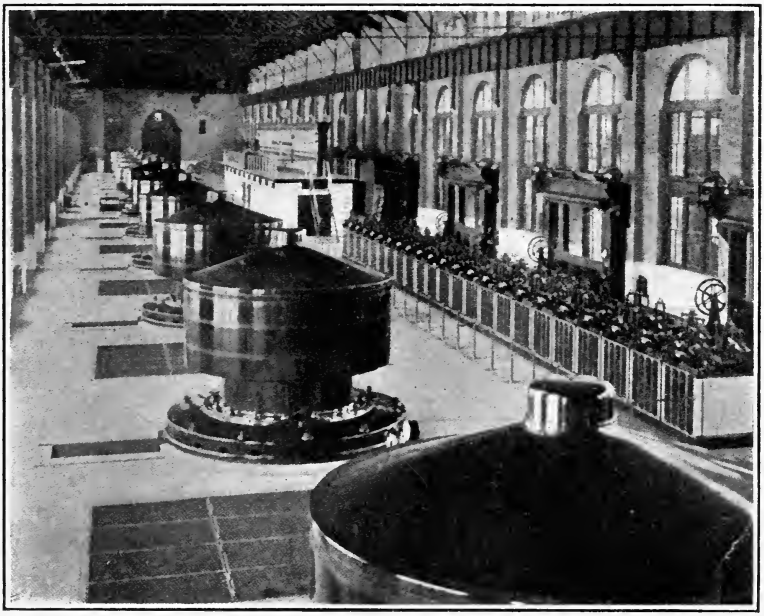


Fig. 135.—4,000 k.w., 2,200-volt generators at Niagara Falls. G. E. Co.

pound levers, this change of pressure is made to operate the guide-vanes of the water-wheels, thus controlling the direction and amount of the water entering the wheel. This system is in use in the new power-house on the River Rhine near Basel and is being installed in the great power-house now under construction at Keokuk on the Mississippi River.

(g) The Rotary Converter.

The so-called rotary converter is essentially a shunt generator or motor with the usual commutator mounted at one end of the armature and with the rings tapped on according to the number of poles and of phases. For instance, in the central distance between two like field poles there must be two taps, one to each ring for single phase, three for three phase and four for two phase, in each case equally spaced. See Fig. 136.

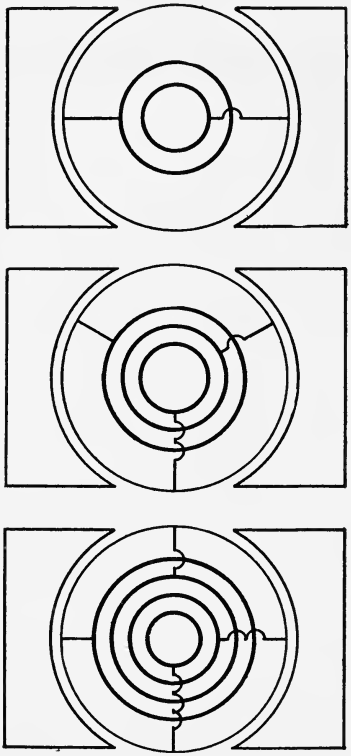


Fig. 136.—Rotary-converter armature connection.

The machine may then be run from the direct-current end and be made to furnish alternating-current or from the alternating-current end and furnish direct-current. See Figs. 137, 138 and 139. The latter method is the usual one. When run from the direct-current end, the machine is spoken of as an "inverted rotary."

The chief use of the rotary converter is to be found in the sub-stations of light and power companies. In order to minimize expense of transmission, it is the custom to generate power in the central station at a high alternating-current e. m. f. This can be transported to great distances over comparatively small wires. In order to be of commercial value, it must be stepped down to a lower voltage, which is easily accomplished by means of the

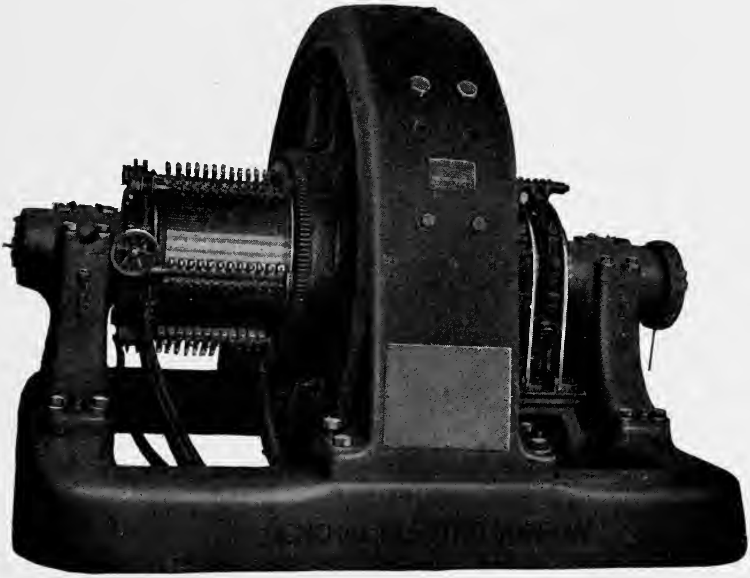


Fig. 137.—G. E. Co.—A modern rotary converter. D. C. end.

transformer. This instrument will receive a brief notice later. But the transformer delivers the power in the alternating-current form. This is serviceable for both incandescent and arc lighting and for operating certain types of motors. There are, on the other hand, applications to which direct-current is much better fitted than alternating-current, as, for instance, traction machinery and motors of varying and controllable speed. Hence in the sub-stations of traction companies the high pressure alternating current received from the main power-house is usually stepped down by means of a transformer and then supplied to the alternating-current end of a rotary converter, from which direct-current is sent out over the feeders to different points of the system.

The behavior of the rotary converter, when operated from the alternating-current end, is very similar to that of the synchronous motor. If directly connected to the line, without the intervention of a transformer or other inductive circuit, a variaton of

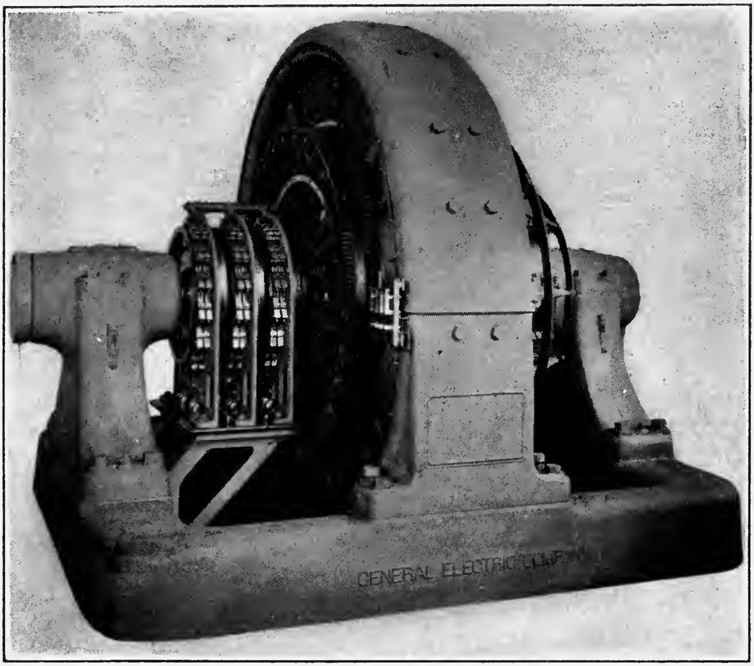


Fig. 138.—G. E. Co. rotary converter. A. C. ends.

field excitation will produce a shift of phase with reference to the supply voltage, but will not much alter the direct-current volts delivered. As in the synchronous motor, the amount of field excitation also determines the phase relation between the current and the impressed alternating-current e. m. f. In case there is inductance in the supply circuit, as, for instance, a transformer, a change of field current may also vary the generated counter e. m. f. and therefore the direct-current volts, but not over a wide range. In the machine shown in Fig. 139, the most

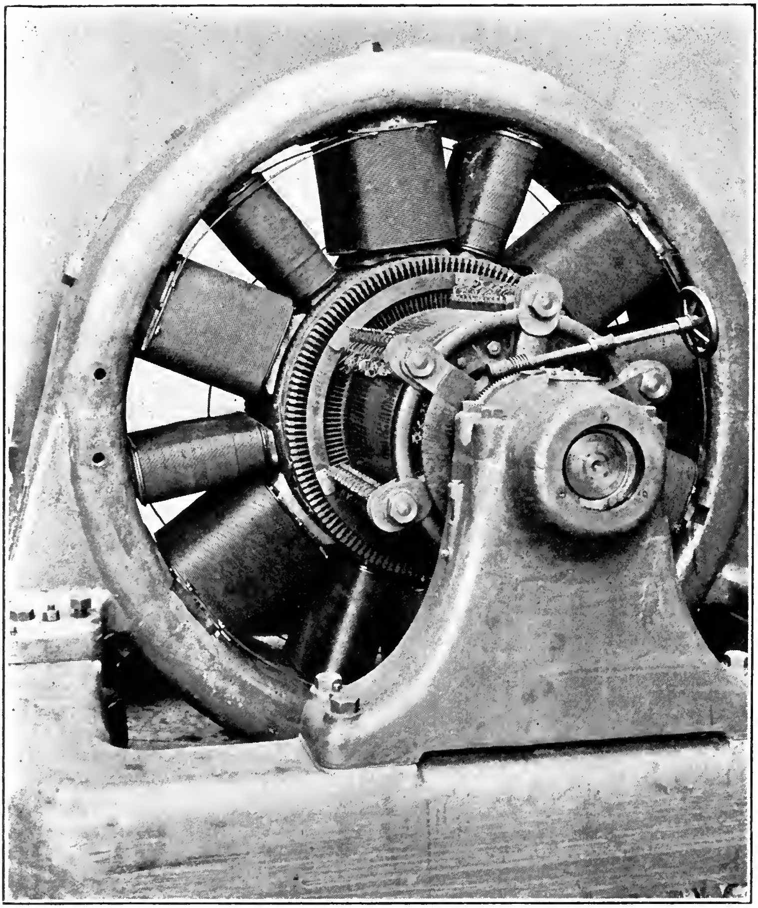


Fig. 139.—G. E. Co. regulating-pole rotary convertor.

recent type, the direct current volts are successfully regulated over a range of 10 per cent. in either direction by means of separate regulating poles. When operated from the direct-current end, a change of field current, although it may increase or decrease the speed as in a shunt motor, has no effect on the alternating-current volts unless the machine is loaded, and then only a slight one.

The theoretical relationship between direct-current and alternating-current volts, whether the machine is operated from either end or is driven as a generator by some prime mover, would be as follows:—

	D. C.	A. C.
Single phase	100	70.7
Three phase	100	61.2
Two phase	100	50.0

This table is on the basis of a sinusoidal e. m. f. In the actual converter, however, this condition is never realized, and the ratio between direct-current and alternating-current e. m. f.'s varies considerably from these values, even at zero load.

When loaded, the armature of the rotary carries both alternating-current and direct-current. In any armature conductor the external direct-current becomes alternating through the agency of the commutator. Thus each conductor has in it two alternating-current components of current, the one theoretically sinusoidal, the other with more abrupt rise and reversal. And these two components are not in phase. The wave-shape of the resulting current therefore departs altogether from the sinusoidal form.

From the foregoing paragraphs it will be clear that there must be two forms of armature reaction present in the loaded machine. The one distorts the field flux in a forward direction, the other against the direction of rotation. The direct-current brushes are therefore to be set on the geometrical axis of symmetry between the poles.

When the machine is operated from the direct-current end and an inductive load is placed on the alternating-current end, the lagging causes a field weakening and an increase in speed which may attain dangerous proportions.

In sub-stations where there are several rotary converters, it is the custom to start the machines from the direct-current end, when they can readily be brought up to speed and synchronized. As one or more machines are always in operation, the requisite direct-current supply is always at hand.

Rotary converters have the fault of hunting, just as alternators when operated in parallel. In both machines this is to a great extent obviated by inserting heavy copper conductors of various forms, , etc., in the faces of the pole pieces, the pole pieces themselves being laminated. A heavy steel shoe across

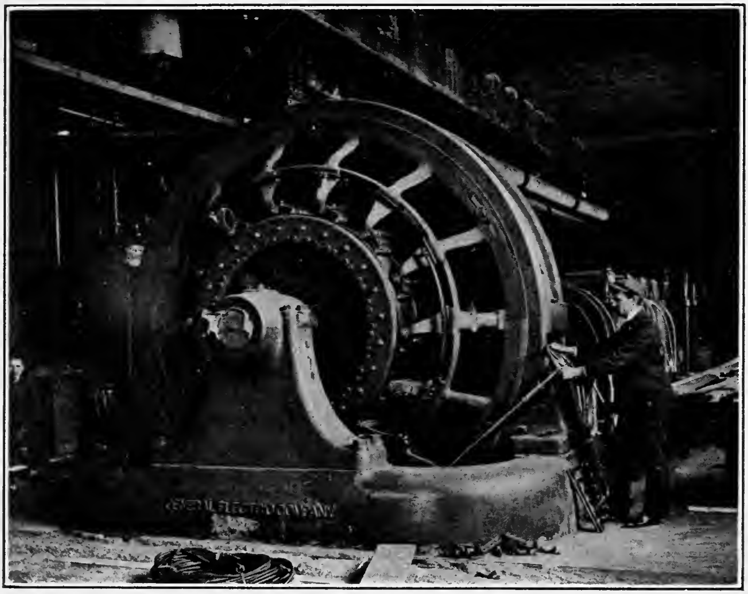


Fig. 140.—Large rotary converter in process of construction. Transformers in the distance.

the face of the laminated pole piece has a similar effect. The eddy-currents set up in these give steadiness of motion and prevent hunting.

(h) The Transformer.

Although the transformer is neither motor nor dynamo, yet a brief notice of this device must be included in the present volume.

It consists of two spools, or windings, of insulated wire placed on a core of laminated iron or surrounded by the same, and usually immersed in oil contained in an iron casing. The function of the oil is to cool and insulate. Forms are shown in Figs. 141, 142 and 143. The alternating flux created by the one coil cuts the other coil, establishing in it an alternating e. m. f.

The coils are known as primary and secondary, and ignoring

Fig. 141.—The transformer. G. E. Co.

losses the respective voltages are in direct ratio to the number of turns in the coils, the currents being in the inverse ratio. The high voltage coil is usually termed the primary, being the one to which the power is furnished, the transformer being chiefly used to step down the voltage of a transmission line. In power stations, however, the instrument is sometimes used to step up the voltage.

It is the transformer which furnishes excuse for the existence of the alternating current as a commercial form of power. Power at a high voltage with small current is far less expensive as regards copper and I^2R loss when transmitted to considerable distances than the same power at low voltage with large current.

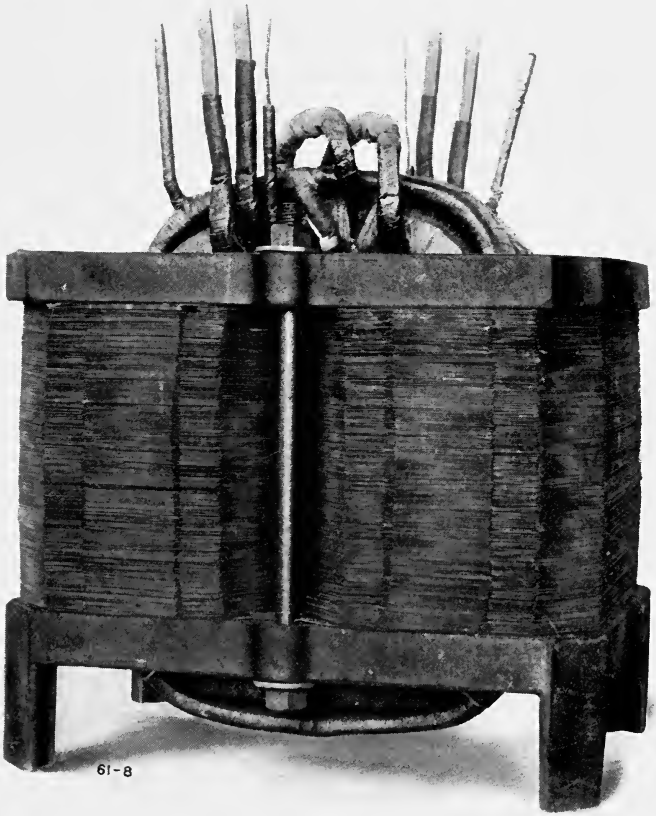


Fig. 142.—Wagner 10-kw. lighting transformer element.

The transformers more than pay for themselves on such a high voltage line, and their efficiency of operation is high, from some 94 to 98 per cent. The ratio commonly used is ten to one.

The losses in transformers are therefore small. The iron loss, that is, the power used for overcoming hysteresis and eddy-currents in the core or shell, as the case may be, ranges from 0.6 per cent. to 1 per cent. in modern transformers and are practically constant for all loads. The copper losses, I^2R, of both windings, range from 1.1 to 1.8 per cent.

The no load, or exciting, current is very small, owing to the

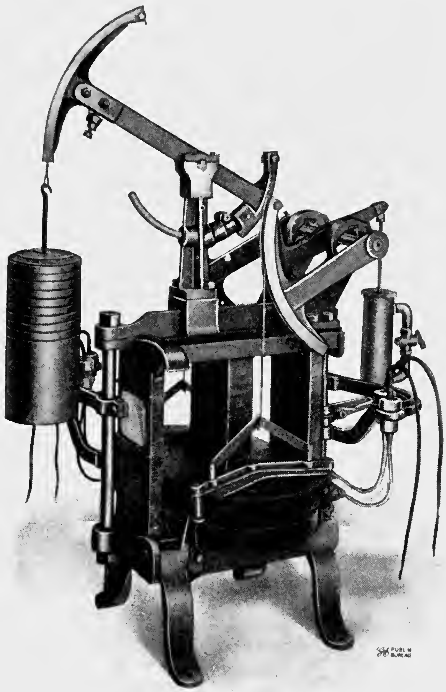


Fig. 143.—Automatic constant current transformer for series lighting system. G. E. Co.

c. e. m. f. of self-induction in the primary circuit. The power factor at no load is also very small, the resistance being comparatively low and the reactance high. The exciting current, therefore, lags almost 90° behind the primary volts. When the load current is drawn from the secondary windings, however, it is at the expense of the primary flux, tending to reduce it. This in turn tends to lower the c. e. m. f. of self-induction and allows the primary current to increase in value in proportion to the load. The flux of the core, or shell, is in this way restored and remains constant in value throughout all loads, and the transformer draws power automatically from the mains, according to the demands made upon it.

Since the capacity of the transformer depends on temperature, and the heat developed in the coils depends on current independent of power-factor, transformer capacity is usually expressed in kilo-volt amperes, K. V. A., rather than in kilowatts. In sizes

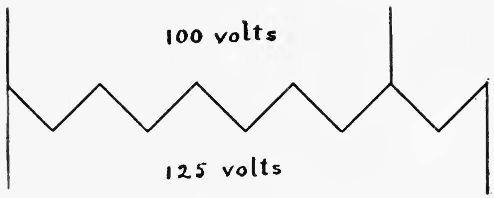


Fig. 144.—The auto transformer.

over 40 K. V. A. the retaining case is usually corrugated to aid the cooling, and in the largest sizes recourse is had to the air-blast or to water circulation.

The auto transformer consists of a single turn on a laminated core, and its action is much like that of the potentiometer in direct-current service. Unlike this instrument, however, voltage may be stepped up as well as reduced by the auto transformer. See Fig. 144.

(i) The Induction Motor.

The induction motor receives its name from the fact that the current in what corresponds to the armature is not drawn from the supply mains but is induced. The armature, more properly called the rotor, is not electrically connected with the outside source of supply. Its current is generated by the alternating flux from the poles of the stationary part, or stator.

In Fig. 145 the stator is wound for a two-phase four-wire circuit, having two poles to each phase. There are thus two distinct windings. Winding AC creates a flux such that the stator iron has a north pole at *b* and a south pole at *d*. The winding BD on the other phase is at this time dead. As the current in AC dies out, that in winding BD builds up (see Fig. 146), so that the north pole is gradually shifted from *b* to *c* and the south pole from *d* to *a*. In the second quarter of the cycle, the current in winding CA builds up in the reverse direction, that in BD

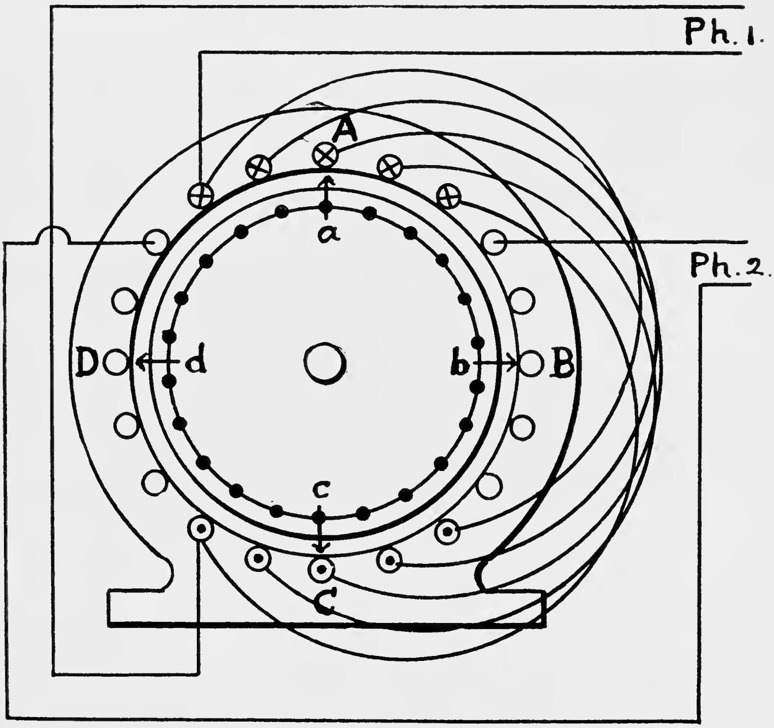


Fig. 145.—The induction motor. Diagram.

dying out, thus shifting the north pole to the positions *d* and the south pole to *b*. By continuing this analysis through the next two quarters, it will be seen that the polarity of the stator iron is made to rotate, in this instance once around for a complete cycle. Were there four poles per phase, it is evident that it would require two complete cycles to cause the polarity of the stator iron to make a complete revolution. That is, the number of revolutions of the stator magnetism per secoud, n, is $\frac{f}{\frac{1}{2}p}$ where f is the frequency and p the number of poles per phase, or

$$n = \frac{2f}{p}.$$

A rotor consisting of a solid cylinder of iron would experience the drag of this flux, and if the friction were not too great, would rotate in synchronism with it. A cylinder or other centrally symmetrical form of any metal would also be put in motion because of the eddy-currents set up in it by the stator flux.

The rotor of the induction motor consists of the usual laminated iron core, either wound similarly to the armature of an alternator or pierced near its periphery by stout copper bars connected in

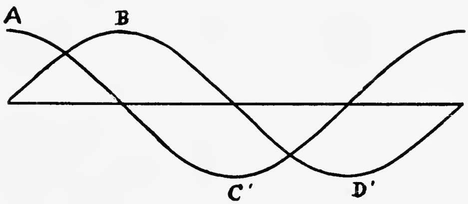


Fig. 146.

~~series~~. The latter is known as a squirrel-cage rotor in distinction from the wound rotor. By a reference to Fig. 145 it will be seen that these windings or bars are not unlike the secondary windings of a transformer, and have for the same reason an alternating e. m. f. induced in them. It is the resulting current on which the stator flux acts in producing rotation. And because the windings or bars give the proper direction to this induced current, the torque effected is much greater than could possibly be the torque on a solid metal cylinder.

If the speed of the rotor be such that it is in exact synchronism with the rotating stator flux, then the rotor conductors will be fixed in their relation to this flux, and no current will be induced in them. As a rule, however, the speed of the rotor is slightly less than that of the stator flux, the ratio of this difference to the speed of the stator flux being technically known as the slip; that is,

$$\%\ \text{slip} = \frac{\text{r.p.m. of stator—r.p.m. of rotor}}{\text{r.p.m. of stator}} \times 100.$$

The greater the load on the pulley wheel, the greater the slip, and the more rapid is the cutting of the rotor conductors through the stator flux, and the higher the e. m. f. and consequent current induced in them.

The increase of current in the rotor which accompanies an increase of load supply calls for additional power supply. This is furnished to the stator by the mains automatically, the process being similar to that by which a load on the secondary of a transformer (the rotor) increases the current supply to the primary (the stator). When the rotor is at rest, the induction motor is essentially a transformer with an unusually large factor of magnetic leakage. It is the factor of magnetic leakage coupled with rotor resistance and inductance which prevents the rotor current from becoming excessive at stand-still. This effect in turn prevents the stator current from rising to a dangerous value at stand-still, as it would in a transformer with short-circuited secondary.

The question of rotor speed and the torque exerted by an induction motor is a very complicated one, and the various governing factors must be taken up in detail. First suppose the torque demanded at the pulley wheel to be doubled. When this has slowed down the speed to such a degree that the slip has been doubled, the rotor current, considering resistance alone, is also doubled, furnishing the required torque.

But other factors enter to disturb this simple ratio between slip and torque. By the increased slip, the frequency of the rotor current and consequently the rotor reactance ($2\pi fL$) is increased. This both reduces the current somewhat and changes its position with reference to the field flux, causing a greater rotor (armature) reaction than otherwise would be the case and augmenting the flux leakage. All these factors combine to make the slip considerably more than twice as great for double torque.

The rotor reaction in particular is considerable and so distorts the stator flux that a large part of it passes from pole to pole through the narrow clearance space between rotor and stator in such a way as not to act on the rotor inductors.

Thus after a certain point is reached the speed of the induction motor falls off rapidly with increase of load; and at a point known as the pull-out torque, the motor stops altogether.

It will be seen, therefore, that the induction motor is similar to the direct-current motor in the fact that a decrease of speed due to load immediately causes an increase of current drawn from the mains. It is unlike a direct-current motor, on the other

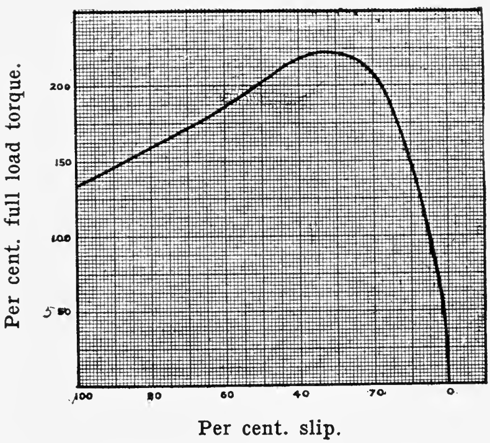


Fig. 147.—Curve of induction motor.

hand, in that when a certain point is reached, the speed falls off rapidly, and a torque of some 100 per cent. more than that for which the motor is rated will in most cases bring the machine to a stand-still.

For any given value of the slip, the torque of an induction motor varies as the square of the voltage. This comes about from the fact that the torque is proportional to the product of stator flux and rotor current. An increase of applied voltage increases this flux and this in turn increases the rotor current an equal amount, hence the square. The converse of this proposition is that with torque constant, the slip will vary inversely with the square of the applied voltage.

The general shape of the speed torque curve of an induction motor may be seen in Fig. 147. It will be observed that at about 35 per cent. slip in this case the torque suddenly begins to fall off, meaning that the so-called pull-out torque has been reached, and the motor is stopping. A means of shifting this turning point to correspond to a slower speed is to put resistance in the rotor circuit. Squirrel-cage rotors having low resistance, are usually started free and come quickly up to speed, after which the load may be applied by means of the friction clutch or shifted

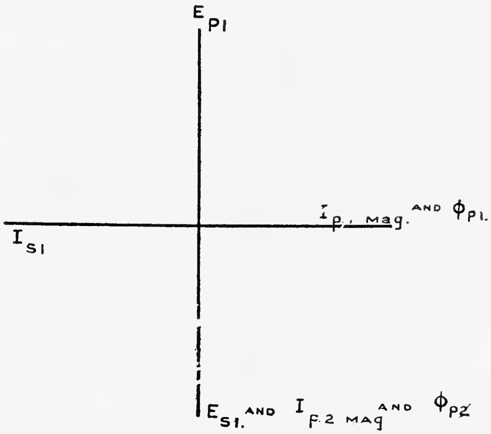


Fig. 148.

belting. For induction motors intended to start under load, however, a starting device is required which consists in part at least of a rotor resistance. The explanation of this principle is as follows:

As in the transformer, the primary flux of phase I, Φ_{p1} and the magnetizing current causing it lag 90° behind the primary e. m. f. E_{p1}, according to Fig. 148. The secondary e. m. f. E_{s1} then lags 90° behind Φ_{p1}. If resistance of the secondary circuit is zero and inductance alone is present, the secondary current, I_{s1}, lags 90° behind the secondary e. m. f., and therefore 180°

behind the primary flux. All this refers to one phase only. Meanwhile the other phase has been following on 90° behind, so that the magnetizing current $I_{p2.mag.}$ and the primary fiux Φ_{p2} due to it are 90° behind Φ_{p1} and 90° ahead of I_{s1}. Under these circumstances, the primary flux of phase 1 can cause no rotation, being in such a direction as to induce current I_{s1} instead (Lenz's law), and the primary flux of phase 2 could cause but little torque, being zero when the rotor current is a maximum, and vice versa. By increasing the secondary resistance we obtain the phase relation expressed by Fig. 149, and

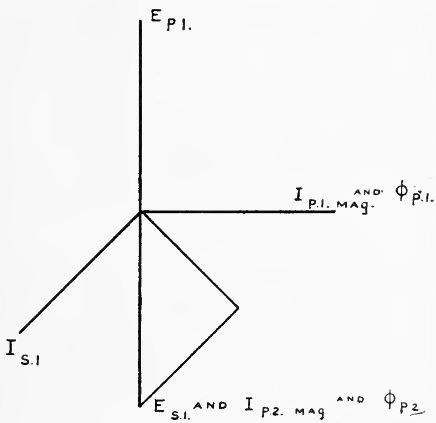


Fig. 149.

although the secondary current is diminished by this means, the torque is increased.

The rotor resistance, which gives the greatest torque at standstill is one such that the resitance and reactance are equal, giving a power factor angle of 45°. A greater resistance than this increases the power-factor causing I_s to swing in closer to E^s in Fig. 149, but at the same time reducing the rotor current so much that the torque is again decreased.

For the formula of the induction motor and detail calculations of its construction, the reader is referred to "Electric Motors," by Crocker and Arendt, published by Van Nostrandt Co., 1910.

(j) Starters for Polyphase Induction Motors.

For starting polyphase induction motors, the device most largely used is a resistance in the rotor circuit. In small motors, up to about 15 horse-power, it may be contained in the space within the rotor surrounding the shaft. One end of the shaft is hollow, and a handle protruding through this operates a sliding contact, which gradually cuts out the resistance, while bringing

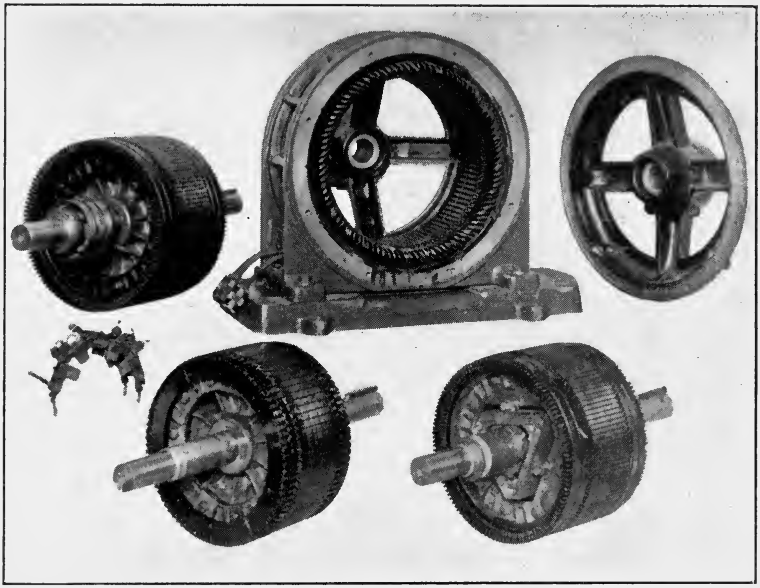


Fig. 150.—Forms of rotor with stator for polyphase induction motors. G. E. Co.

the motor up to speed. Resistance coils so placed are never heavy enough to be more than starting resistances. On larger machines and in cases where the device is not only for starting, but is a means of obtaining variable speed, the rotor windings are brought out to rings with contractors, and wires lead from these to external resistances. The rotor is usually wound three-phase, Y connected, and the resistances are varied by means of a controller. Fig. 150 shows these various types of rotor. Fig. 150 also shows usual startor winding.

Fig. 151 shows curves obtained with various resistances in the rotor circuit. These are so chosen with respect to the rotor circuit that the total resistance will enable the motor to develop its maximum torque at standstill (100 per cent. slip), and then as the speed increases, the resistance may be reduced by the controller in such amounts as to maintain a comparatively constant

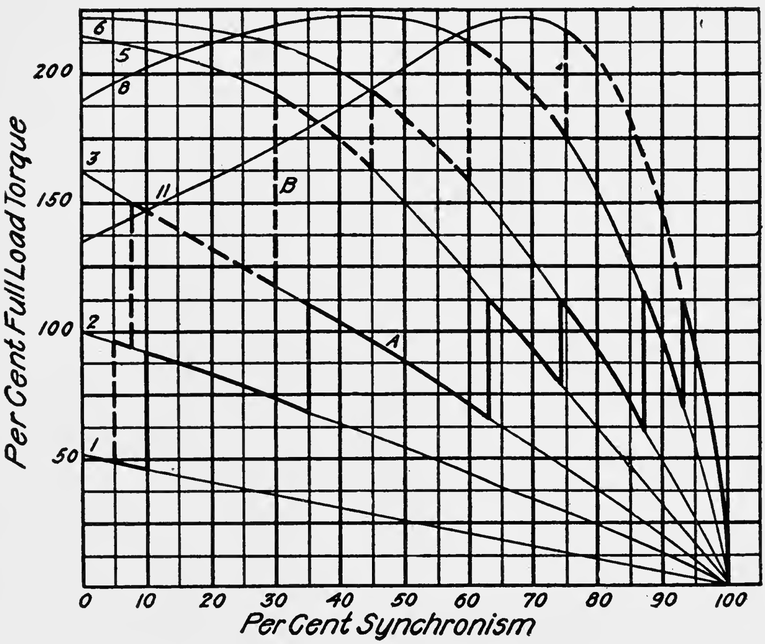


Fig. 151.—Curves of polyphase induction motor. G. E. Co.

torque. The heavy line represents the portions of the curves used during this process of starting under load. When the resistance coils are sufficiently heavy to stand the current without undue heating, this starting device may be employed to obtain variable speeds of operating. The usual practice is to build these rheostats for intermittent use from zero to half rated speed of the motor, and for constant service for half to full speed. Figs. 152 and 153 represent controller and rotor resistance.

Another means of reducing the current at starting is to lessen the e. m. f. applied to the stator. This is usually accomplished by means of an auto-transfer in the stator circuit. Figs. 154 and 155 represent one method of connection for a three-phase circuit.

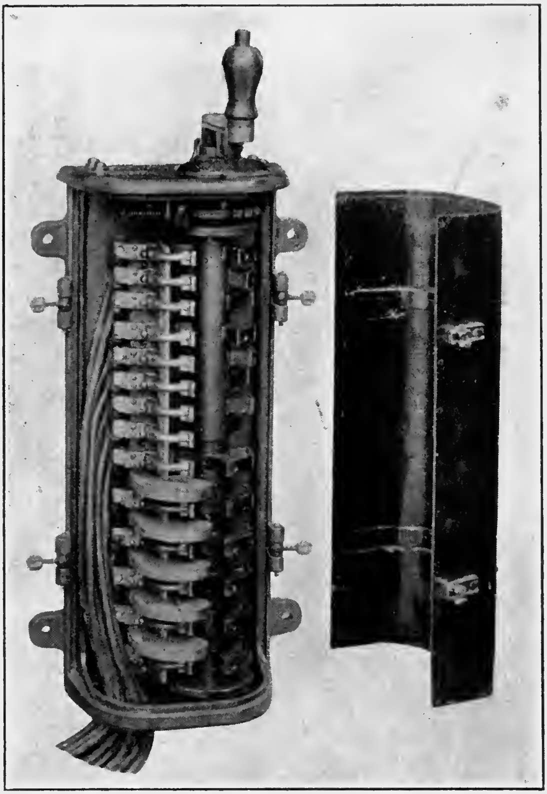


Fig. 152.—Controller for polyphase induction motor. G. E. Co.

When the motor has attained the full speed possible under these conditions, the stator is thrown directly onto the line by means of the controller or a double throw switch. This device is applicable to both squirrel-cage motors and those with wound rotors, but is clumsy and costly when made for large machines.

The Bell Electric Motor Co. of Garwood, N. J., have very recently placed upon the market a new type of polyphase motor known as their "Compensated type." The characteristics of this machine in operating are very interesting. There are two separate windings on the armature core. One is a progressive winding somewhat similar to a four pole direct current armature wind-

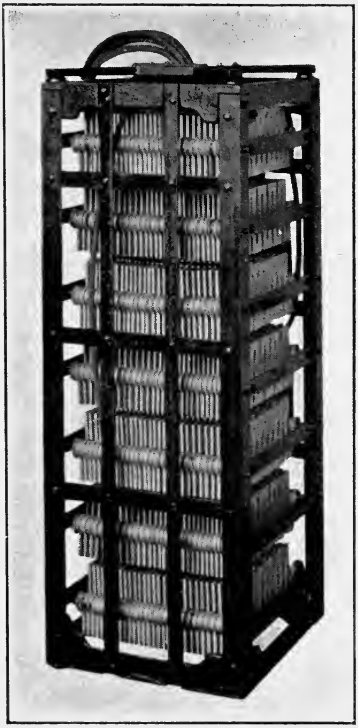


Fig. 153.—Rotor resistance of polyphase induction motor. G. E. Co.

ing, leads of which are brought out to commutator segments. Upon this winding but insulated from it there is placed a squirrel-cage winding of high resistance, which is entirely short-circuited upon itself. These two windings of high resistance give the motor considerable torque. After the armature has arrived at a predetermined speed, the commutator segments are short-circuited

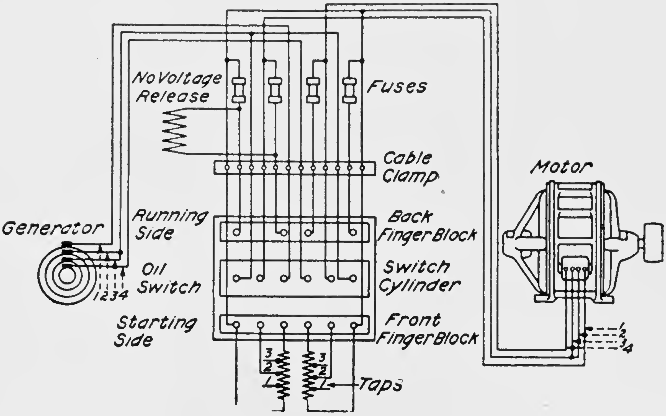


Fig. 154.—Starting compensator. Connections for three-wire two-phase. G. E. Co.

Fig. 155.—Starting compensator. Exterior. G. E. Co.

by a centrifugal device. This throws in the entire copper of the armature, and we then have what are practically two separate squirrel-cage armatures that are probably in inductive relation to each other, but are not electrically connected. In starting, all that is necessary for operation is an ordinary knife-switch, no compensators, starting boxes or resistances of any kind being employed. These motors will bring their full-load torque up to speed on twice full-load current. The power factor and efficiency on all sizes is extremely high. These motors are endorsed by electric-lighting companies, as they do not seriously interfere with the line voltage, when starting.

(k) The Single-Phase Induction Motor.

Motors of the induction type in sizes up to fifty horse-power are now manufactured for operating on the single-phase current. If built in all other respects like a poly-phase motor, such a

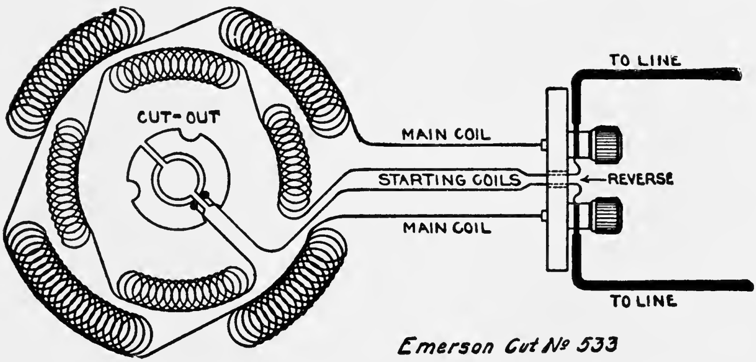


Fig. 156.—Emerson phase-splitting device. Diagram of connections.

machine would have only an oscillating, not a rotating, field, and therefore no starting torque, and until a certain speed is attained it could exert no torque at all. Such a motor, however, if once brought up to a sufficient speed, will fall into step with its oscillating field, and may then be loaded like any other induction motor. If the rotor slots are comparatively near together, a motor of this type may be started, running light, by hand, a few quick turns by means of the pulley-belt being sufficient. When the machine has attained full speed, the load is applied by a sliding belt, or a friction clutch, etc. Other devices, however, for starting these motors are enumerated below.

The Emerson motor employs a small secondary stator winding

Fig. 157.—Single-phase stator, showing shading-coils.

of high inductance, in which the current lags about 90° behind that in the main stator winding, thus producing a rotating field flux similar to that in the two-phase motor. This is known as the split-phase method. The secondary winding is cut out automatically, when the motor has attained full speed. See Fig. 156

For small fan motors, a simple phase-splitting device known as the shading coil is frequently used. It consists of a copper band placed about one tip of each pole-piece as shown in Fig. 157. It has the effect of causing the flux from the pole-tip to be in a different phase from the main part of the flux, and thus to create a torque sufficient to start the motor.

One of the best starting devices for single-phase induction motors is that of the General Electric Co. represented in Fig. 158. The stator is wound as if for three-phase, one of the terminals being excited through a "condenser-compensator," which has a

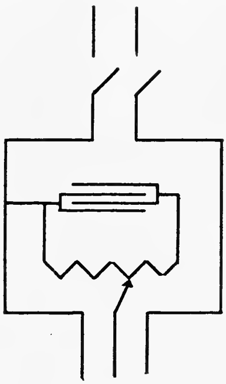


Fig. 158.—Condenser-compensator starter.

phase-splitting effect, reducing the angle of lag for a portion of the current. One form of this starting-box requires the handle to be pressed down for starting. When the motor has attained full speed, the handle is released, and a spring lifts it clear of the contact of the compensator circuit.

The Repulsion Motor.—A form of single-phase induction motor which develops a considerable starting-torque is made with a rotor in all respects like the armature of a direct-current machine with a commutator at its end, the same as that of a single-phase induction motor. The brushes are placed at an angle and permanently short-circuited, as represented in Fig. 159. The usual method of explaining the action of this motor is to consider the alternating flux, Φ, which is produced by the stator current, as made up of two components. Of these the component Φ_t acts

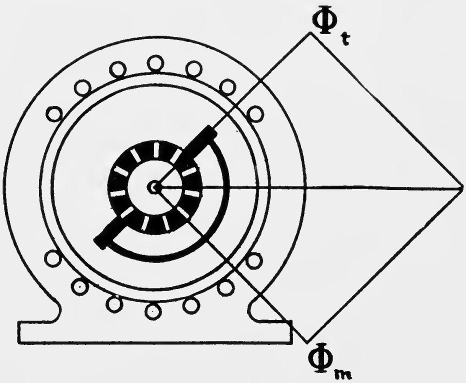


Fig. 159.—Repulsion motor.

like a transformer flux, inducing current in the short-circuited armature; and the component Φ_m acts like the ordinary field flux of any motor, exerting a torque on the armature inductors.

One of the chief uses of this type of motor is that it furnishes a starting device for the single-phase induction motor, when required to exert a large starting torque. The first manufac-

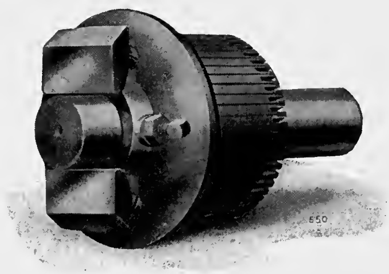


Fig. 160.—Bell short-circuiting device.

turers to develop this method of starting were the Wagner Electric Co., but this type of machine is now manufactured by others. The method consists in applying to the armature of the ordinary repulsion motor a short-circuiting ring, which is pushed into place

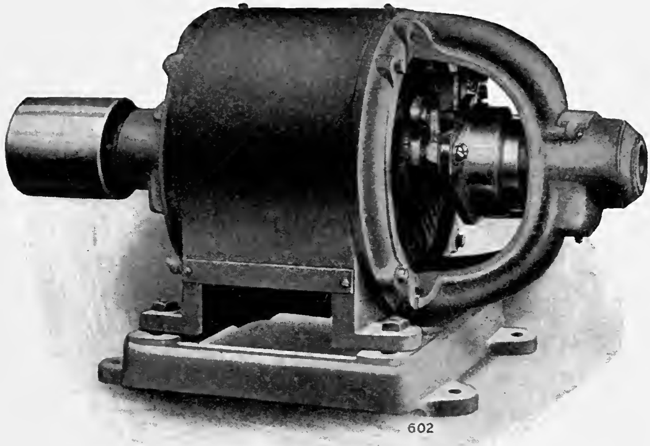
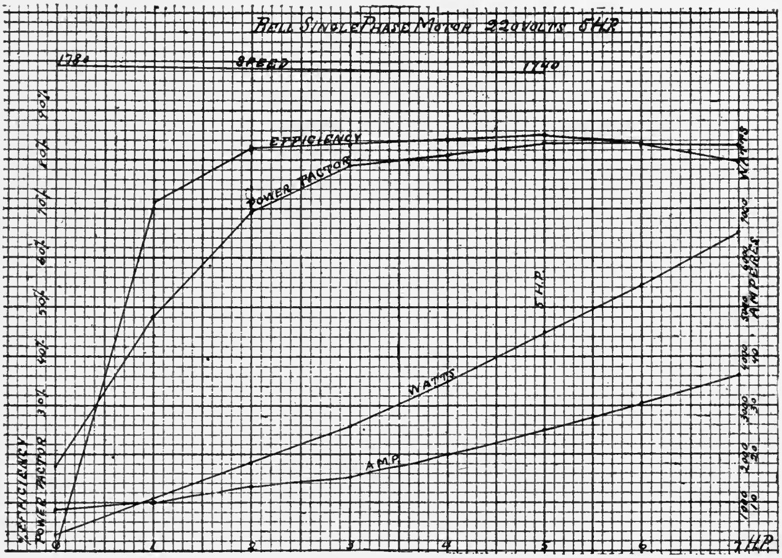


Fig. 161.—5 h-p. single phase motor.



Test Curve of 5 H. P., 1800 R P M., 220 Volts, 60 Cycles Bell High Efficiency Single Phase Motor

Fig. 162.

against the commutator bars when the motor has attained nearly synchronous speed. This is done automatically by a centrifugal device, attached to the shaft. When the motor is at rest, this ring is removed by a spring. Figs. 160 and 161 show the method employed by the Bell Electric Motor Co., and Fig. 162 is a set of curves representing the performance of one of their machines.

(k) Practical Remarks Regarding Induction Motors.

In specifying an induction motor for any definite work, the

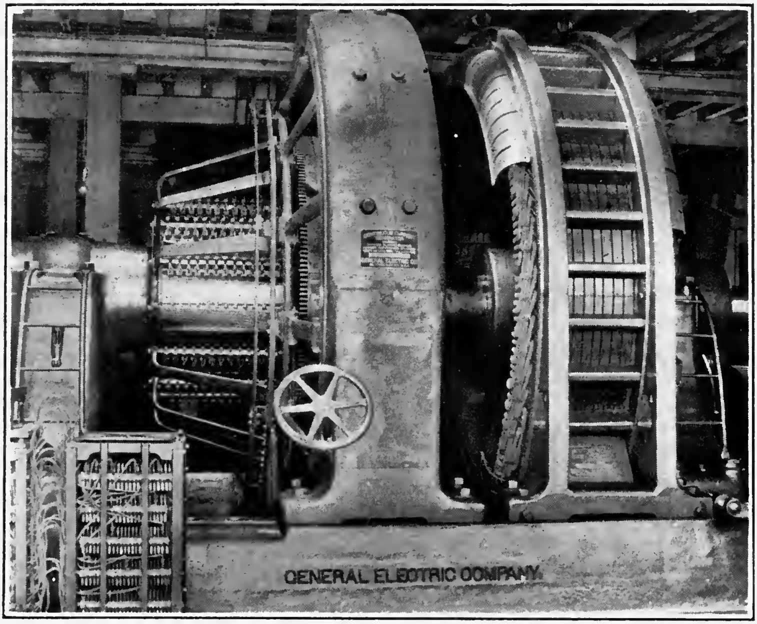


Fig. 163.—1,400 k.w. motor-generator set with 11,000-volt induction motor. G. E. Co.

engineer has to consider the two following points: First, the machine must be large enough to develop the full torque that will be demanded of it, which can in most cases not exceed more than 200 per cent. of the rated full load torque of the machine; and second, the motor must not be larger than actually necessary, because induction motors act with low power factor and low efficiency, when the load is much below rated value.

Induction motors made a few years ago were considerably larger of frame than those now manufactured with the same

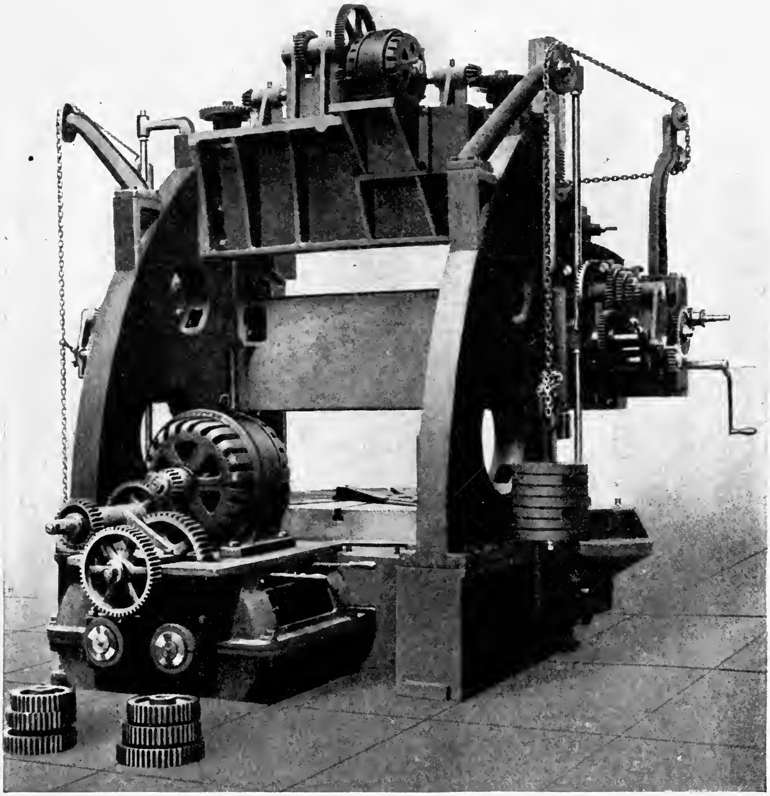


Fig. 164.—Motors geared to a 10-foot vertical boring mill. Main motor 15 h-p. Elevating motor 3 h-p. Westinghouse Co.

power rating. The present practice of manufacturers is to have stated sizes of rotor and stator punchings of sheet iron, and to make one size punching serve for two or more sizes of motor, according to the number of such laminations used. In this type of machine the open form furnishes good ventilation, the laminations being bound together by horizontal rods secured to the end-plates. See Fig. 163.

Fig. 164 shows some applications of the induction motor.

(1) The A. C. Series Motor.

The action of the alternating-current series motor and its characteristic curves are not far different from those of the direct-current series motor. Owing to the low flux density of alternating-current machinery generally, the alternating-current series motor weighs considerably more and is larger than its direct-current counterpart.

In the action of the alternating-current series motor, the following peculiarities are to be noted:—

The iron losses are much larger than in the direct-current machine, owing to the alternating flux in not only the armature core but also the field. On this account, the field core has to be laminated, which considerably increases its size.

Besides the c. e. m. f. always present in a rotating armature, there is developed in the armature windings another e. m. f. by transformer action from the alternating field-flux. This e. m. f. neither aids nor opposes the counter e. m. f., the division of armature inductors in respect to direction of this e. m. f. being at right angles to the axis of commutation, so that one half counteracts the other. This transformer e. m. f., however, greatly increases the tendency to spark in the coil short-circuited by the brushes.

The current in the short-circuited coils is sometimes reduced by inserting a high resistance where the armature coils are connected to the commutator bars.

Another device found in series alternating-current motors is the compensating winding. It consists of several turns of wire let into grooves in the pole faces, and serves to reduce armature reaction and the self-induction of both field and armature circuits.

Figs. 165 and 166 enable the reader to make a comparison of the characteristics of the alternating-current and the direct-current series motor.

It is sometimes necessary to operate alternating-current series motors on a direct-current circuit, as in the case of electric loco-

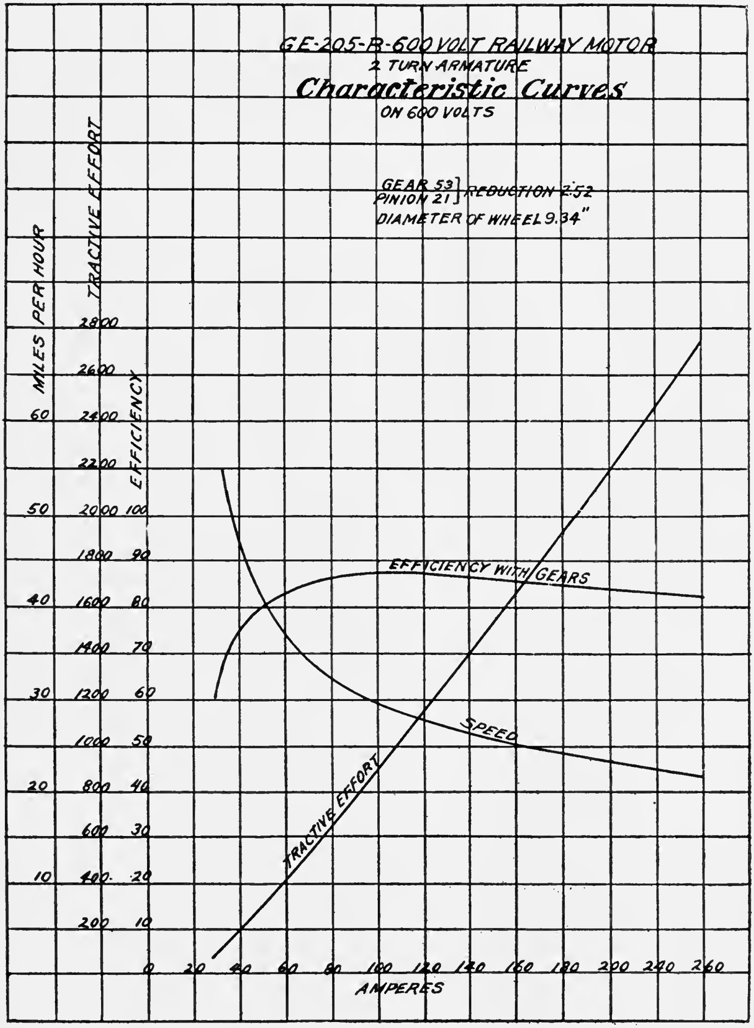


Fig. 165.—Direct-current motor. G. E. Co.

motives operating on two differently equipped roads. Small fan motors and the like also capable of operating on either alternating-current or direct-current circuit are now manufactured.

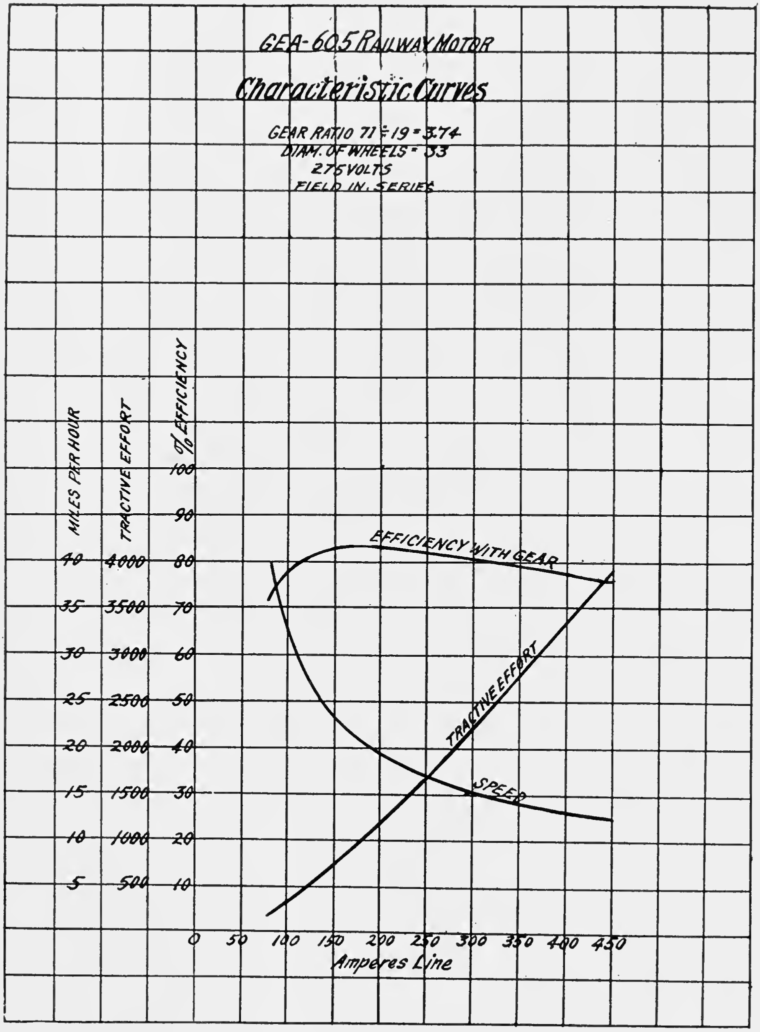


Fig. 166.—Alternating-current motor. G. E. Co.

INDEX

ERRATA.

Page 4. "For air then $\mu = l$" should be "For air then $\mu = 1$."

Page 16. The formulae at the foot are for some connections only approximate. If we write I_sR_s, instead of I_aR_s, they will apply to all cases.

Page 152. "stout copper bars connected in series" should read "stout copper bars connected in parallel."

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