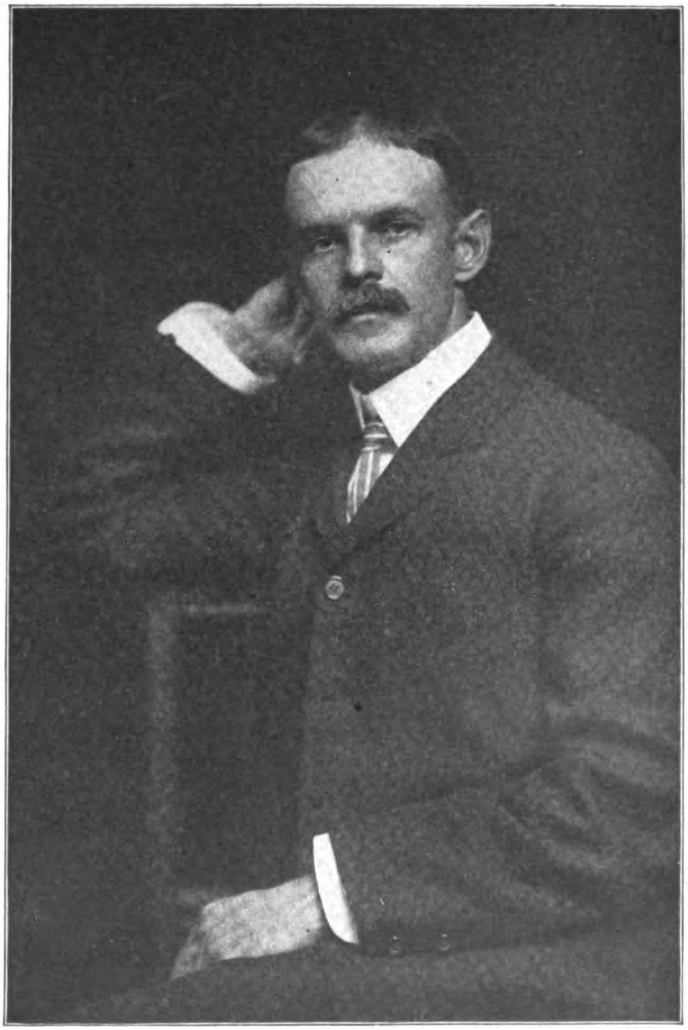

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Dynamo-Electric Machinery

An Authoritative Treatise

ON THE THEORY, CONSTRUCTIVE DETAILS, CALCULATION, CHARACTERISTIC CURVES, AND DESIGN OF DYNAMO-ELECTRIC MACHINERY

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Foreword

IN recent years, such marvelous advances have been made in the engineering and scientific fields, and so rapid has been the evolution of mechanical and constructive processes and methods, that a distinct need has been created for a series of *practical working guides*, of convenient size and low cost, embodying the accumulated results of experience and the most approved modern practice along a great variety of lines. To fill this acknowledged need, is the special purpose of the series of handbooks to which this volume belongs.

¶ In the preparation of this series, it has been the aim of the publishers to lay special stress on the *practical* side of each subject, as distinguished from mere theoretical or academic discussion. Each volume is written by a well-known expert of acknowledged authority in his special line, and is based on a most careful study of practical needs and up-to-date methods as developed under the conditions of actual practice in the field, the shop, the mill, the power house, the drafting room, the engine room, etc.

¶ These volumes are especially adapted for purposes of self-instruction and home study. The utmost care has been used to bring the treatment of each subject within the range of the common understanding, so that the work will appeal not only to the technically trained expert, but also to the beginner and the self-taught practical man who wishes to keep abreast of modern progress. The language is simple and clear; heavy technical terms and the formulæ of the higher mathematics have been avoided, yet without sacrificing any of the requirements of practical instruction; the arrangement of matter is such as to carry the reader along by easy steps to complete mastery of each subject; frequent examples for practice are given, to enable the reader to test his knowledge and make it a permanent possession; and the illustrations are selected with the greatest care to supplement and make clear the references in the text.

¶ The method adopted in the preparation of these volumes is that which the American School of Correspondence has developed and employed so successfully for many years. It is not an experiment, but has stood the severest of all tests—that of practical use—which has demonstrated it to be the best method yet devised for the education of the busy working man.

¶ For purposes of ready reference and timely information when needed, it is believed that this series of handbooks will be found to meet every requirement.

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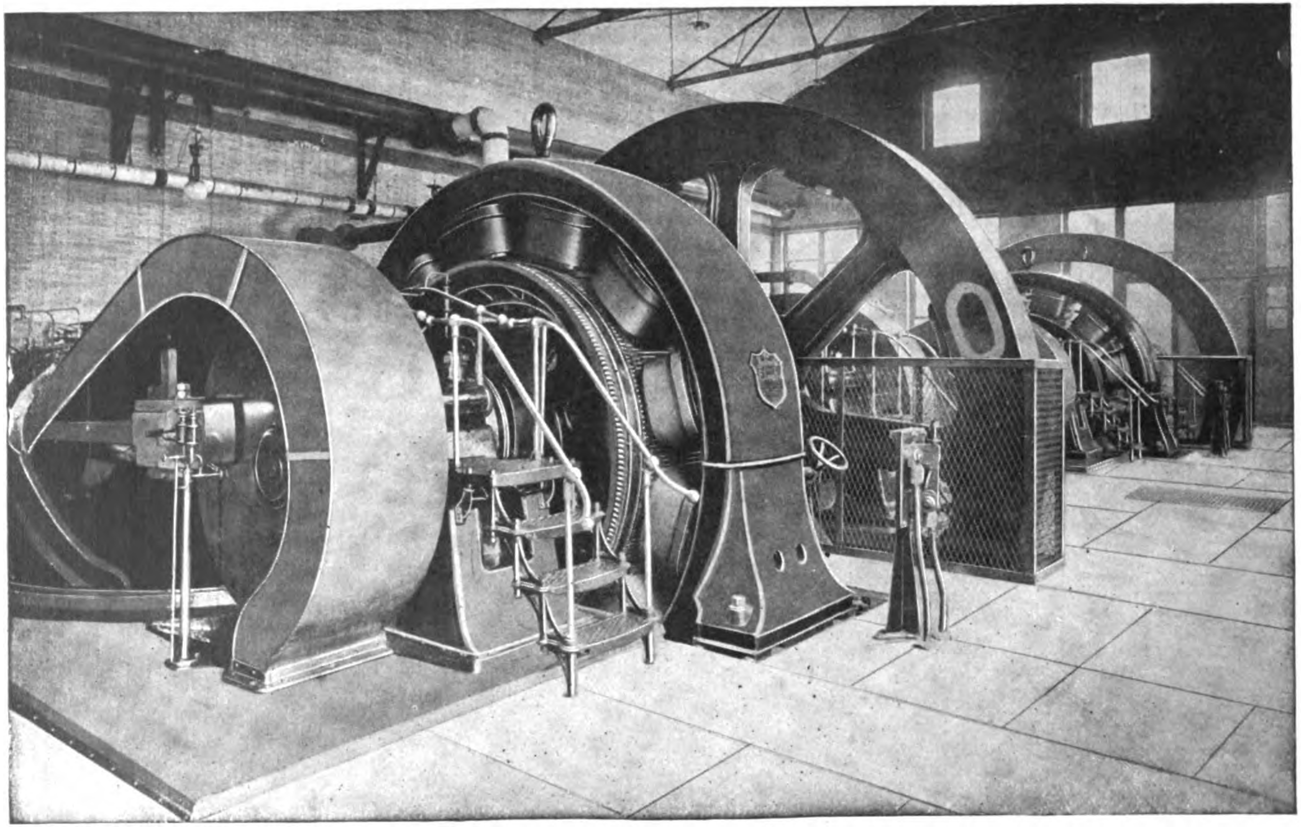

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DYNAMO-ELECTRIC MACHINERY

PART I

THEORY OF DYNAMO-ELECTRIC MACHINERY

A *dynamo-electric machine* is one which converts mechanical into electrical energy, or *vice versâ*, by means of the relative motion of a conductor carrying an electric current, and an interlinked magnetic field. When the conversion is from mechanical to electrical energy, the machine is called a *generator;* and when the conversion is from electrical to mechanical energy, the machine is called a *motor*. In order fully to understand the design and construction of these machines, it will first be necessary to consider the principles which govern their action.

Magnetic Field. It was early found that pieces of a certain kind of iron ore were capable of attracting bits of iron. From the name

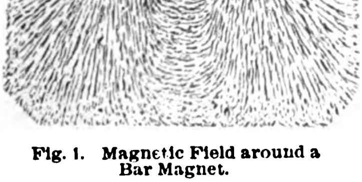


Fig. 1. Magnetic Field around a Bar Magnet.

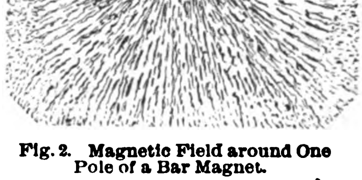


Fig. 2. Magnetic Field around One Pole of a Bar Magnet.

of the country in which this peculiar oxide of iron was first found, came the name of articles made of it—*i.e.*, *magnets*, from "Magnesia," in Asia. This oxide of iron is Fe_3O_4, commonly called *Magnetite*.

If one of these magnets shaped as a straight bar is held under a piece of cardboard upon which iron filings are sprinkled, it will be found that the filings settle down in curved lines forming a magnetic figure, the general form of which is shown in Fig. 1. When one of the poles of the magnet is held toward the cardboard, the filings will arrange themselves as shown in Fig. 2. These experiments show that the medium surrounding a magnet is in a state of stress, the space so affected being called a *magnetic field.* The influence of a magnet is supposed to extend in all directions indefinitely; *but as the force due to the magnet varies inversely as the square of the distance from it,* the effect is rendered practically negligible beyond a comparatively limited area.

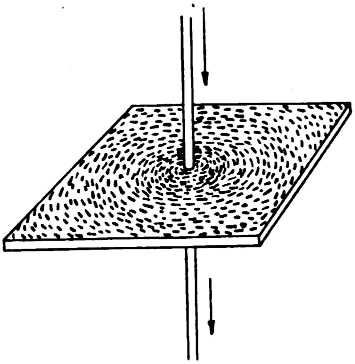


Fig. 3. Magnetic Field around a Current-Carrying Conductor.

When a conductor carrying a current of electricity is passed through a piece of cardboard with iron filings sprinkled on the board as before, we see (Fig. 3) that the filings arrange themselves in curved lines similar to those of Fig. 2; while, if the return circuit of the conductor be also poked through the card, the filings assume the alignment shown in Fig. 4. From the similarity of the phenomena, it may be concluded that a conductor carrying an electric current is surrounded by a magnetic field whose strength is a direct function of the current. This was first noted by Oersted, who in 1820 observed that a compass needle was deflected when placed near a conductor carrying a current of electricity, the direction of motion of the needle depending upon the direction of flow of the current.

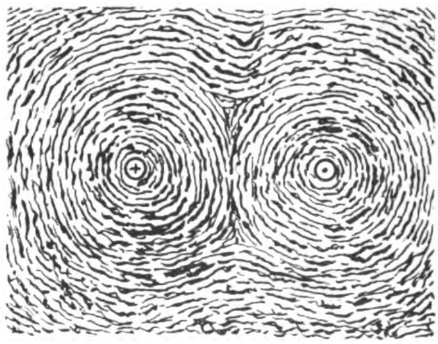


Fig. 4. Magnetic Field around Conductor and Return Circuit.

Lines of Magnetic Force. The magnetic figures in the previous paragraph indicate that the stresses in the medium surrounding a magnet or current-carrying conductor follow certain definite lines, the lines showing the direction of stress at any point. These are called *lines of magnetic force.* If, in addition, there be drawn as many lines per square centimeter cross-section of the field as there would be dynes of force acting upon a unit magnetic pole* placed at that point, then the total number of lines of magnetic force represents the *magnetic flux* through that cross-section; and the lines per square centimeter, the *flux-density.*

Solenoids. Now, suppose that a wire is bent in the form of a circular loop as in Fig. 5, and furthermore suppose that a current is traversing the conductor in the direction indicated. Then, according to a rule suggested by Maxwell,

> "The direction of the current and that of the resulting magnetic force are related to one another, as the rotation and travel of an ordinary (*i. e.,* right-handed) screw."

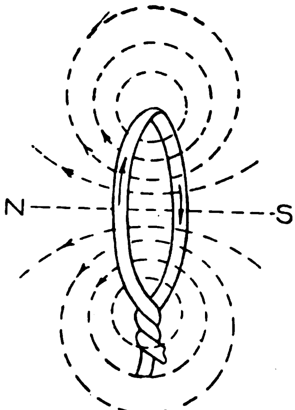


Fig. 5. Magnetic Field around a Conducting Loop.

Consequently the lines of magnetic force would surround the loop in the manner shown. The field of such a loop, on being explored with a compass needle or filings, will be seen to retain the general character of the field surrounding a straight conductor; and consequently all the lines will leave by one face and return by the other; the entire number passing through the loop. Hence one face of the loop will be equivalent to the north pole of a magnet, and the opposite face will correspond to the south pole. In fact the loop will act exactly as if it were a thin disc magnetized perpendicularly to its plane.

By placing side by side several of these current loops, with their transverse axes in the same straight line, there is formed a *solenoid* (Fig. 6); and exploration of the resulting field by any of the above methods shows that the lines of force pass right through the interior of the solenoid, leaving by one end and returning by the opposite end as suggested by Maxwell's rule. A cylinder of soft iron inserted in the space within the solenoid will be found to act strongly as a

* A *unit magnetic pole* is one which, when placed at a distance of one centimeter from a similar pole, in vacuum or practically air, exerts upon it a force of one dyne.

magnet when the current flows around the solenoid; but if the current is interrupted, the magnetic effect almost disappears. Reversal of the current will be found to reverse the polarity of the core, while increasing the current augments the magnetic strength of the coil.

Toroid. Bend the solenoid of the previous paragraph around until its ends meet; or produce the same winding by turning insulated wire around an endless ring core of circular cross-section. The arrangement thus produced will be a *toroid*, commonly called *Faraday's ring;* and if the wires are wound closely and uniformly over the whole periphery, the lines of force will be closed curves whose paths lie entirely within the turns; consequently there are no external poles—a unique electromagnetic condition.

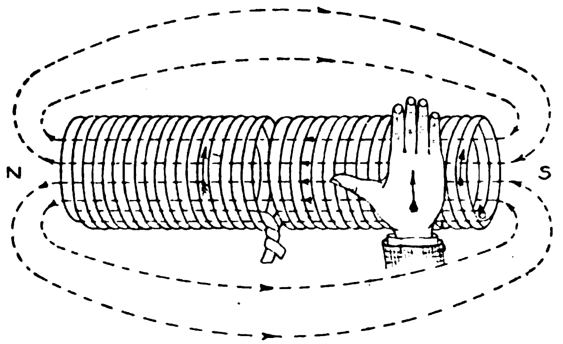


Fig. 6. Arrangement of Conductive Loops Forming a Solenoid, with Surrounding Magnetic Field.

Magneto-Electric Induction. Thus far the condition of the magnetic field has been determined by means of filings or magnets; but neither of these methods can be used to explore the interior of an iron-cored toroid. It is possible, however, to employ for this purpose the principles of *magneto-electric induction* discovered by Faraday in 1831. One of the laws governing this phenomenon, first enunciated by Neumann in such manner as to permit determination of the electromotive force developed, is as follows:

"Whenever the flux interlinked with a circuit is varying, there is an e. m. f. acting around the circuit, proportional to the time rate of change of the flux, the positive direction of the e. m. f. and the positive direction of the flux passing through the circuit being related to each other as are the rotation and travel of a right-handed screw. That is, if a circular loop is moved in the field of a magnet in such a way that it does not enclose the same amount of flux at any two successive instants, then there is induced in the loop an e. m. f. whose value is proportional to the change of enclosed flux per unit time. A similar effect will be obtained by keeping the loop fixed, and moving the magnet."

We thus have a way to investigate the condition of the field within the solid-cored toroid previously mentioned. Suppose a loop of insulated wire to be placed around the toroid in Fig. 7, and suppose the terminals of this loop to be led to a ballistic galvanometer (that is, an instrument which will measure current impulses). Then if the magnetizing coil of the toroid be energized by passing a current through it, the galvanometer will give a sudden throw the instant the current is started. Similarly, when the circuit is broken and the current ceases, the galvanometer indicates the passage of another current impulse through the loop, the deflection, however, being in the opposite direction.

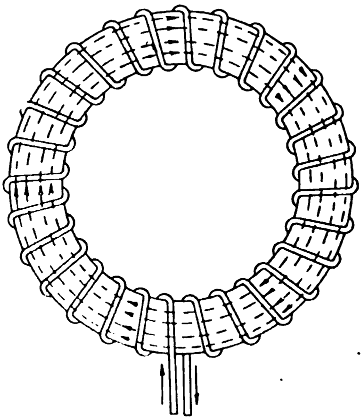


Fig. 7. Lines of Force in Toroid Surrounded by a Magnetizing Coil.

The loop is next removed from the toroid and placed in front of an iron-cored solenoid which can be energized or de-energized at will by closing or opening a switch, and it will be found that similar effects are produced. Let, now, the electromagnet be energized and de-energized periodically, and the loop or exploring coil be turned so that its axis occupies every possible direction in space, the center of the loop remaining stationary throughout. It will be found that when this axis is in one particular plane, no impulse will pass through the exploring coil when the exciting current of the electromagnet is caused to flow, to cease, or to reverse. From what has been explained previously, we see that in this case the loop interlinks with no flux, hence its plane must be parallel to the direction of the flux. Also we see that when the plane of the loop takes any other position, the flux interlinked with it depends upon the relation between the plane of the loop and the direction of the flux. If we call the angle between the direction of the flux and the axis of the loop a, the flux enclosed by the loop for any given value of the exciting current of the electromagnet will be proportional to the cosine of a. The quantity we are thus investigating is a directed quantity, and may therefore be represented by a vector.

Lines of Magnetic Induction. This quantity is called the *magnetic induction* or *flux*, and its direction at any point is defined as that of the axis of the loop when in the position giving the greatest inductive effect on energizing or de-energizing the electromagnet. Its direction is also defined by Neumann's law. If, now, a curve be drawn following the direction of the flux, this curve will be a line of magnetic induction. The flux and flux-density are defined in a way precisely similar to magnetic force.

Relation between Magnetic Force and Magnetic Induction. In the earliest of Faraday's experiments with solenoids, he found that the flux through any of these was much greater when iron was inserted than when air or wood was enclosed by the coil of wire. He ascribed this peculiar circumstance to the greater "conducting power of the magnetic medium for lines of force." Lord Kelvin introduced the phrase *magnetic permeability* for this property of magnetic materials, and it is defined as the ratio between the magnetic induction (B) produced in the medium and the magnetic force (H) to which that induction is due; *i. e.*,

$$\mu = \frac{B}{H}.$$

Magnetic Permeability. The precise notion now attached to this term is that of a numerical coefficient, and it is analogous to electrical conductivity. Its value is dependent upon the character of the substance and the magnetizing force or m. m. f. applied to the substance. For vacuum its value is unity; for air it is practically unity; for magnetic materials it is greater than 1 and may reach 2,500 for soft iron; while for diamagnetic materials it is slightly less than 1. The permeability of such non-magnetic materials as silk, cotton, and other insulators, also of brass, copper, and other non-magnetic metals, is taken as unity, being practically the same as for air.

The permeability of iron, however, varies very greatly with the degree to which it has been magnetized. In all kinds of iron (after passing the initial stage mentioned below), the magnetizability of the material becomes diminished as the actual magnetization is pushed further; in fact, there is a tendency to magnetic saturation. In other words, when the piece of iron has been magnetized up to a certain degree, it becomes less permeable to further magnetization; and although actual saturation is never reached, there is a limit beyond which the magnetization cannot be increased with practical advantage. This is shown in Fig. 8, which represents the permeability curve of a sample of good iron or steel as used in dynamo magnet construction. The practical limit of the flux-density (B) in good wrought iron and in mild steel, is about 20,000 lines of magnetic induction per square centimeter; and in cast iron the saturation limit in practice is about 12,000 lines per square centimeter. In square-inch units these limits are, for wrought iron and mild steel, about 125,000 or 130,000 lines per square inch; and for cast iron, about 70,000 lines per square inch.

Magnetic Circuit. Returning to the toroid of Fig. 7, we see that the lines pass through the interior of the toroid, forming a closed magnetic circuit. Now, it is found that the total flux within the toroid is equal to the ratio between the magnetomotive force acting around the magnetic circuit and the reluctance of that circuit; that is

$$\phi = \frac{\text{m. m. f.}}{R},$$

in which,

ϕ = Total flux;

m. m. f. = Magnetomotive force;

R = Magnetic reluctance.

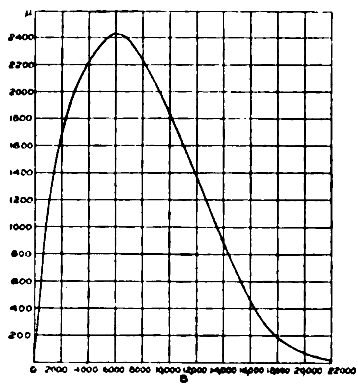


Fig. 8. Permeability Curve of Iron or Steel Used in Dynamo Magnet Construction.

Magnetomotive Force. By this term is meant the total magnetizing power of an electric current circulating in a coil. It is found, when a current flows in a wire wound several times around a core, as in Fig. 9, that the magnetizing power is proportional both to the strength of the current and to the number of turns of wire. The magnetizing power is independent of the size of the wire or the coils and of their shape, remaining also the same whether the spirals are close together or wide apart. Hence if T be the number of turns in the coil, and I be the current in amperes passing through each turn, the magnetomotive force is,

$$\text{m. m. f.} = \frac{4}{10}\,\pi \times I\,T = 1.257\,IT.$$

A straight conductor carrying an electric current of which the return is very distant, as in Fig. 10, is surrounded by circular concentric lines. Taking one of these lines at a distance r centimeters from the axis of the wire, which we suppose to be carrying I amperes (that is, $\frac{I}{10}$ units of current in C. G. S. electromagnetic units), the intensity of the field at any point at radius r has the uniform value $\frac{2I}{10r}$, and its direction is that of the given line, of which the length is $2\pi r$. Hence the total force around the circle of radius r concentric with the axis of the conductor, will be the product of the force at any point of its circumference into the length of this circumference; *i. e.*,

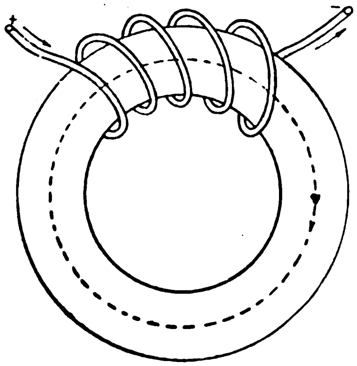
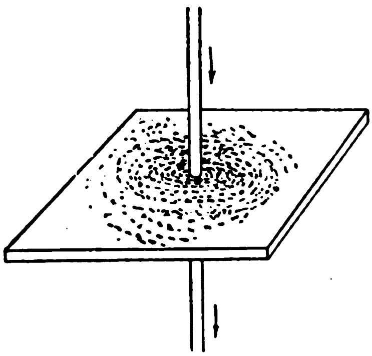


Fig. 9. Showing Relation between Magnetizing Power of a Coil and Its Number of Turns.

$$\frac{2I}{10r} \times 2\pi r = \frac{4\pi}{10} I.$$



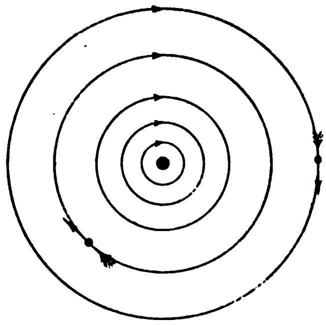


Fig. 10. Illustrating Variation in Intensity of Magnetic Field Surrounding a Conductor with Distant Return.

And if the single wire be replaced by T turns, the force will be T times as large, or $\frac{4\pi}{10} I\ T$, $I\ T$ being called the *ampere-turns*.

Reluctance. We have seen from the equation of the magnetic circuit, that the total flux is inversely proportional to the reluctivity of the materials of which it is composed; it is directly proportional to the permeability which is the reciprocal of the reluctivity. The reluctance or magnetic resistance of a circuit is therefore obviously proportional to its length, and inversely proportional to its area of cross-section and its permeability; that is,

$$R = \frac{l}{\mu A}$$

In designing electromagnets, before calculations can be made as to the size of the iron core required, it is necessary to know the magnetic properties of that particular iron; for it is obvious that inferior permeability demands a larger cross-section to obtain a given flux, or inferior permeability will require more turns of copper wire to be used.

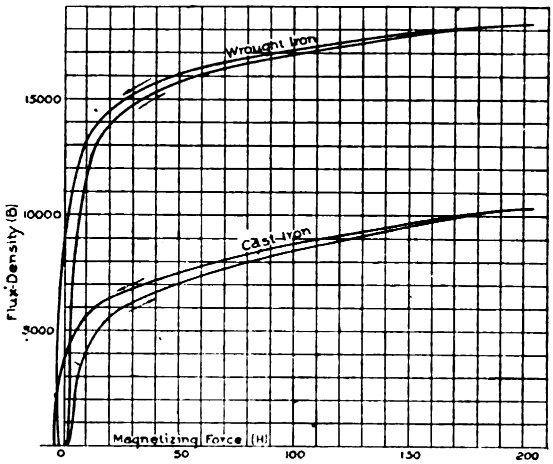


Fig. 11. Magnetization Curves of Wrought Iron and Cast Iron.

Magnetization Curves. A convenient method of studying the magnetic facts respecting any particular brand of iron, is to plot as a diagram the *curve of magnetization*—that is, the curve representing the relation between the magnetic force plotted horizontally, and the magnetic induction plotted vertically.

The upper curve in Fig. 11 gives the behavior of annealed wrought iron. The ascending curve shows the relation between the intensity of the magnetizing force H and the flux-density B during the process of increasing the magnetizing force from zero to about 210 units; and the descending line shows the same relation during the process of decreasing the magnetizing force to zero, and then reversing it so as to remove the residual magnetic lines. The lower curve shows the behavior of grey cast iron.

Every sample of iron will show a similar set of results, which can be plotted in the form of a curve that is characteristic. The curves for cast iron and hard steel always have lower values than those for wrought iron or mild steel. In addition, it will usually be noted that when a fresh piece of iron or steel is subjected to a gradually increasing magnetizing force, the lowest part of the curve presents near its origin a small concavity (see Fig. 11), showing that under certain magnetizing forces the permeability is greater than at the initial stage. This concavity is more pronounced in the case of hard iron and steel than in the case of soft iron, but the curves differ in detail even in different specimens of the same sort of iron.

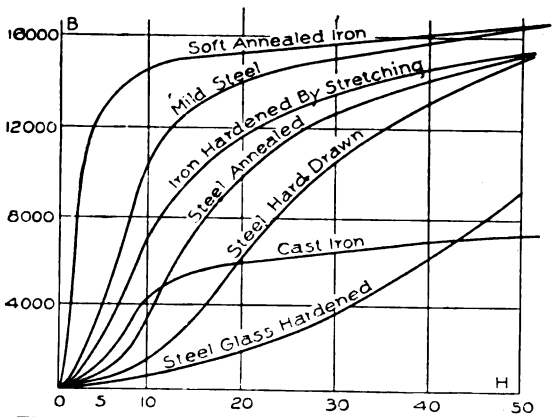


Fig. 12. Magnetization Curves of Various Irons and Steels Used in Dynamo Construction.

Fig. 12 gives a comparative idea of the relation between the magnetic properties of the various irons and steels used in dynamo manufacture.

Effect of Air-Gap in Magnetic Circuit. Thus far we have considered the magnetic circuit as made up of a solid, endless ring of iron. But suppose it to be built up partly of iron and partly of some non-magnetic material, as air or copper. We then have, as the total reluctance of the magnetic circuit, the sum of the reluctances of the various parts of the circuit. For example, if we have a ring made up of l_i centimeters of iron and l_a centimeters of air, the reluctance of this magnetic circuit would be,

$$R = \frac{l_i}{\mu_i A_i} + \frac{l_a}{\mu_a A_a},$$

in which μ and A are respectively the permeability and cross-sectional area of the materials denoted by the subscripts.

It follows, then, that the total flux of such a circuit would be,

$$\phi = \frac{0.4 \pi I T}{\frac{l_i}{\mu_i A_i} + \frac{l_a}{\mu_a A_a}},$$

in which $I T$ represents the ampere-turns and $.4 \pi = 1.257$ as before.

Since the magnetic permeability of air is constant and practically equal to unity, we see that an air-gap or its equivalent introduced into a magnetic circuit previously consisting of iron, will increase the m. m. f. required to produce the same flux as before, due to the inferior permeability of the non-magnetic portion.

S. P. Thompson makes this plain by a graphical method as follows:

"The curve OcC (Fig. 13) represents the relation between the number of magnetic lines in an iron bar and the ampere-turns ($= Hl \div 1.257$) needed to force these magnetic lines through the iron. For example, to reach the height c, the excitation has to be of the value represented by the length Ox_1. On the same diagram the line ObB represents the relation between the magnetic flux across the air-gap and the ampere-turns of current (stream) required to force this flux across. If the gap were 1 centimeter long, 0.795 ampere-turn would produce the field $H = B = 1$ In the present case the gap is supposed to be shorter than 1 centimeter, the line sloping up at such an angle that the length Ox_2 represents the ampere-turns requisite to bring the magnetic flux up to b, the same height on the scale as c. The total amount of excitation required to force these magnetic lines through air and iron will (neglecting leakage) be the sum of the separate amounts. The point x_3 is chosen so that Ox_3 is equal to the sum of Ox_1 and Ox_2, or that the distance of the point r from the vertical axis is equal to the sum of the respective distances of c and b. If the same thing is done for a large number of corresponding points, the resultant curve OrR may be constructed from the two separate curves. It will be seen, then, that in general the presence of a gap in the magnetic circuit has the effect of causing the magnetic curve to rake over, *the initial slope being determined by the air-gap.*"

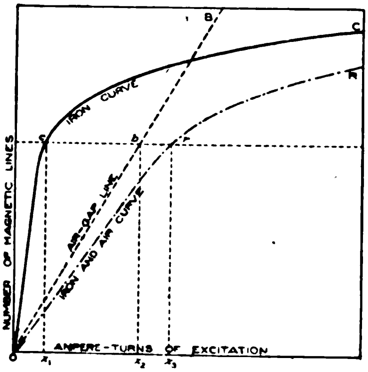


Fig. 13. Graphical Method of Showing Effect of Air-Gap in a Magnetic Circuit.

Effect of Joints in the Magnetic Circuit. Ewing* tried the effect of different numbers of joints in the iron of a magnetic circuit for various magnetizing forces, his results being given in Fig. 14. They refer to a bar of wrought iron cut across, first into two pieces, then into four, and finally into eight pieces. He also found that when the faces of a cut were carefully surfaced up to true planes, the disadvantageous effects of the cut were considerably reduced, and under

* "Magnetic Induction in Iron and Other Metals," London, 1892, pages 208 to 273.

considerable pressure applied externally almost vanished. An ordinary joint is equivalent to an air-gap of about .005 cm. = .002 inch.

Effects of Heat. When iron is raised to 600°C., it begins to lose its magnetic properties; and, if the temperature is increased to 780°C., they entirely disappear. At temperatures between 0°C. and 100°C., various other effects have been noted, such as *aging*—that is, an increase in the hysteresis. In dynamos, however, these effects are practically negligible, since the working temperature should not exceed 75°C.

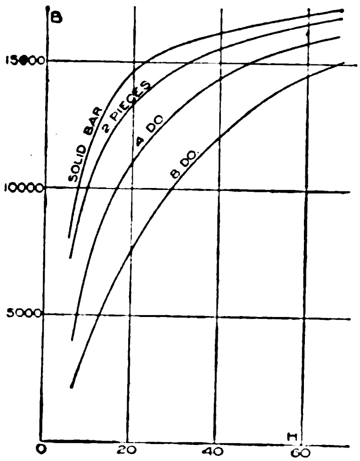


Fig. 14. Curves Showing Effects of Joints in Magnetic Circuit.

Residual Magnetism. It has been found, when the magnetizing forces have been removed from a specimen of iron, that it still exhibits some phenomena of magnetism. This residual magnetism depends for its magnitude upon the character of the iron or steel, being greater in the harder grades than in the softer ones.

Referring to Fig. 11, it will be seen that when a specimen of wrought iron was magnetized to a high flux-density, and the m. m. f. then reduced to zero, the flux-density diminished only to about 7,300 lines per square centimeter, the descending curve of magnetization being above the ascending one. The name *remanence* is given to the lines per square centimeter so remaining. Furthermore, in order to remove this remanence, it is necessary to apply a certain negative magnetizing force, termed by Hopkinson the *coercive force.* It varies in magnitude from 2 for soft wrought iron, to about 80 units or more for hard steel.

Effects of Cycles of Magnetization. This tendency of the magnetic effects to lag behind the forces producing them has been named by Ewing *hysteresis,* and is best studied by subjecting the iron specimen to one or more complete cycles of magnetization. For instance, suppose the m. m. f. applied to a piece of iron to be increased gradually from zero to a maximum value, then decreased through zero to an equal negative maximum, and finally to reverse and return through zero to the positive maximum value. The magnetic changes for such a complete cycle are shown in Fig. 15 for specimens of iron and steel respectively.

The process as shown by the diagram, is started with the flux-density and m. m. f. at zero. The latter is then increased to about 60 units, in the case of the piece of iron, the resulting flux-density being 16,000. The m. m. f. is then reduced to zero, the flux-density only decreasing to 12,800. At a m. m. f. of -3, the flux-density is brought to zero; that is, −3 is the coercive force, and 12,800

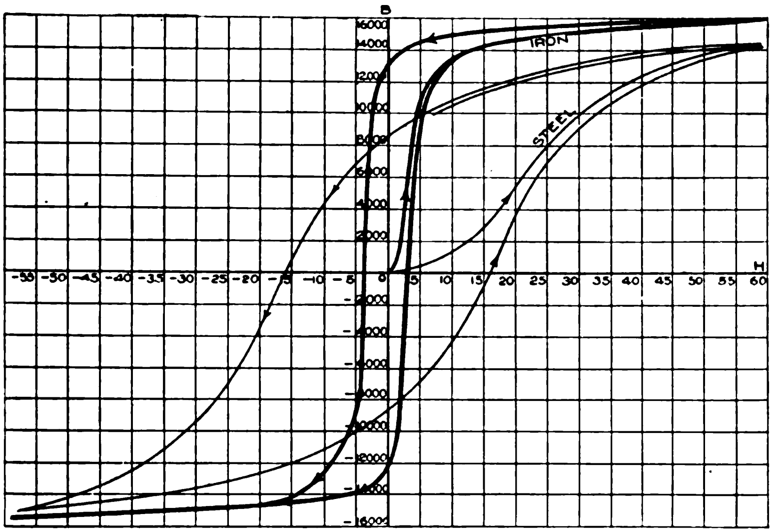


Fig. 15. Curves Showing Magnetic Changes in Iron and Steel Due to Complete Cycles of Magnetization.

the remanence. With a m. m. f. of −60, the flux-density is −15,500; and varying the m. m. f. from this point to zero, leaves the specimen with a flux-density of −12,000. Further increasing the m. m. f. until the flux-density becomes zero, the final m. m. f. is found to be + 3. From this point the m. m. f. is increased to its former maximum value, this ascending curve differing a little from the first. Thus we see that when a specimen of magnetic material is put through a complete magnetic cycle, the coincident values of the m. m. f. and the flux-density form a close curve. The area thus enclosed has been shown by Warburg and Ewing to represent the energy wasted as

TABLE I

Hysteretic Constants for Different Materials

Material	Hysteretic Constant η	Material	Hysteretic Constant η
Very soft iron wire	.002	Soft annealed cast steel	.008
Very thin soft sheet iron	.0024	Soft machine steel	.0094
Thin good sheet iron	.003	Cast steel	.012
Thick sheet iron	.0033	Cast iron	.016
Most ordinary sheet iron	.004	Hardened cast steel	.025
Transformer cores	.0045		

heat in the material, when the specimen is put through a complete cycle; and its value depends upon both the character of the material, and the degree of magnetization, being greater for hard steel than for soft iron with the same range of magnetization.

Iron, when placed in an alternating magnetic field, is not only subjected to the hysteresis phenomena above considered, but it also becomes subjected to a set of parasitic electrical currents. These tend further to heat the iron, and are called *Foucault* or *eddy currents;* their path, by Maxwell's law, is perpendicular to the direction of the flux. Their value may be lessened by increasing the resistance of their path—that is, by *laminating the iron in a direction parallel to the direction of the flux and perpendicular to the path of these currents,* each sheet of iron being insulated from its neighbors. In practice, these laminæ vary from about 15 to 25 mils (0.015 inch to 0.025 inch) in thickness.

Calculation of Heat Waste in Iron Cores. From consideration of a great many tests of hysteretic losses, Dr. C. P. Steinmetz proposed the following law connecting the hysteresis loss h in ergs per cubic centimeter per cycle and the maximum flux-density B attained during a cycle:

$$h = \eta B^{1.6},$$

wherein η is a coefficient called the *hysteretic constant,* depending for its value upon the quality of the material. Some of these constants are given in Table I for ordinary frequencies. This law is practically true for all cycles ranging up to 200 per second.

By applying the proper transformation factors, the Steinmetz formula reduces to:

$$W_h = 0.83 \times \eta \times f \times B^{1.6} \times 10^{7},$$

wherein

W^h = Hysteresis loss in watts per cubic inch of iron;
f = Frequency in cycles per second;
B = Flux-density in lines per square inch.

In Fig. 16 are given graphically the hysteresis losses in watts per cubic inch of iron per cycle per second, with various hysteretic constants.

Besides the hysteretic loss in iron cores, there is also the eddy-current loss, which varies directly as the square of the thickness of the iron laminæ, as the square of the maximum flux-density, and as

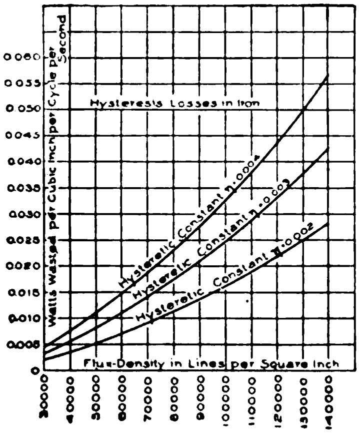


Fig. 16. Curves Showing Hysteresis Losses in Iron with Various Hysteretic Constants.

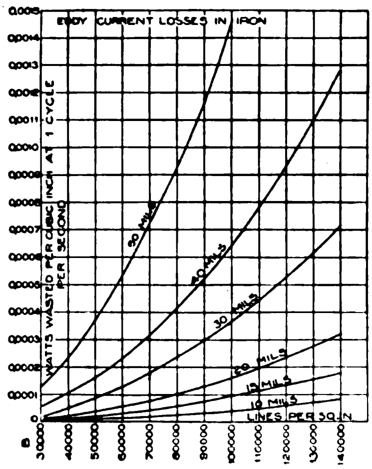


Fig. 17. Curves Showing Eddy-Current Losses in Iron of Varying Thickness under Varying Flux-Density.

the square of the frequency. The formula obtained by calculation and found to agree closely with practice, is:

$$W_e = 40.6 \times t^2 \times B^2 \times n^2 \times 10^{-12},$$

wherein

W_e = Watts loss due to eddy currents per cubic inch of iron;
t = Thickness of the iron plates, in inches; and the other symbols have the meanings previously assigned.

Fig. 17 exhibits values of W_e graphically for various thicknesses of iron over wide ranges of flux-density at one cycle per second.

The sum of these losses for any electrical machine is called for brevity the *iron-losses* of that machine. Calculations for actual machines will be given later.

Rotational Hysteresis. When a piece of iron is rotated in a magnetic field, it passes through a magnetic cycle, but in a way far different from that which has been described. Mordey found the losses to be slightly lower for rotation than for reversal; while Baily went further and showed (Fig. 18) that the former loss was slightly greater than the latter for flux-densities up to 15,000 lines per square centimeter, but that beyond this point the loss due to rotation rapidly diminished with increase in flux-density.

Owing, however, to eddy-current losses, the flux-densities in those parts of electrical machines which rotate in a fixed magnetic field are not allowed to exceed 15,000 lines per square centimeter (15,000 × 6.45 lines per sq. in.), except in the armature teeth of direct-current machines. We may therefore neglect this difference, as is usual in practice, and may calculate both kinds of hysteresis loss by the formula previously given. According to Ewing, this rotation loss is *molecular magnetic friction* and not true hysteresis, because the magnetization does not necessarily lag behind the m. m. f.

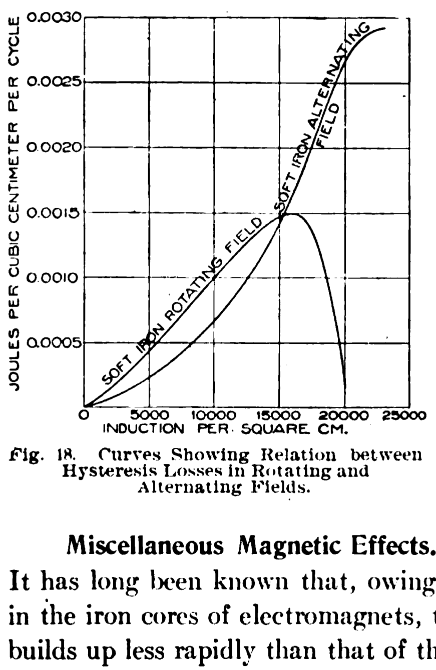


Fig. 18. Curves Showing Relation between Hysteresis Losses in Rotating and Alternating Fields.

Miscellaneous Magnetic Effects. *Retardation of Magnetization.* It has long been known that, owing to the eddy currents produced in the iron cores of electromagnets, the magnetism of the inner part builds up less rapidly than that of the outer parts. Similarly, when the m. m. f. is cut off, the inner part of the core retains its magnetism longer than the outer parts. In dynamos with large field-magnets, several minutes may elapse before the field will build up or change, and Hopkinson has shown that the retardation varies as the square of the linear dimensions of the core.

Magnetic Creeping. Ewing found that when a steady m. m. f. was applied to a specimen of iron, and the magnetism measured at intervals, the flux-density kept continually creeping up although the m. m. f. was absolutely constant. He named this *viscous hysteresis;* but it is a true magnetic lag, and must not be confounded with the lag in phase resulting in the formation of a loop, or the lag due to self-induction occasioned by eddy currents in the iron.

Slow Changes in the Magnetic Properties of Iron. When iron is continually subjected to rapidly alternating flux-densities, especially when the temperature rises above 100°C., it is found that the hysteretic loss is perceptibly increased. This effect has been observed in connection with transformers, where the iron losses play an important part in the working; but in continuous-current dynamos and motors the effect is negligible. (See page 12).

Magnetic Dampers. If a magnetic flux, whether in air or iron, be surrounded by a closed electrical circuit, any change in the value of the flux will induce an e. m. f. in that metallic circuit, tending to oppose the flux change. It has suggested itself, therefore, to builders of dynamos, to surround the magnet-poles with copper bands in order to reduce the possibility of sudden field fluctuation. This feature is employed extensively in alternating-current generators, synchronous motors, and rotary converters, under the name of *dampers* or *damping rings.*

Generation of E. M. F. by Cutting Flux. Whenever lines of magnetic flux are cut by a conductor, an e. m. f. is produced in that conductor, the value of the e. m. f. being one volt when 100,000,000 or 10^8 lines are cut per second. In other words, the e. m. f. depends solely upon the *time rate* of cutting, so that one volt would also be set up if 10^6 lines were cut in one-hundredth of a second. In both cases the time rate of cutting is supposed to be uniform throughout the given time.

The generation of e. m. f. is absolutely certain, no matter when or by what process the lines are cut. A *current,* however, will flow only when there is a closed electrical circuit. A straight bar of copper, for example, cutting across a magnetic field, would have a potential difference established between its ends; but, excepting a slight displacement current at the start, no current would flow until the electrical circuit was completed. We should distinguish, therefore, between the generation of an e. m. f. and the flow of a current. Thus, it may happen that two or more opposing voltages neutralize each other, so that no current whatsoever flows, even though the electrical circuit is complete. This is the case when a copper ring is moved in its own plane across a uniform field; the two halves cut an equal number of lines, and the e. m. f. produced in one half is exactly equal but opposite to that produced in the other half of the ring, making the current-flow zero. This explains the fact that the flux in a coil of wire must be varied in order to permit a current to flow; or, in other words, the coil must be filled with and emptied of, lines of magnetic induction, in which case an alternating current is produced. This is often stated so broadly, however, that it seems to mean that an e. m. f. cannot be obtained in a uniform field. As already stated, an e. m. f. *must* be produced whenever magnetic lines are cut, though a flow of current may not result.

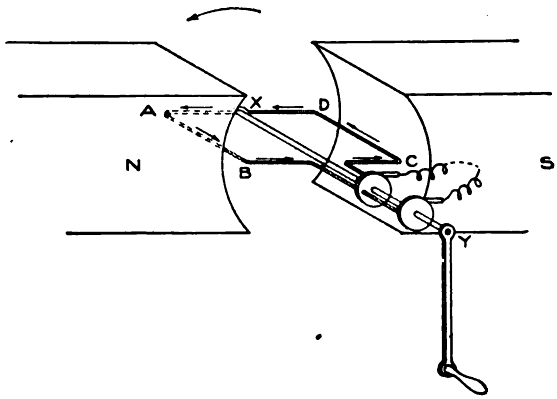


Fig. 19. Illustrating the Elementary Principles of the Generator.

Elementary Generator. The simplest form of generator consists of a loop of wire arranged to rotate in a uniform magnetic field, Fig. 19. The generation of e. m. f. in such a dynamo will be as follows: Assume the loop with its plane parallel to the direction of the flux. If, then, the loop be rotated counter-clockwise about its axis *XY*, the sides *AB* and *CD*, which cut lines of magnetic induction, will have an e. m. f. induced in them that will tend to cause a current flow in the directions indicated by the arrows. The value of this e. m. f. will depend upon the speed or *time rate* of cutting; and since this rate is greatest when the plane of the loop is parallel to the direction of the flux, the e. m. f. developed at the instant represented in Fig. 19 will be a maximum. As the loop approaches the 90° or vertical position, the generated e. m. f. gradually decreases because the rate of cutting is diminishing, until, at the 90° position, the cutting of the flux and the generated e. m. f. are both zero. If the rotation is continued, the rate of cutting gradually increases until the 180°

position is reached, where it again becomes a maximum, so that the e. m. f. generated at this intant is also a maximum. The cutting, however, in the two quadrants following the 90° position, has been in the opposite direction to that occurring in the first quadrant, so that the direction of the e. m. f. generated in the second and third quadrant is reversed with respect to that generated in the first quadrant. In passing from the 180° position to the 270° position the rate of cutting and the generated e. m. f. again diminish to zero; and from 270° to the 360° or 0° position, the rate of cutting increases and the direction of the generated e. m. f. is the same as that produced in the first quadrant, the e. m. f. rising once more to a maximum value at the 360° position.

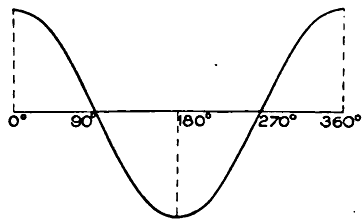


Fig. 20. E. M. F. Curve of Simple Generator Shown in Fig. 19.

Plotting the various instantaneous values of the e. m. f. so generated, we obtain the curve shown in Fig. 20. Such an e. m. f.

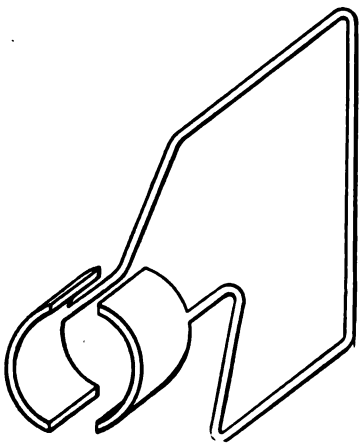


Fig. 21. Simple Commutator Connected to Loop with Single Turn.

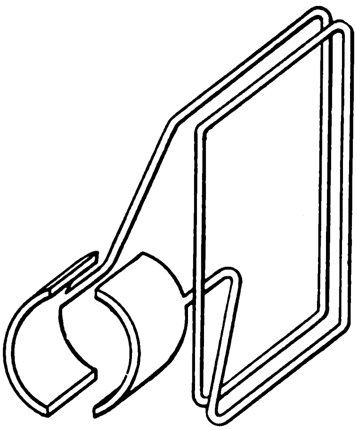


Fig. 22. Simple Commutator Connected to Loop with Double Turn.

is called an *alternating* one, because of its reversal from positive to negative values; that is, it tends to produce a current, first in one direction and then in the other direction, through the circuit. If, however, it is desired to supply the external circuit with a direct or continuous current, a special rectifying device called a *commutator* must be added.

In its simplest form, a commutator consists of a metallic tube slit longitudinally into two equal parts and mounted on a cylinder of insulating material, each half being connected to one terminal of a loop as indicated in Fig. 21. Fig. 22 shows a similar arrange-

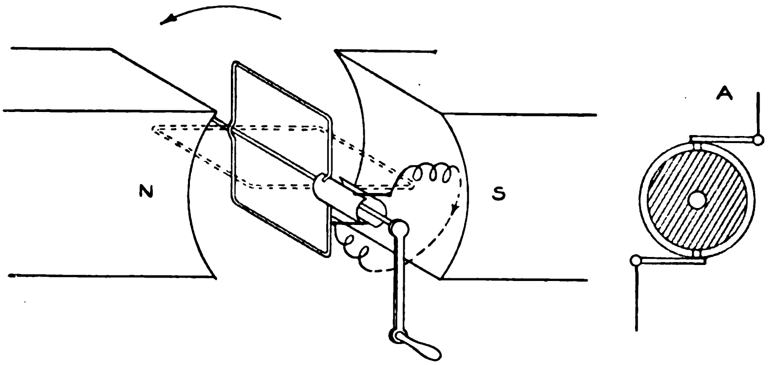


Fig. 23. Simple Form of Generator, Showing Arrangement of Brushes in Contact with Commutator to Give Unidirectional Current in External Circuit.

ment, except that the loop has two turns instead of one. Against this commutator, at diametrically opposite points, press a pair of metallic springs or brushes which lead the current due to the generated e. m. f. to the external circuit. If, as in Fig. 23, these brushes are so set that each half of the split tube moves out of contact with one brush and into contact with the other brush at the instant when the loop is passing through the positions where the time rate of cutting is minimum (as indicated in the enlarged end view of commutator shown at A), the alternating e. m. f. generated will produce in the external circuit a rectified, commutated, or unidirectional current. That is, the current in the external circuit will flow in one direction. If this external current be plotted, it will be of the pulsating character shown in Fig. 24. This explanation need not be changed, if, for a single loop, we substitute a coil wound on an iron ring as in Fig. 25. The effect of this is to increase the generated e. m. f. by increasing the number of times the electrical circuit cuts the flux. Now, referring again to Fig. 21, suppose, instead of one coil as there shown, we have two coils mounted side by side and

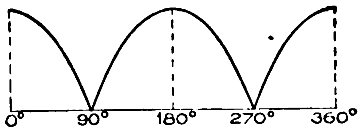


Fig. 24. Curve of Commutated Current.

connected in parallel to the commutator segments, we shall then obtain the elementary conditions shown in Fig. 26. If, then—similarly to the arrangement developed in Fig. 25—we place an ex-

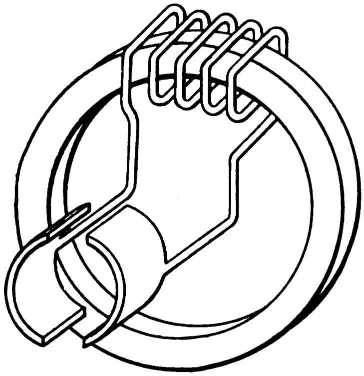


Fig. 25. Simple Ring Armature with One Coil.

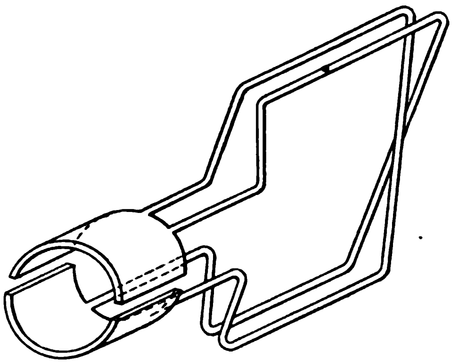


Fig. 26. Simple Loop Armature with Two Coils in Parallel.

actly similar coil at the opposite side of the ring, as in Fig. 27, we see that when its terminals are connected to the same two half-rings as the first, the two coils are in parallel, and though the

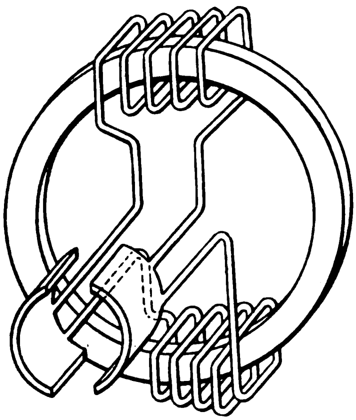


Fig. 27. Simple Ring Armature with Two Coils in Parallel.

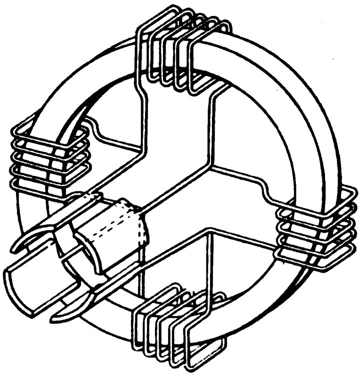


Fig. 28. Four-Part Ring Armature (Closed Coil).

voltage generated by revolving this winding with two coils is no greater than with one coil, the current-carrying capacity of the resultant winding is evidently doubled.

The current obtained, however, from this arrangement has the disadvantage of being pulsating, as already shown. To give continuity to the external current we must multiply the number of gen-

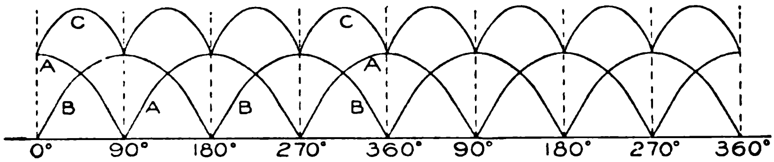


Fig. 29. Curve of E. M. F. and Current Generated by Armature Arrangement of Fig. 28.

erating coils, and also the number of commutator segments, arranging the coils around the armature so that one set will come into action before the other set goes out. If, then, we place upon the iron ring two additional sets of coils at right angles with the first set, as in Fig. 28, one set will be in the position of maximum activity when the other is in the position of least action; and Fig. 29 will represent the resulting external e. m. f. and current, which, although continuous (*i.e.*, never becoming zero), is not quite steady, having four slight undulations per revolution. By increasing the number of coils and commutator segments to a hundred or more, an external current can be obtained in which no undulations can be detected except by the telephone.

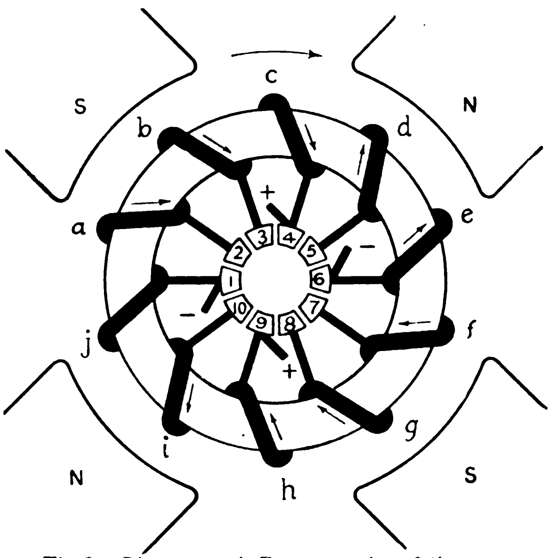


Fig. 30. Diagrammatic Representation of Gramme Ring Winding.

On examination of the winding represented in Fig. 28, it is apparent that the four coils are wound in series, the end of the first being connected to the beginning of the second, and so on, the end of the fourth being finally connected to the beginning of the first—the whole of the winding constituting, therefore, a single, closed coil. Also, it may be noted that the beginning of one coil and the end of preceding one are connected to the same commutator bar. In the practice the commutator is usually made up of a number of parallel

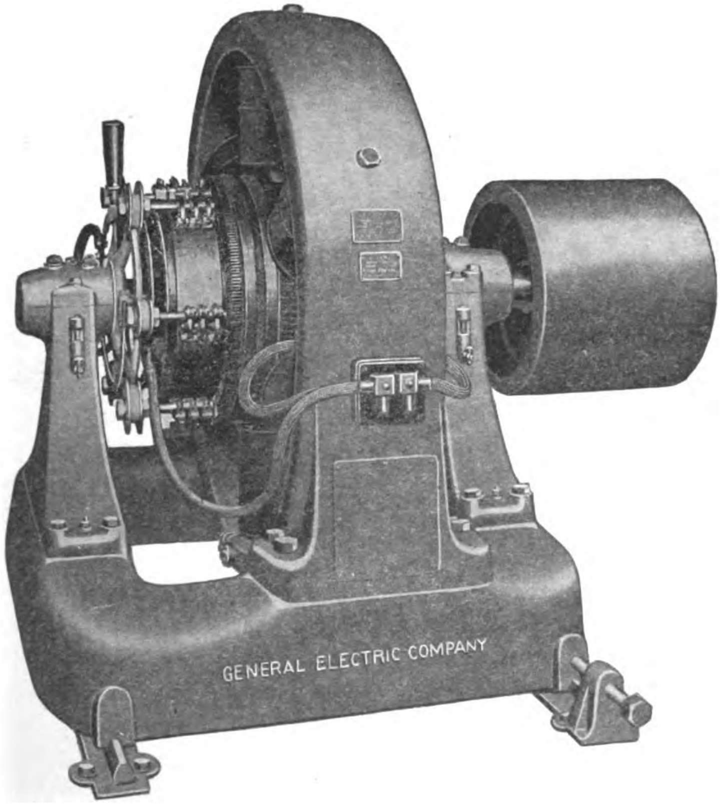


Fig. 31. Typical 6-Pole Belt-Driven Generator, Showing Armature, Field-Magnets, Commutator, and Brushes.

bars of copper set around on, and separated from each other by, insulating material; and the armature is made up of a number of sections as in Fig. 30, which represents a Gramme ring winding. This, and other windings, will be treated more fully later.

Organs of Continuous-Current Dynamos. We have seen that the dynamo in its simplest form consists of two main portions—an *armature,* which in revolving in a magnetic field generates an e. m. f.

in the conductors wound upon it; and a *field-magnet*, whose function it is to provide a flux for the conductors to cut as they revolve. These two parts are always present in all generators, whether for continuous current or for alternating current; and they are easily distinguished (Fig. 31). In almost all continuous-current machines, the field-magnet is a comparatively simple electromagnet which remains stationary; the armature, however, is more complex and usually rotates. In addition, we have seen that continuous-current machines require a commutator, while alternating-current machines are provided with *collecting* or *slip rings*. In either case, brushes are required to connect the revolving commutator or collector rings to the external circuit.

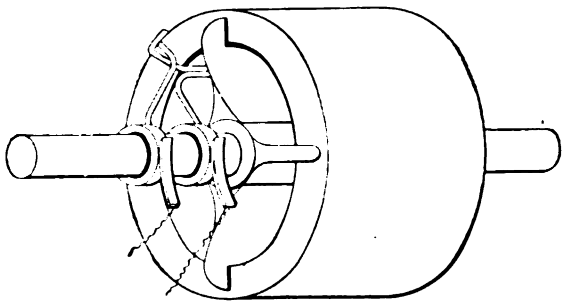


Fig. 32. Armature of Gramme Ring Type.

In continuous-current machines the field-magnet, being usually stationary, is combined with the bearings and bed-plate to form the frame of the machine. Similarly, the armature and commutator are supported by a spider and shaft, which rotate in the bearings attached to the frame. The complete machine comprises, in addition, various other mechanical parts taken up in detail later.

Armatures. Any electrical conductor—as, for example, a simple coil of wire—revolving in a magnetic field so as to cut the flux, would act as an armature and tend to have an e. m. f. generated in it. In order to obtain a practically steady direct current, together with maximum effect for a given amount of material, and to secure compactness, convenience of working, and other practical conditions, armatures have resolved themselves into the following types, although, theoretically, any figure of revolution around which coils are placed symmetrically, would answer:

(1) *Ring armatures*, in which the coils are grouped upon a ring core of iron whose axis of symmetry is also its axis of rotation.

(2) *Drum armatures*, in which the coils are wound longitudinally over the surface of a drum or cylindrical iron core.

(3) *Pole armatures*, in which the conductors are wound around radial iron cores projecting outward from a central hub.

(4) *Disc armatures*, in which the conductors are arranged in the form of a flat disc the plane of which is perpendicular to the axis of rotation, and usually not comprising an iron core.

The *ring armature* was first employed by Pacinotti in 1860, and described by him in 1865; but it is commonly known by the name of *Gramme*, the French electrician, who reintroduced it in 1870. Gramme wound the coils around the entire surface of the annular core, which he made of varnished iron wire in order to reduce the wasteful effects of eddy-currents; while Pacinotti had the coils wound

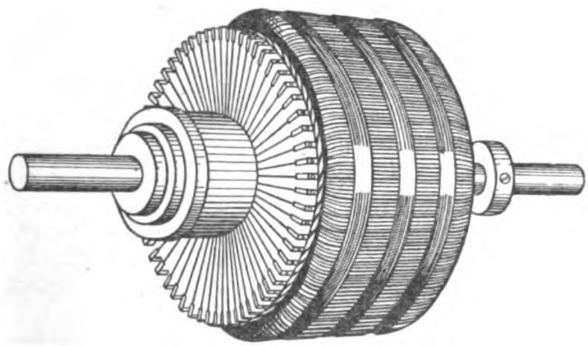


Fig. 33. Ring Armature of Gramme Dynamo.

between projecting teeth upon an iron ring. In ring armatures, the parts of the copper winding which pass through the interior of the ring do not cut any flux, and so are inoperative unless there are pole-pieces of the field-magnet projecting internally, which is not usually the case in practice.* Hence the ring type of winding offers a certain amount of wasteful resistance, which, however, can be made small compared with the resistance of the external circuit. Fig. 32 represents an armature of the Gramme ring type as generally used, although some machines are so designed as to have the outside of the ring act as a commutator, the current being collected directly from the winding by brushes which trail on the periphery of the ring, the inner parts of the conductors cutting the flux. Fig. 33 shows a completely wound Gramme ring armature.

* In case of magnetic leakage through the opening in the ring core, the internal parts of the winding would produce an e. m. f. in the opposite direction to that generated by the outer sections, thus decreasing the effective voltage.

Drum armatures were introduced by Siemens, who wound cores of iron wire upon a frame of non-magnetic material. In their complete form, they were first brought out in 1871 by Von Hefner Alteneck, and improved later by Weston and others. As seen from Fig. 34, this type is even simpler than the ring, and consists in placing the elementary loop before described upon a supporting cylinder of magnetic material, so as to reduce the magnetic reluctance of the gap between the two faces of the field-magnet poles. This type of armature is almost exclusively used for continuous-current machines of to-day. In Fig. 35 is shown a partly-wound drum armature.

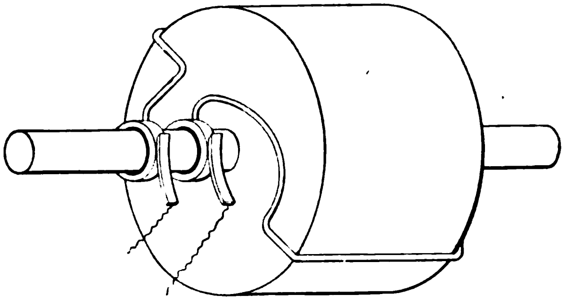


Fig. 34. Illustrating Method of Drum Winding.

Pole armatures—those having the coils wound upon projecting poles—were devised by Allan, Lontin, Weston, and others. They were used in Lontin's machines, as shown diagrammatically in Fig. 36. Owing, however, to the great self-induction thus introduced into each section of the winding, and the consequent sparking at the commutator, these machines were not successful. Pole armatures are to some extent used in alternating-current generators.

Disc armatures, illustrated in Fig. 37, have never been very widely used. The interesting feature of this type is the fact that there is no necessity for magnetic conducting material between the two faces of the field-magnet.

Armature Cores. The function of the armature core is two-fold: it supports the generating conductors, and carries the flux from one face of the field-magnet to the other face. On account of its high permeability and its great strength, iron is by far the best material for armature cores. We have seen, however, that when a mass of iron (or other conductor) is rotated in a magnetic field, wasteful eddy currents are set up in the mass. In order to reduce them as much as possible, it has become the practice to build up armature cores of thin soft iron or mild steel discs, insulated from each other by varnish, rust, or paper. These discs are arranged to have their planes parallel to the direction of the flux and perpendicu-

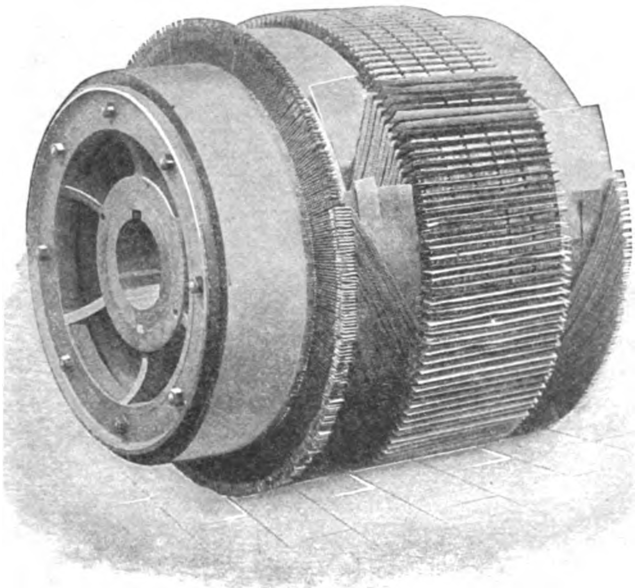


Fig. 35. Partly-Wound Drum Armature.

lar to the flow of eddy-currents. Solid cores of metal should on no account be used in any armature.

Field-Magnet Excitation. In order to generate an e. m. f. in the armature conductors, they must cut a flux. This flux is supplied by a magnet, and may be excited therein by five simple methods. These methods may be grouped under two headings, according to whether the armature of the machine furnishes the magnetizing current or m. m. f. required, or whether it is provided from some other source.

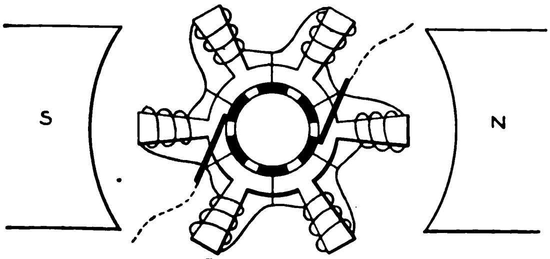


Fig. 36. Armature of the Pole Type.

(1) *Magneto-Machine.* In this type of generator, historically the first, the flux was provided by a permanent magnet as shown diagrammatically in Fig. 38. This method has the disadvantage of requiring a much bulkier machine in comparison with the methods to be described later, since permanent magnetism cannot be maintained at the high flux-density which may be produced by an exciting coil. It has, however, the advantages of simplicity and constancy, but is used only in the smallest of generators employed for example,

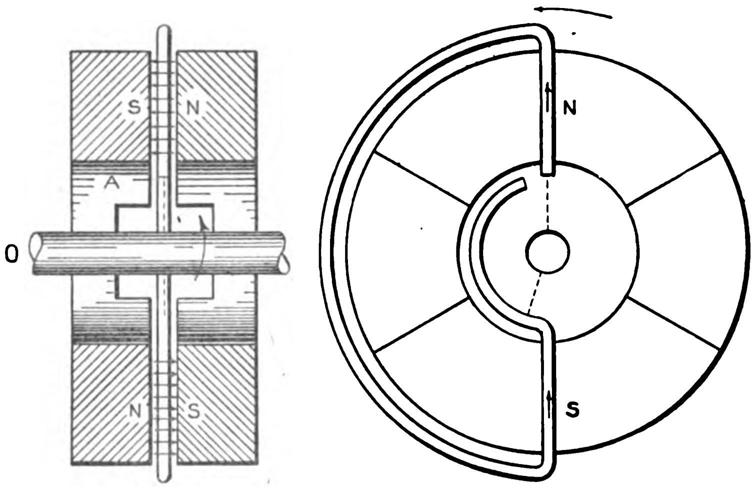


Fig. 37. Armature of Disc Type with Two Inductors in Series.

to furnish current for ringing bells, for ignition in internal-combustion engines, etc.

(2) *Separately-Excited Generator.* The next step was to excite the field-magnets by means of a coil fed from some source of electrical energy other than the generator itself. This method, outlined in Fig. 39, produces the same results as the magneto method, without the disadvantage of great bulk. It requires, however, a separate machine or battery for excitation purposes solely, and the method is not employed in continuous-current practice, except where many machines are in operation, or where their terminal voltage exceeds 800 volts. It is largely employed in exciting the fields of alternating-current generators, since an alternating current will not produce a unidirectional magnetic field.

In either of the methods just mentioned, the e. m. f. of the machine may be governed in three ways—namely, by (*a*) altering the speed of rotation of the armature; (*b*) by varying the number of effective conductors by moving the brushes; and (*c*) by changing the magnetic flux through the armature. The latter is altered in the case of magneto-machines by shunting the flux away from the armature through an auxiliary piece of iron. In the case of separately

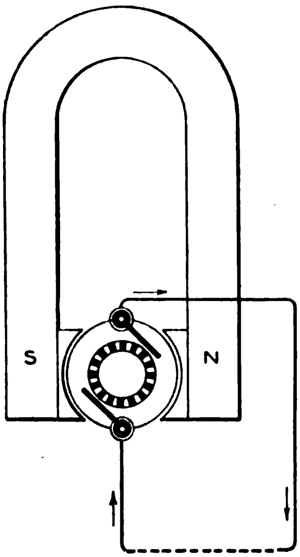


Fig. 38. Diagrammatic Representation of Magneto-Generator.

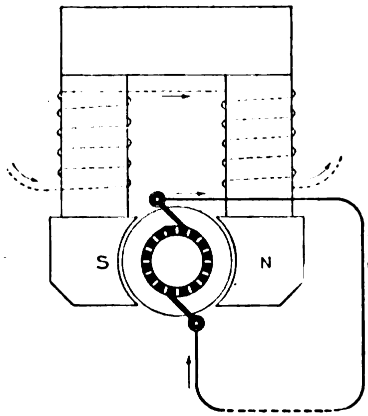


Fig. 39. Diagrammatic Representation of Separately-Excited Generator.

excited machines, the flux is varied by regulating the exciting current or the number of turns of the solenoid.

Generators of the continuous-current type may be made *self-exciting* by either of four methods. The whole current supplied by the machine to the external circuit may be passed through the solenoid, or a part of the total current may be passed through the field-winding; or two field-windings may be employed, one traversed by the load current and the other by the shunt current; or, finally, the field-exciting current may be produced by an e. m. f. generated by a separate winding on the armature of the generator.

(3) *Series Dynamo.* The series continuous-current generator outlined in Fig. 40 has but one circuit. It has, however, the disadvantage of not starting to generate until a certain speed has been reached or unless the resistance in the external circuit is below a certain

limit. It also is liable to become reversed in polarity, thus unfitting it for electrolytic work. Any increase in its external resistance, at a given speed, diminishes the current stream that excites the magnetic circuit, thereby lowering the e. m. f. Conversely, reduction of external resistance tends to increase the e. m. f. of the machine until the *IR* drop and the armature reaction become so large that the available voltage falls more rapidly than the field stream increases. The only series generators actually employed supply *arc lamps in series*, and are provided with automatic regulators to maintain constant current; hence the external voltage and power are directly proportional to the external resistance.

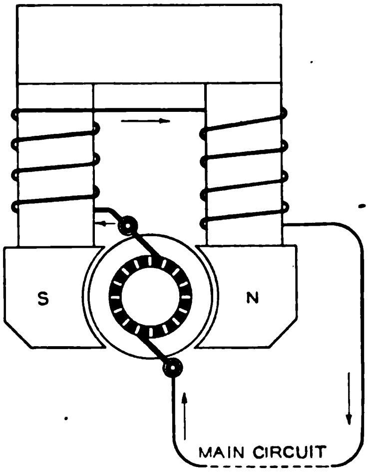


Fig. 40. Diagrammatic Representation of Series Continuous-Current Generator.

(4) *Shunt Dynamo.* In the shunt-wound generator, Fig. 41, only a small part of the current in the armature passes through the field winding. The field-exciting circuit F_{sh} has, therefore, a relatively high resistance compared with that of the external circuit. This machine is tolerably self-regulating within certain limits, when properly designed; but if overloaded, its internal actions are such as to reduce its generated e. m. f. to zero. Its polarity never reverses of itself; and although it is a trifle more expensive to buy than the corresponding series machine, its self-regulating properties more than overbalance this. The amount of energy required for excitation in either series or shunt field-windings for identical machines, is precisely the same, since to produce a given flux (as shown in the discussion of the magnetic circuit) demands a definite number of *ampere-turns*. In the series machine, the *turns* of wire are few in number, while the current in *amperes* is relatively large. In the shunt type, the reverse is the case.

(5) *Separate-Circuit, Self-Exciting Generator.* The third type of self-exciting machine is that in which the field circuit is supplied by only part of the armature, or by separate windings on the armature,

as represented in Fig. 42. This arrangement is adopted for A. C. generators and for D. C. machines in which the e. m. f. generated is over 800 volts, since it is undesirable to apply such voltage to field excitation. In effect, however, it is almost the same as the separately excited machine (No. 2, above).

Generator Regulation. In all the simple methods of field excitation just described, the e. m. f. generated by the dynamo varied more or less with load. If the load were constant (*i.e.*, if the same number of lamps were being supplied all the time), the generator could be designed to give a predetermined terminal voltage. But under usual working conditions, the load connected to an electric generator—such as lamps, motors, or other devices—is continually changing, so that it is essential to provide some device whereby its e. m. f. may be varied to suit the varying load. The generated e. m. f. is the sum of the terminal voltage and that lost in overcoming internal reactions, the latter quantity varying with load. As stated previously, there are three methods for regulating the generated e. m. f. of the dynamo—namely, by varying the speed of rotation of the armature, by varying the magnetic flux, and by changing the number of effective or active armature conductors.* Of these three possible methods, however, the only one utilized is that of varying the magnetic flux, it having been found more convenient to regulate the prime mover for constant speed than for speed increasing with load, while the method of changing the effective armature conductors by shifting the brushes is conducive to bad sparking at the commutator. As has been noted, the most advantageous way to vary the magnetic flux is to vary the current in the energizing coils.

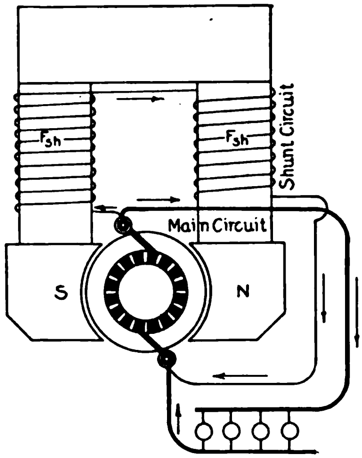


Fig. 41. Diagrammatic Representation of Shunt-Wound Generator.

*The expression "active armature conductors" refers to those conductors which are actually cutting flux and generating an e. m. f. at any instant.

Since the current in the field-exciting coils is dependent upon the e. m. f. impressed at their terminals and upon their ohmic resistance, we can increase the magnetic flux by decreasing the resistance of the field-exciting circuit or by increasing the terminal voltage impressed there. Also, the flux may be made to increase with load, by passing the external current of the generator through a few turns of thick wire, called *series turns* or *compounding turns*, placed upon the field-cores. The first method is usually non-automatic, and is applicable to shunt and separately excited machines; the second is applicable to separately excited machines; and the third, to both types; and a generator thus equipped is called a *compound generator.*

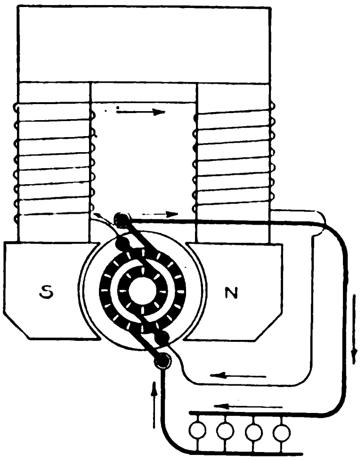


Fig. 42. Diagrammatic Representation of a Separate-Circuit, Self-Exciting Generator.

Methods of Compounding. (1) *Separate and Series* (Deprez). The connections are shown diagrammatically in Fig. 43, a separate source of e. m. f. being used to produce the initial and constant excitation, while the external current of the machine is led through a series winding, thus compensating for the internal drop of the generator to any desired degree, even *increasing* the terminal voltage with load if desired.

(2) *Shunt and Series.* By far the most widely used of all compounding schemes, however, is the one in which series turns are added to the plain shunt winding, as illustrated diagrammatically in Fig. 44. By properly proportioning the ampere-turns in the shunt and series coils, the terminal voltage-load curve may be made to take any desired form. For instance, it may be made constant, increasing or decreasing throughout the rated load range of the machine. This arrangement will be considered in detail later on.

(3) *Booster Method.* This consists essentially of an auxiliary generator in series with the main machine, the e. m. f. of the former being low; and since its field winding is in series with the external circuit, it will automatically regulate the voltage of the combination in accordance with the load

(4) *Miscellaneous Methods.* If the generator armature be wound according to a special scheme devised by Sayers,* the field excitation may be produced by a simple shunt winding, and a compounding effect produced by giving the brushes a backward lead. Other methods of compounding may be found in S. P. Thompson's "Dynamo-Electric Machinery."

Actions in the Armature. Thus far we have considered the armature and the field of the generator separately, assuming that the former did not affect the latter. It is found, however, that when the armature of a generator or motor is carrying current, its action is not the same as when it carries no current, owing to the distortion of the field flux by the magnetization of the armature. In order

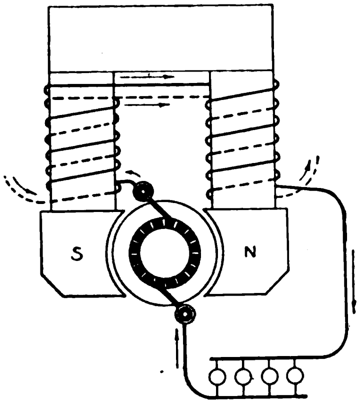


Fig. 43. Separate and Series Method of Compounding.

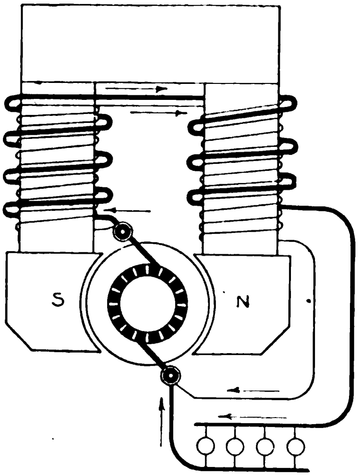


Fig. 44. Shunt and Series Method of Compounding.

to study the effects produced, we shall consider a dynamo of the simple bipolar type (Fig. 45) with a ring armature, when the machine is operating without and under load.

Suppose the armature to be rotating clockwise, when viewed from the commutator end, and that the north pole of the field-magnet is at the right of the armature, the south pole being on the left, as in Fig. 46. The flux will then pass from right to left through the armature; and the e. m. f. generated in the moving conductors of the armature is, in accordance with Maxwell's law, as follows:

* See E. Arnold's *Gleichstrommaschine* (Erster Band, Berlin, 1902), pages 417, 449, *et seq.*

In all the conductors which are ascending, the generated e. m. f. is directed toward the observer; while in all the descending conductors, the generated e. m. f. is directed away from the observer. If the circuit through the armature is closed, the generated e. m. f. will produce a current flowing in the same direction; and in Fig. 46 the current-flow in the armature is toward the top and away from the bottom on both sides. This result is obtained when the armature is wound right-handedly, being the opposite if the winding is left-handed. With a drum-wound armature, the result is the same; but the diagram is more complex on account of the end connections.

It will be noted that the path of the current is from brush to brush, through each of the armature coils, without going to the commutator except where it passes out to or returns from the external circuit. We have seen, however, in the ideal dynamo, that the e. m. f. generated in an armature coil is proportional to the time rate at which the flux is cut. In the case illustrated in Fig. 47, no two armature coils are cutting the same amount of flux at any given instant, so that the voltage generated in each coil depends upon its position in the field. Since one-half of the coils are connected in series between the brushes, the total difference of potential (p. d.) measured at the latter will at any instant be the sum of the instantaneous e. m. f.'s generated in the individual coils.

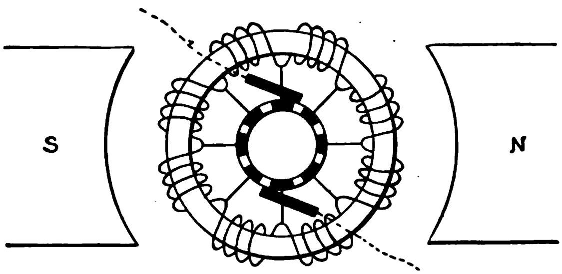


Fig. 45. Diagrammatic Representation of Simple Ring Armature.

If the field were uniform, it is plain that the flux cut at a given instant by any one coil would be proportional to the sine of the angle which it makes with the direction of the field at that instant; so that if we plot the values of these instantaneous potentials as ordinates, and the corresponding angles as abscissæ, we obtain Fig. 47.

Thus it is seen that the p. d. obtained at the brushes may be compared to that obtained at the terminals of a battery connected as shown in Fig. 48, each cell representing an armature coil and being supposed to supply an e. m. f. equal to that generated by the coil it replaces. The terminal voltage will then be obtained by adding all these potentials between the 0° and the 180° positions in Fig. 47, or integrating the voltage curve between these limits, the negative part being exactly equal to the positive half if the dynamo is symmetrical. The sum thus obtained grows slowly at first, then rapidly, and slowly again as it reaches its highest value, repeating this program in the other half-circumference. These facts are shown at reduced scale in Fig. 49. In the actual dynamo, this integration is effected because the coils are connected in series; and it is possible to demonstrate this experimentally.

Exploration of Potentials around a Commutator. Several more or less simple ways of showing the distribution of the generated e. m. f. around the commutator of a dynamo, have been suggested,* but only one, Mordey's method, will be taken up here. It consists in connecting one terminal of a voltmeter, preferably an electrostatic one, to one brush of the machine, and the other terminal to a small pilot brush *b* (Fig. 50), which can be moved from point to point around the commutator. The armature of the generator is then rotated at its rated r. p. m. (revolutions per minute); and, starting at the brush *N*, *b* is placed in successive positions around the commutator, the voltmeter reading in each position being noted, together with the corresponding angular situation of *b*.

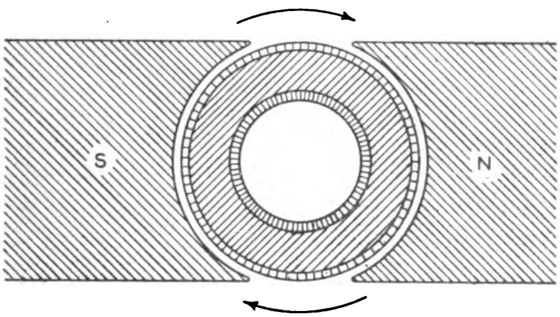


Fig. 46. End View of Ring Armature in Bipolar Field.

These results, plotted with the voltage readings as ordinates and the corresponding values of angular situations of *b* as abscissæ, are as represented in Fig. 51, when the armature is carrying no current. The curve so obtained is not usually a true sine curve in commercial machines, because the magnetic field in which the armature rotates is not uniform. Also, we shall see later that when the armature

* See S. P. Thompson's "Dynamo-Electric Machinery," Vol. I. (N. Y., 1904), page 204.

carries a current, its presence causes a further distortion in the distribution of the flux. Furthermore, the setting of the brushes or an injudicious shaping of the pole-pieces will cause irregularities to be present in this curve, examples of which have been given by Von Gaisberg*, Kohlrausch**, M. E. Thomson***, Ryan†, and Shephardson††.

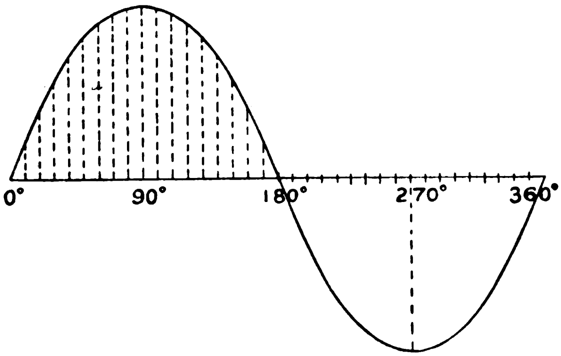


Fig. 47. Curve of Induced E. M. F.

Reactions in the Armature. This leads us to consider the reac-

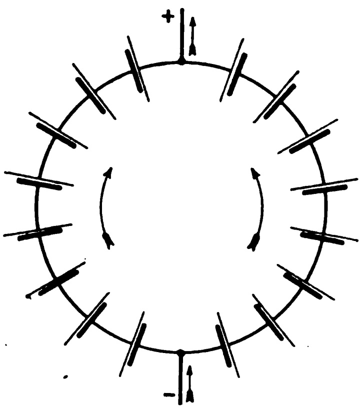


Fig. 48. Battery Analogy of Simple Dynamo.

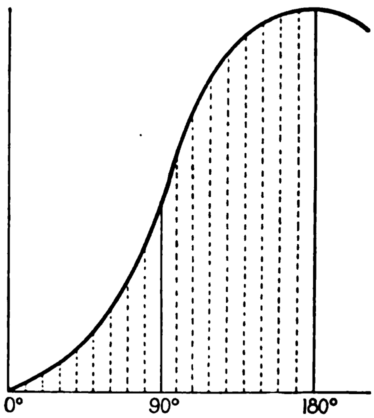


Fig. 49. Integrated Curve of Potentials.

tions of the armature when the generator is operating, which are manifested in many ways, the most important being:

(1) A tendency to *cross-magnetize* the armature.

(2) A proneness to spark at the brushes.

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* *Elektrotechnische Zeitschrift*, vii 67, Feb. 1886.

** *Centralblatt für Elektrotechnik*, ix 419. 1887.

*** "Electrical World," xvii 392, 1891.

† Trans. Amer. Inst. Elec. Engrs., vii 3, 1890.

†† "American Electrician," x 453, 1898.

(3) Variation of the neutral point of the armature with the amount of current.

(4) The consequent necessity of shifting the brushes.

(5) A resultant tendency to demagnetize the armature.

(6) Losses due to eddy currents in the pole-pieces, armature core, and coils.

(7) A resulting difference between the input and output.

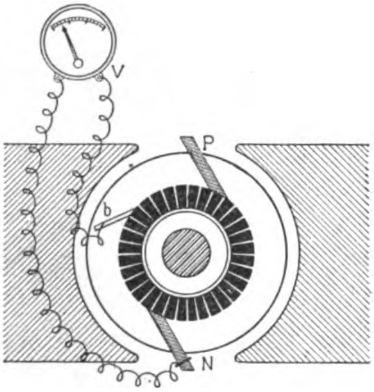


Fig. 50. Mordey's Method of Exploring Potentials around Commutator.

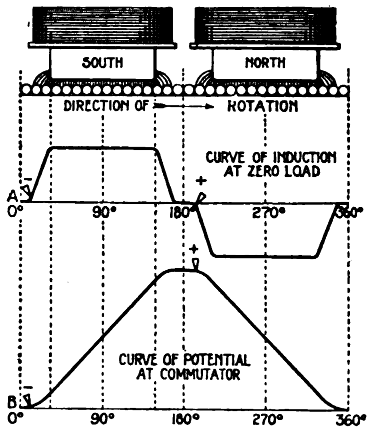


Fig. 51. Undistorted Field.

As these reactions have much effect upon the operation of the commercial machine, they will be considered in detail.

Cross-Magnetizing Effect of Armature Current. We have seen from Fig. 48 and the accompanying text, that the armature of a generator may be likened to a combination of voltaic cells; but the armature carrying current manifests a magnetic effect absent in the latter.

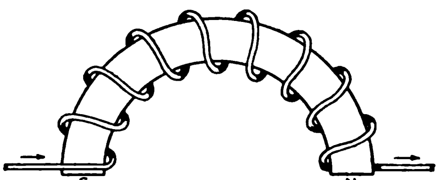


Fig. 52. Poles on Half-Ring.

If we consider the solenoid of page 4 to be bent around so as to form a semicircular ring, and to have inserted into it an iron core of the same form, one end of this core would act as a north pole, and the other end as a south pole, when current circulates in the winding (Fig. 52). By taking an exactly similar semicircular ring and placing the two together so that their north poles and the south poles are respectively coincident, we are able to reproduce the magnetic effect of current flowing in the armature. That is, when the generator supplies energy to the external circuit, the armature has poles produced in it corresponding to the brushes—namely, where the current enters and leaves the winding. This magnetization of a simple Gramme ring armature (Fig. 53) is indicated in Fig. 54, the general direction of the flux being through the armature core along both paths from *a* and *b* to *n* and *s*, where it emerges into air, forming respectively the poles of the armature. The main portion of this flux returns outside the ring, while a small portion passes across the interior. This latter portion is extremely small in commercial machines, on account of the presence of large masses of iron in the pole-pieces which are outside.

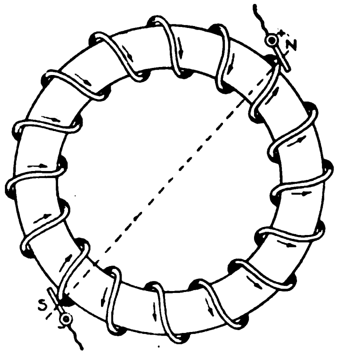


Fig. 53. Circulation of Current around Ring Armature.

The cross-magnetization of the armature produces a distortion of the flux in it; but this would have small effect upon the e. m. f. if the line of commutation did not also change with the armature current. This change necessitates the moving of the brushes; and then the armature not only produces a cross-magnetizing effect, but also has a demagnetizing tendency. It is this latter which diminishes the generated e. m. f.

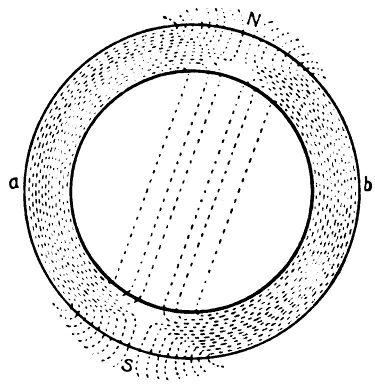


Fig. 54. Magnetization Due to Armature Current.

In order to study the result, let us suppose the simple bipolar dynamo of Fig. 45 to be arranged so that current may be passed through its field windings, its armature when rotating, or through both. When the field alone is excited, the flux distribution will be substantially as indicated in Fig. 55—that is, quite uniform in the pole-pieces, air-gaps, and armature. If, now, the field-exciting circuit be opened, and if a current be supplied to the rotating armature equal to its rated load current, the flux distribution shown in Fig. 56 will exist. By combining these two conditions of the flux, there is produced the distortion shown in Fig. 57, which is the resultant flux distribution in the generating portion of the machine. The magnetism is distorted in the direction of rotation, as if the armature tended to draw after it the flux issuing from the field-poles. But this is not the physical fact, because we find that in electric motors the flux is distorted in a direction *opposite* to that of the rotation of the armature. In fact, the flux-distribution is the same whether the armature turns one way or the other, or not at all. On account of this flux distortion, brushes must be set, not midway between the field-poles, but, in the case of generators, somewhat ahead of this line of symmetry. Consequently the armature m. m. f. will be oblique to that due to the field-magnet, and a further distortion will result.

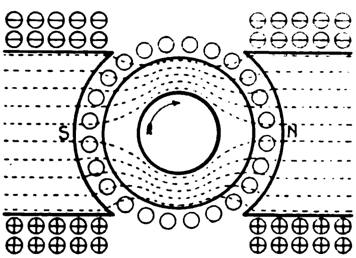


Fig. 55. Flux Due to Field Alone.

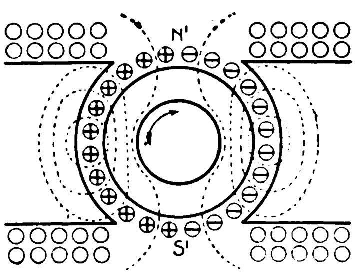


Fig. 56. Flux Due to Armature Alone.

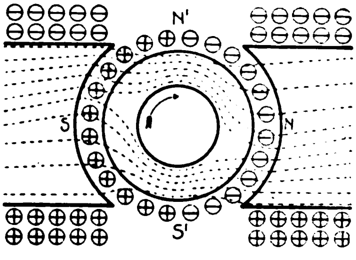


Fig. 57. Flux Due to Field and Armature.

These relations are shown vectorially in Fig. 58, the line OF representing in direction and magnitude the flux due to the field-magnet, and the line OA' the direction and magnitude of the flux set up by the armature current with the brushes in the line of symmetry or vertical position. In this case, OR' represents the resultant flux in value and direction, and the brushes should be shifted to the line OA'', perpendicular to OR'. The armature component of the flux also shifts to this direction, but with unchanged magnitude because the ampere-turns and other relations of the magnetic circuit are not varied. This will produce a new resultant OR'', and the brushes should be shifted until the line of commutation OA is approximately perpendicular to OR, the final flux vector. These conditions are also represented in Fig. 59, OF being the field-magnet flux, OA the armature flux with the brushes shifted, and OR the resultant with the main line of the flux (PQ) as an extension of it.

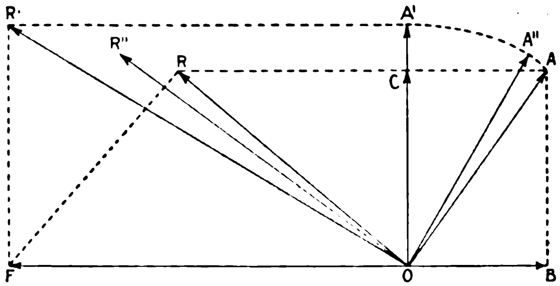


Fig. 58. Magnetic Reactions in Armature.

In the case of drum-wound armatures, the phenomenon is similar but not so easily traced. In consequence of the overlapping of the end-connections, the magnetizing effects of some of the coils are neutralized, and as a result the production of poles is not so marked. Neither can there be any internal field. As a matter of fact, drum-wound armatures are not troubled to the same extent with induction effects as are ring-wound ones. With these exceptions, however, the facts here considered apply equally to drum-wound and ring-wound armatures.

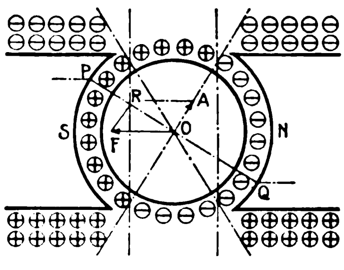


Fig. 59. Back and Cross Ampere-Turns.

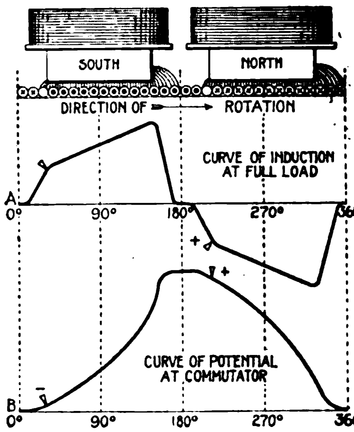


Fig. 60. Curve of Armature Distortion.

The distortion of the flux through the armature also produces a distortion in the wave of induction, as may be shown by exploring the potential differences around a commutator by Mordey's method, when the machine is carrying its rated load. Such a curve is shown in Fig. 60.

Sparking at the Commutator. On page 20 we have seen that the rotation of the armature in the field of the machine generates alternating currents in the conductors. A consideration of Fig. 57 shows that all the current flows toward the spectator in the conductors which are rising, and away from the observer in all the descending conductors, the brushes in this case being supposed present at *N′* and S′. Thus, when a coil passes under one of the brushes, the direction of the current in that coil is *reversed.* Owing to the fact that even a single armature coil possesses some self-induction, the current cannot change instantaneously; that is, a certain definite interval of time is required, dependent upon the self-inductive property of the armature coil, as well as upon its resistance. During this interval, and until the whole current can take the new path through the coil, a portion of the current continues to flow from the receding commutator bar, through the air, to the brush, in the form of a spark. It is the interruption of this latter current, as the commutator bar leaves the brush, that produces the spark.

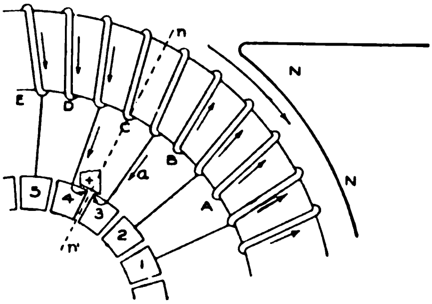


Fig. 61. Illustrating Requirements for Non-Sparking Condition of Commutation.

Commutation. In order to understand exactly what happens when a current is commutated, let us consider what takes place in one section of an armature winding, and at the two commutator bars attached to the latter, when the bars pass under a brush.

Fig. 61 shows a portion of a ring-wound armature with its coils *A*, *B*, *C*, *D*, and *E* connected to segments 1, 2, 3, 4, and 5 of the commutator, and a positive brush just beyond the leading tip of one of the pole-pieces. The line *nn′* represents a line drawn in space so as to cut the commutator at a point where the voltage between the brush and the bars thus passed through is zero. The brush is assumed placed in this line.

Now, before any given section of the winding reaches the brush shown in the figure, a current will be flowing in it in the direction of the positive brush; and after the section has passed the brush, the current, although reversed in direction, is still flowing towards the brush.

The figure shows the instant at which coil *C* is short-circuited by the brush through the commutator bars 3 and 4; and it is during the brief interval of this short circuit that the current in coil *C* must be reduced to zero, reversed, and then built up again in order that there shall be no tendency for a spark to form between the brush and the bar 3 at the instant they part.

As to the establishment of a reversed current in section *C* while it is short-circuited by the brush, it must be remembered that this coil is at this instant supposed to be occupying a position such that there is no e. m. f. being generated in it; that is, it is in a neutral position. In coils to the immediate left and right of coil *C*, however, e. m. f.'s are being generated in such a direction as to cause the resulting current to flow *towards* the brush. If, therefore, we move the brush forward—that is, in the direction of rotation—from its present position in the neutral line, the section short-circuited by that brush will be placed in a region where a p. d. will be generated between its terminals in such a direction as to assist the reversed current above mentioned. Also, the greater the forward lead—that is, the further away from the neutral line in the direction of rotation the brush is moved—the greater will be the p. d. so generated; so that by trial, a position of the brush may be found where the condition of sparkless collection is fulfilled.

The use of high-resistance carbon brushes tends to cause a decrease to zero of the current existing in the sections before they reach the brush, since the latter forms part of the short circuit. Their use also aids the establishment of the reversed current in the short-circuited section, before the brush and segment part company. This is due mainly to the contact resistance between the brush and the commutator, as follows:

The current flowing across the contact area of the brush and leading segment under it (in the figure, segment 3), produces a drop of potential there, which is small on account of the large area of contact, at the instant depicted. A moment later the brush is making better contact with segment 4, and poorer contact with segment 3, so that the voltage drop across the contact area of the brush and 3 has risen above that of the brush and 4. Hence a current will tend to flow from segment 3 to segment 4, as a reverse current through *C*, being produced by the difference of potential between them. This state is comparable to that of the ordinary potentiometer, where a "drop" acts as an e. m. f. in producing a current flow. The voltage resulting from this potential difference across the two contact areas mentioned, assists that tending to produce reversal.

Thus, as the commutator moves under the brush (assuming the latter to have a forward lead), the e. m. f. for reversal, the p. d. due to the varying contact area of the brush, and the resistance of the short-circuited coil, combine to reduce the current in the latter to zero, while the self-induction of the coil tends to prevent any change of the current in it.* This zero condition should occur when the areas of contact between the brush and the two (in this case) bars passing under it are equal. Then, when the segments leave this position, the p. d. between them will increase, thus assisting the direct e. m. f. (produced in the coil by the flux from the hindward pole-horn) in establishing a current in the coil in the reverse direction. Opposing this are the resistance and self-induction of the coil. With proper conditions, the various reactions mentioned may be so proportioned as to produce in the coil from which the short circuit is about to be removed, a current equal in amplitude and direction to that flowing towards it from the preceding coil. In the figure, coil

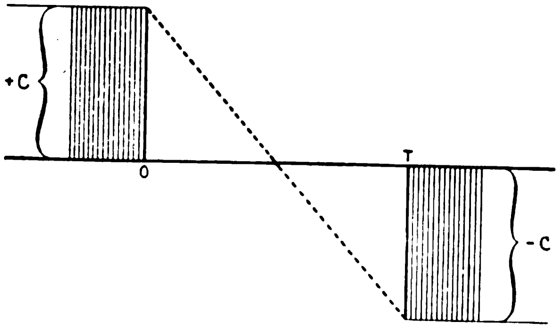
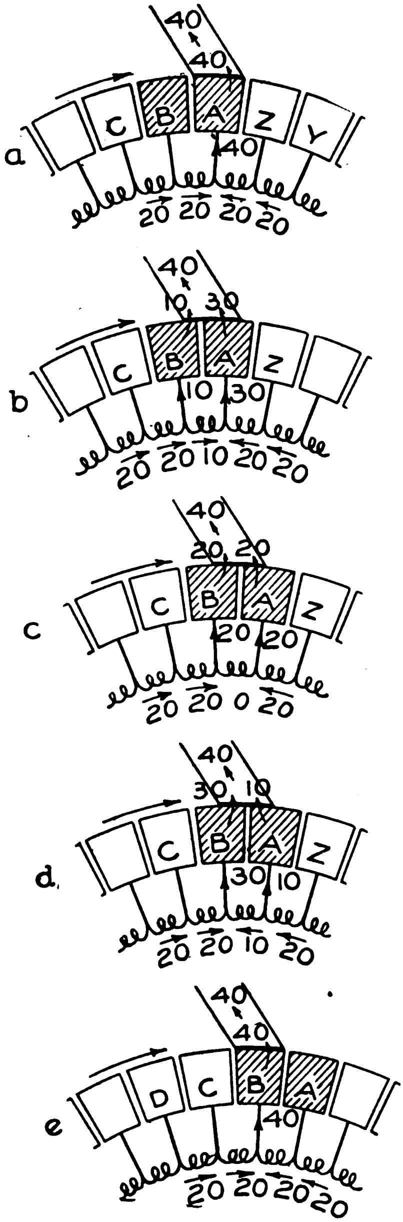


Fig. 62. Curve of Commutation—Ideal Case.

* See S. P. Thompson's "Elementary Lessons in Electricity and Magnetism," N. Y., 1903, pp. 466 *et seq.*



(*a*) Instant before Commencement of Commutation in Section *AB*.

(*b*) End of First Quarter of Period of Commutation in Section *AB*.

(*c*) End of Second Quarter of Period of Commutation in Section *AB*.

(*d*) End of Third Quarter of Period of Commutation in Section *AB*.

(*e*) Commutation in the Section *AB* Completed.

Fig. 63. Process of Commutation.

C would be the one to have the short circuit removed; and B, the preceding coil. Then segment 3 will pass out of contact with the brush without a spark attempting to follow.

Resistance during Reversal. Let us assume that during commutation the brush contact resistance is inversely proportional to the area of contact. Then, in the ideal case, where the coils of the armature are devoid of resistance and inductance, the curve of commutation will be as shown in Fig. 62, C representing the value of the current to be commutated, O the instant when commutation commences, and T the period requisite for this action. Here the current gradually diminishes to zero at the middle of the commutation period, and reaches its negative maximum value at the end of the time T. This process is shown in detail in Fig. 63, the brush being wide enough to span one commutator bar.

In this case 20 amperes flow from either side of the armature to the brush, the latter leading away 40 amperes. If we suppose the brush area to be one square inch, then, when the commutator is in the position indicated by Fig. 63 (*b*), the area of contact of the segment A is reduced to $\frac{3}{4}$ square inch, while that of the segment B has become $\frac{1}{4}$ square inch, so that 10 amperes will flow into the brush from B and 30 amperes from A, the additional 10 amperes through the latter coming from the short-circuited coil. When the commutator has moved forward so that the area of contact of each brush is the same—that is, $\frac{1}{2}$ of a square inch—A and B will each pass 20 amperes to the brush from either side of the armature, the coil undergoing commutation carrying no current at this instant (see Fig. 63, *c*). At the end of the third quarter of the commutation period, the commutator has reached the position shown in Fig. 63 (*d*), the area of contact of segment A with the brush being $\frac{1}{4}$ of a square inch, while that of B is $\frac{3}{4}$ of a square inch. Hence A will contribute 10 amperes and B 30 amperes to the brush, the coil undergoing commutation now carrying a current in the direction reverse to that indicated in Fig. 63 (*b*), and in the same direction as the current in the coils on the right. At the end of the commutation period, the current in coil A–B has increased to the full value of that flowing in its right-hand neighbor; and when the brush and segment A part company no spark will result.

Fig. 62 shows the variation of the current during this period, if we neglect the resistance and inductance of the armature coils. It therefore remains to consider the effect of these reactions.

Commutation Curves. If the resistance of the armature coils be not negligible in comparison with the contact resistances, then the current collected will not be rigidly proportional to the areas of contact. For, suppose that in Fig. 63 (*b*) the contact resistance over *A* is 0.04 ohm, and that that over *B* is 0.12 ohm; then, if the resistance of one coil of the armature be taken at the exaggerated value of 0.01 ohm, 29.6 amperes will go through *A*, and 10.4 amperes will pass through *B*. In other words, the presence of resistance in the coils of the armature reduces the ratio of currents during the first half of the commutation period, and increases this ratio during the second half. This is shown graphically by the curved line in Fig. 64, the straight line indicating the ideal case.

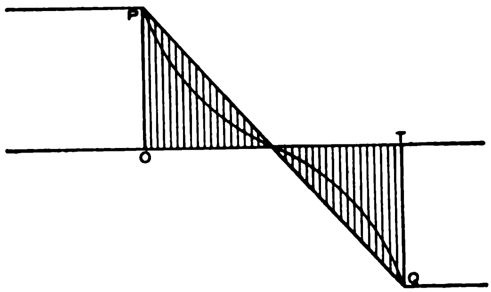


Fig. 64. Curve of Commutation.

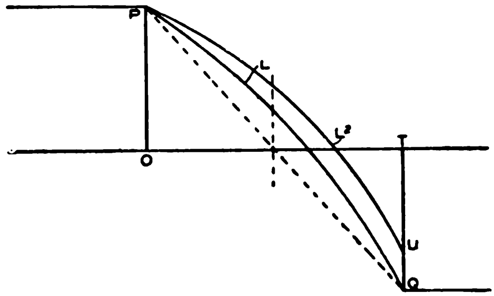


Fig. 65. Curve of Commutation, with Self-Induction.

The effect of self-induction, although not easily shown quantitatively, would modify the ideal current curve as indicated by PL^1Q in Fig. 65, PL^2U showing the result obtained with increased self-induction. Self-induction tends to retard any change in the current, so that the same is not completely reversed at the end of the commutation period. At the last instant, then, as the surface of contact between the segment *A* and the brush diminishes to zero, the contact resistance rises with extreme rapidity. The product of this resistance and the still uncommutated part of the current, will constitute a p. d. between the retreating segment *A* and the tip of the brush. This p. d., represented graphically by *QU* in Fig. 65, tends to set up a spark, and may be briefly called the *sparking* or *maintaining* e. m. f.

The resulting commutation curve for any machine is made up of these two effects, the quantity of each depending upon the design, and of some details at present obscure. Messrs. Everett and Peake* found experimentally that the curve had the form shown in Fig. 66. Curve *A* indicates the initial rise which may obtain at light loads, with an oval resultant at the negative end. *B* illustrates under-commutation with insufficient lead. *C* shows, with increased load, a rapid reversal at the beginning of the commutation period, but under-commutation toward the end. *D* represents a gradual fall of the current, which slackens toward the end.

Effect of Increasing Breadth of Brush. Increasing the breadth of the brush not only lengthens the period of commutation, but also permits commutation to start in one coil before the preceding coil has entirely passed through this stage.

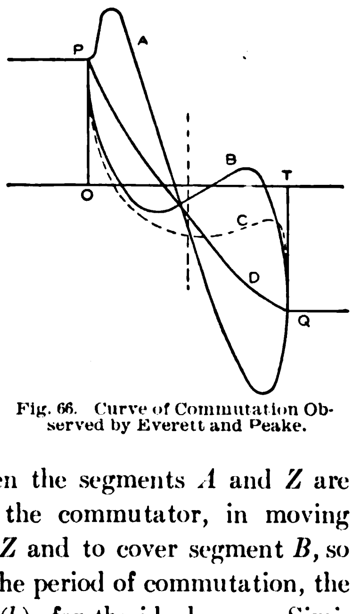
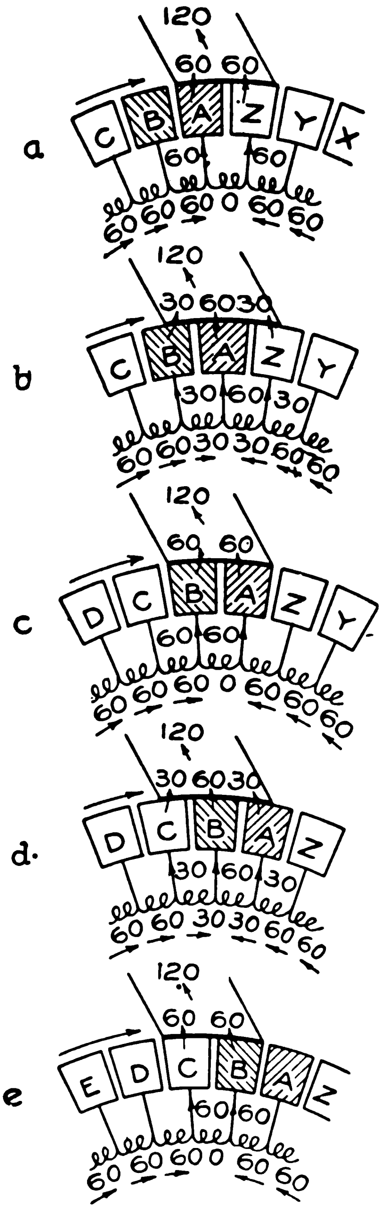


Fig. 66. Curve of Commutation Observed by Everett and Peake.

In Fig. 67, let us assume the brush to have an area of 3 square inches, and that it can completely cover two segments at one time, the current collected by the brush being 120 amperes. Then Fig. 67 (*a*) shows the state of affairs when the segments *A* and *Z* are under the brush. An instant later, the commutator, in moving clockwise, starts to uncover segment *Z* and to cover segment *B*, so that at the end of the first quarter of the period of commutation, the result will be as indicated in Fig. 67 (*b*), for the ideal case. Similarly, in Fig. 67, *c*, *d*, and *e* represent respectively the conditions at the end of the second, third, and fourth quarters of the commutation period, the direction of current and its magnitude in each coil being indicated by arrows and figures. We see from these that the conditions of Fig. 63 (page 44) obtain throughout, the current in the short-circuited coils being zero at the middle of the period of commutation; so that we may conclude that the act of commutation is not altered by increasing the width of the brush.

* See *Electrician*, London, Vol. 40, p. 461; Vol. 42, p. 328.



(*a*) Instant before Commencement of Commutation in Section *AB*

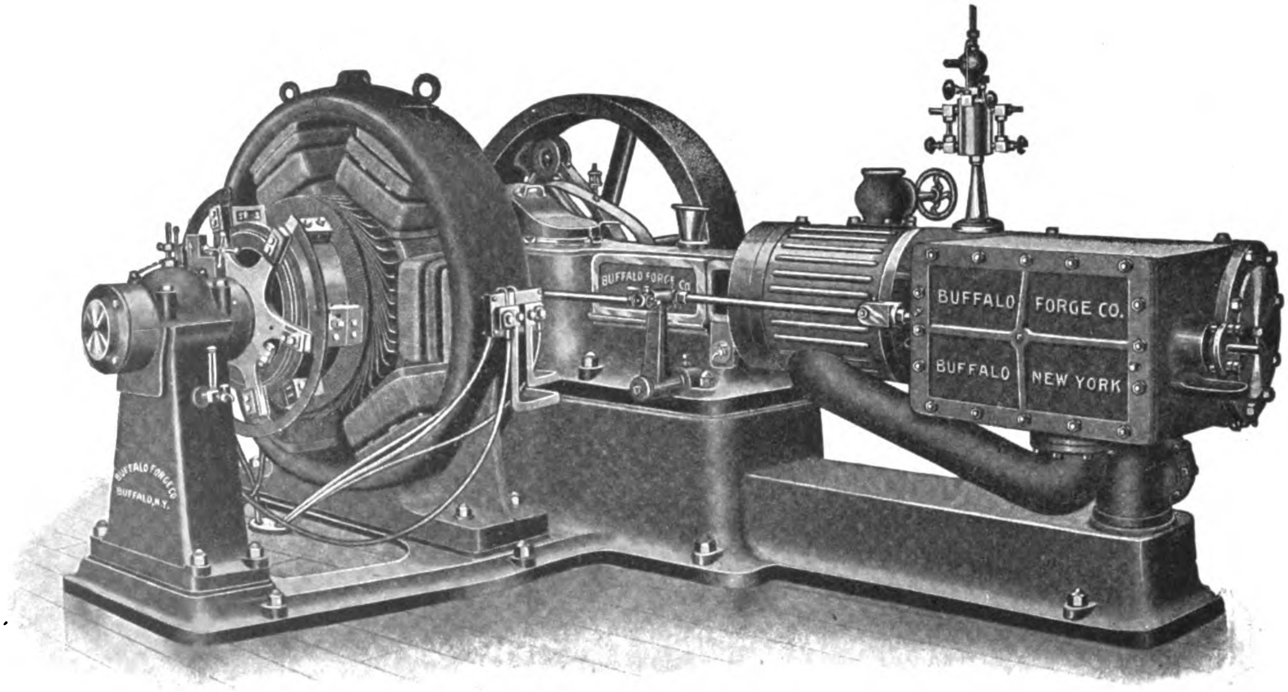
(*b*) End of First Quarter of Period of Commutation in Section *AB*.

(*c*) End of Second Quarter of Period of Commutation in Section *AB*.

(*d*) End of Third Quarter of Period of Commutation in Section *AB*.

(*e*) Commutation in Section *AB* Completed.

Fig. 67. Process of Commutation.—Brush Covering Two Segments



HORIZONTAL TANDEM-COMPOUND ENGINE.
Direct-Connected to Generator.
Buffalo Forge Company.

Summary of Results. The considerations above indicated as to means for controlling the sparking at the commutators of continuous-current machines, may be summed up as follows:

(1) Keep the inductance of the armature coils low, by decreasing the number of turns per commutator segment, by saturating the teeth, and by properly shaping the pole-pieces to produce a reversal fringe.

(2) Keep the volts per segment of the commutator low by having a large number of commutator segments.

(3) Control distortion of the main flux in order to have the field under the hindward pole-horn sufficiently strong.

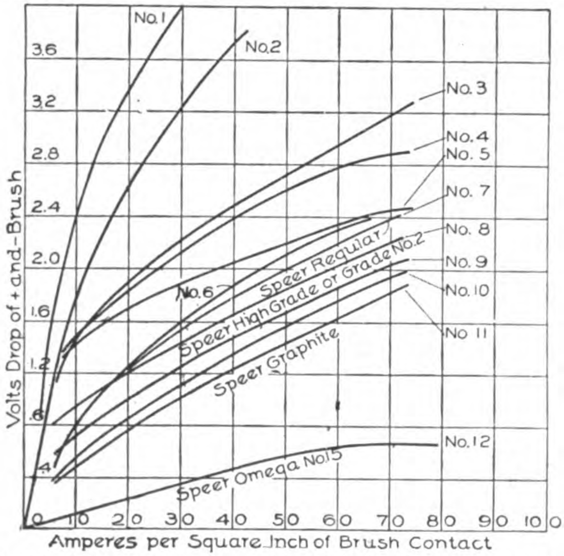


Fig. 68. Voltage-Drop Curves of Various Grades of Carbon and Graphite Brushes at Different Current-Densities.

(4) Properly dimension and design the commutator-brushes,* brush-holders, and other brush-gear, so as to permit the shifting of the brushes to the proper position, and to enable the brushes to make contact with the commutator at all times.

(5) Keep the surface of the commutator smooth.

(6) Add special features to the machine.

To see clearly the application of most of these special features, it is desirable that we first consider another property of an armature carrying current—namely, its demagnetizing effect.

Demagnetizing Effect of Armature. To eliminate sparking at the commutator, we have seen that it is necessary to shift the brushes ahead of the neutral line in generators, and back in case of motors. The resultant effect is to produce in the armature a magnetomotive force (m. m. f.) opposed to that of the field-winding. Considering Fig. 69, wherein the brushes are supposed to be shifted to the line *nn'*, the remainder of the figure being as before, it is seen that the currents

* With respect to material and thickness, see Fig. 68.

are flowing toward the observer in the armature conductors to the left of the neutral line *nn'*, and from the observer in those to the right of that line. Now, suppose the two vertical lines *ad* and *bc* to be drawn across the section of the armature and through the points of commutation. The armature conductors are thus divided into two bands, those to the right of the line *ad* and to the left of the line *bc* tending to cross-magnetize the armature, while those included between these lines produce a m. m. f. opposed to that of the main field, since the current in these turns passes around the flux in a direction opposed to that of the field-exciting current. The breadth of the belt of demagnetizing windings is evidently proportional to the angle of lead, since it subtends double that angle. In such an armature generating 50 amperes, each conductor would carry 25 amperes, since there are two paths in parallel; and as the number of cross-magnetizing turns is 12, and the number of demagnetizing turns is 4, the "cross-ampere-turns" would be 25 × 12 = 300; and the number of "back ampere-turns" would be 25 × 4 = 100.

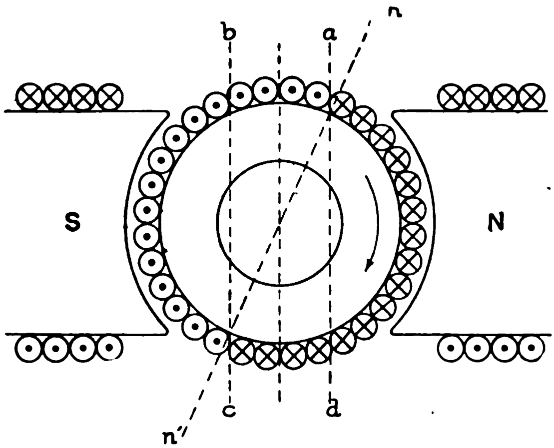


Fig. 60. Demagnetizing Action of Armature Current of Generator.

This demagnetizing influence, which is proportional to the angle of lead of the brushes, tends to weaken the field in general, while the cross-magnetization, proportional to the ampere-turns not included in the demagnetizing effect, tends to weaken the flux under the hindward pole-horn, and strengthen that under the forward pole-tip. Hence the impressed m. m. f. (that of the field-magnets) must be strong enough to force through the air-gap in the magnetic circuit sufficient flux to permit of sparkless commutation in spite of the demagnetizing effects. Since the cross-magnetization is responsible for the distortion which produces sparking, it remains to consider the remedies.

Cross-Reluctance Remedies. Fig. 70 shows that increased air-gap in the magnetic circuit *HAGDH* will diminish the cross-flux. This method is somewhat objectionable, however, because, in order to produce the same

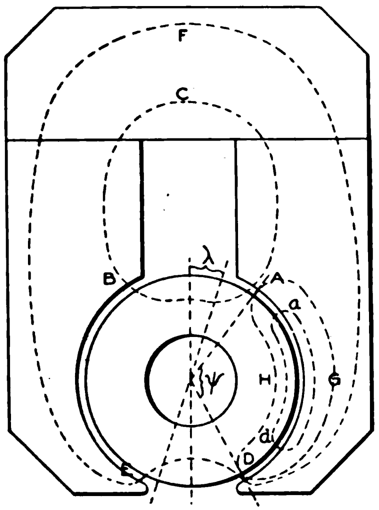


Fig. 70. Armature Interference.

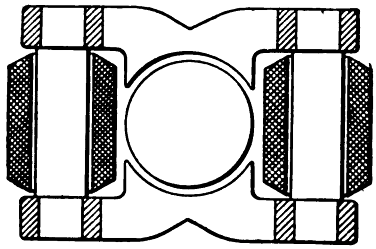


Fig. 71. Prevention of Cross-Reluctance by V-Groove in Back of Polar Mass.

flux through the field-circuit, a greater m. m. f., and hence a larger number of field-exciting turns, are required. This disadvantage may be overcome in some types of generators by forming a V-groove in the polar mass behind the face, as shown in Fig. 71.

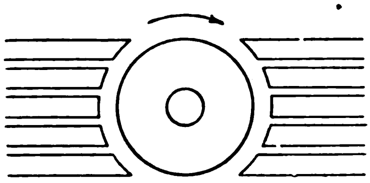


Fig. 72.

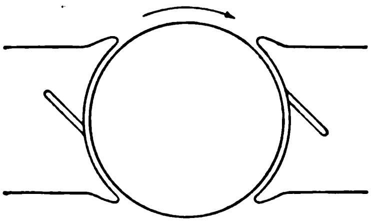


Fig. 73.

Remedies for Cross-Reluctance.—Pole-Pieces Made with Longitudinal Gaps or Oblique Slots.

Another plan is to thin down or actually separate the two halves of the circuit, and thus throttle the cross-flux. S. P. Thompson has suggested constructing the field-cores of pieces of iron with longitudinal gaps, as indicated in Fig. 72, or slotting the pole-piece obliquely as in Fig. 73, the neck of the casting here becoming highly saturated and offering large reluctance to the cross-field.

Another arrangement consists in making the forward horn of cast iron, and the rearward horn of cast steel, the joint being oblique, as indicated in Fig. 74.

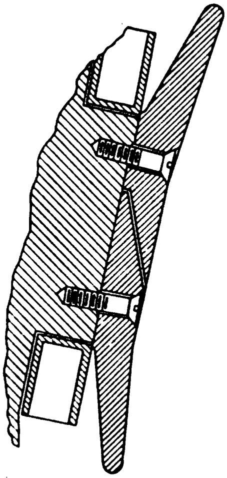


Fig. 74. Composite Pole-Shoe, Forward Horn Cast Iron; Hindward, Cast Steel, Meeting Obliquely to Minimize Magnetic Distortion at Full Load.

Cross-Compounding Remedies. Some designers provide a m. m. f. equal but opposed to the cross-magnetic m. m. f. Elihu Thomson placed a series ("compounding") coil on a separate frame surrounding the armature, and tilted it in a direction counter to the rotation so as partially to counteract the cross-flux. Swinburne suggested that a small auxiliary coil in series with the armature be wound around the pole-tip in order to maintain a field for reversal at this point (Fig. 75, *a*).

Menges, Mather, Swinburne, and others have advocated the use of auxiliary poles at right angles to the main poles, excited by coils in series with the armature. This feature is now embodied in the *Inter-pole* motor. S. P. Thompson proposed the use of compound winding having series and shunt coils at different angles, so that, as the armature reaction tended to shift the main flux forward,

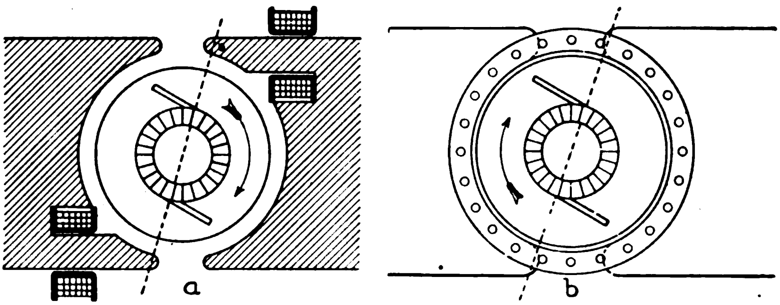


Fig. 75. Devices for Sparkless Collection of Current—(*a*) Swinburne; (*b*) Hutin and Leblanc.

the increased current in the series coils would produce a m. m. f. tending to drive it back. Menges suggested winding series turns upon the polar parts of machines with double magnetic circuits. He was the first to suggest (1884) a cross-compound winding having the auxiliary poles set to produce a flux at right angles to the main flux.

Fisher-Hinnen, Professor Forbes, Mordey, and S. P. Thompson wind these coils in a notch at the center of the pole-face. Elihu Thomson also suggested the use of *unwound* auxiliary poles at right angles to the main poles, thereby leading off the cross-flux to strengthen the main flux.

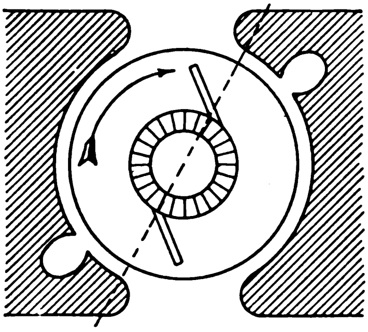


Fig. 76. Sayers' Device for Sparkless Collection of Current.

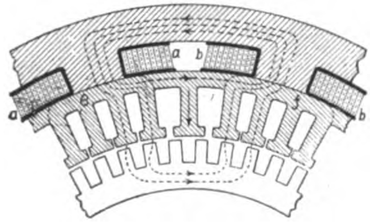


Fig. 77. Ryan's Compensating Devices.

The most complete solution was proposed independently by Professor Ryan and Fisher-Hinnen, who insert a number of coils

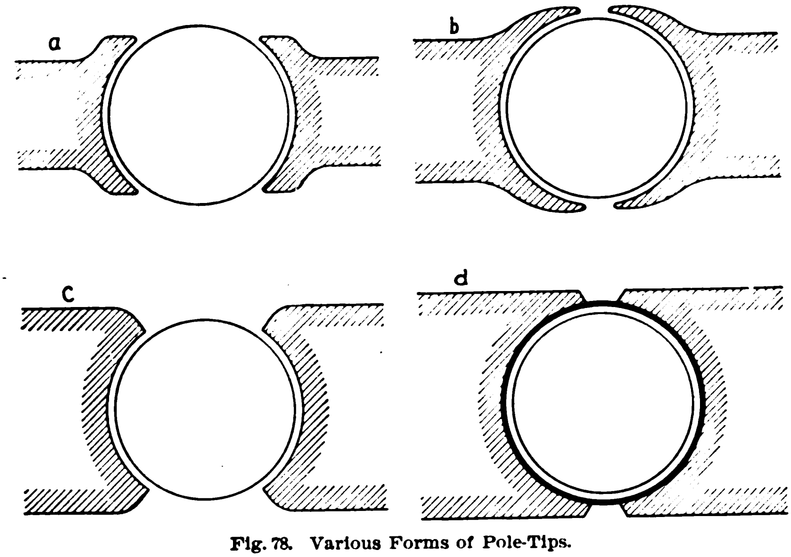


Fig. 78. Various Forms of Pole-Tips.

in slots cut in the face of the pole parallel to the shaft, the coils being connected in series with the external circuit, and constituting a stationary winding which produces a m. m. f. equal but opposed to that due to the armature, Fig. 77. This device is not extensively employed, however, on account of the increased heating as well as complication and cost.

Hutin and Leblanc proposed the placing of rods of copper in the pole-face, which rods are short-circuited upon themselves. This arrangement is intended to prevent oscillations in the direction of the magnetic flux at commutation. It is much used in alternating-current machines, to facilitate parallel operation (see Fig. 75, *b*).

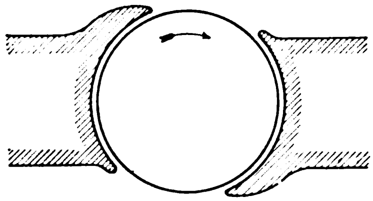


Fig. 79. Unsymmetrical Pole-Pieces Designed to Concentrate Field.

Concentration of Field. Sparkless commutation may also be accomplished if the field is magnetically rigid—that is, not easily distorted. This stiffness may be partially secured by properly shaping the pole-faces or by making notches in them (Fig. 76), as suggested by Sayers, thus concentrating the flux at the tip. In Fig. 78 are shown various forms of pole-tips, of which type *a* is not always good, but may be either extended as in *b*, or cut off as in *c*. An extreme arrangement, suggested by Dobrowolsky, surrounds the armature completely with iron, as in *d*.

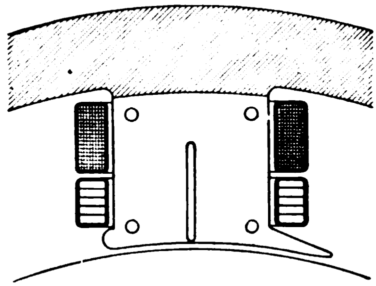


Fig. 80. Lundell's Form of Pole.

Another scheme, proposed by M. Gravier, employed the unsymmetrical form of poles shown in Fig. 79. When the machine is working at small loads, the flux in the gap is nearly uniform; but at large loads, the distortion due to armature current forces the flux forward and saturates the forward pole-horn, thus preventing much change in its flux-density, on account of the saturation and the diminished area. Lundell combines this device with the slotted-pole method, and produces the pole shown in Fig. 80. Another plan is to make the pole-cores of laminated wrought iron or steel, to which a cast-iron pole-piece is attached.

A similar effect is produced by making the poles non-concentric with the armature, as in Fig. 81. This secures a suitable fringe and at the same time maintains a fair magnetic rigidity. Mr. C. E. L. Brown finds that inwardly projecting poles of circular cross-section, without any pole-shoes or extensions, produce excellent results in generators which deliver large current. Other devices for securing a gradual entrance of the armature conductors into the field, are to skew the hindward edge of the pole-shoe as indicated in Fig. 82; to shape the pole-shoes with polygonal ends, Fig. 83; or to provide clawed edges, Fig. 84. Some manufacturers leave out every other lamina in the pole-tips, the resulting extra saturation helping to resist the effects of armature distortion. A somewhat similar device is that patented by Marshall, which consists in attaching to the pole-piece groups of short, laminated iron plates with narrow spaces between them, thus reducing the net area of the shoe, while preserving the same effective area.

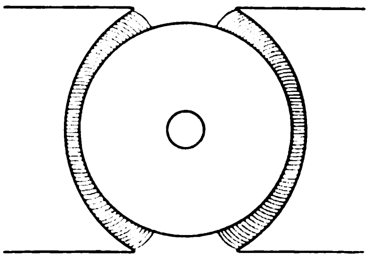


Fig. 81. Non-Concentric Poles.

Self-Compensating Armatures. The devices of Swinburne and Mordey, which relate to chord winding, have met with considerable

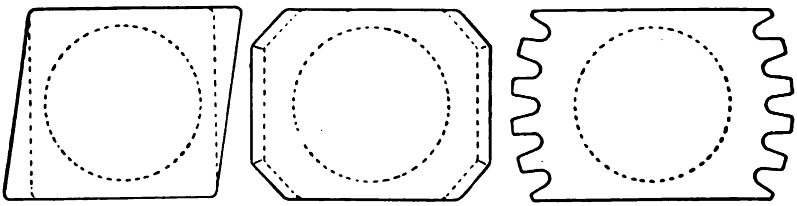


Fig. 82. Fig. 83. Fig. 84.

Devices for Securing Gradual Entrance of Armature Conductors into Field.

success. The most prominent of these methods is that of Sayers, who connects the commutator-bars to the armature winding through auxiliary compensating coils. One end of each commutator coil, Fig. 85, is attached to the junction between two main armature coils, and the other end is connected to a commutator segment. The armature and commutator coils are represented while short-circuited by the brush, a rapid reversal of current being produced by the commutator coil and auxiliary pole. With this method of winding, the brushes may be given a backward lead, thus making the generator self-compounding without a series field-coil.

This completes the list of special features that may be added to generators or motors to eliminate sparking at the commutator; but most of these methods are not likely to be employed, on account of increased complications and reduced efficiency. In the largest

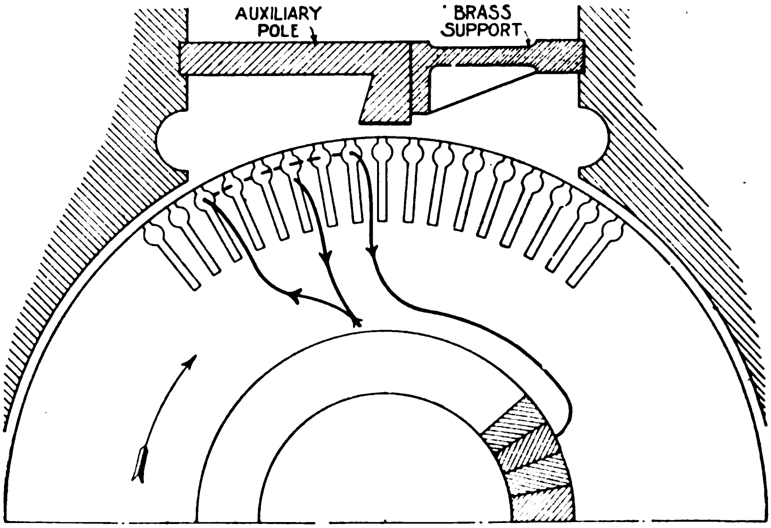


Fig. 85. Sayers Compensating Winding, with Commutation Coils.

machines built by the best manufacturers, none of these special features are present, because it is found that the heating limit of the machine is usually reached before sparking occurs. One prominent designer pays no attention to armature reaction, but relies upon a large number of commutator segments to keep the e. m. f. per segment at a very low figure, also minimizing the self-inductance of each armature coil by making it of few turns and of short length parallel to the shaft. For medium sizes or high-speed work, this design is now much used, especially where large distorting effects are present.

Conclusions. The special points to be observed in order to prevent sparking at the commutator may therefore be stated as follows:

1. The armature ampere-turns per pole should not exceed certain definite values in machines of a given type. If the volts per commutator segment are 5 or less, the armature ampere-conductors should not exceed

20,000 per pole; while with 10 volts per segment, the ampere-conductors should not exceed 10,000.

2. Long air-gaps are unnecessary if the armature teeth are highly saturated—that is, have a flux-density of from 20,000 to 23,000 apparent lines* per square centimeter, or 125,000 to 150,000 apparent lines per square inch, both of the injurious effects of armature reaction being diminished.

3. Armatures should be as short as possible in order to reduce the self-inductance of the armature coils.

4. Number of volts per commutator segment should be low.

5. Inductance of the short-circuited coils should be low compared with brush-contact resistance, and the current-density in carbon brushes should be about 35 amperes per square inch.

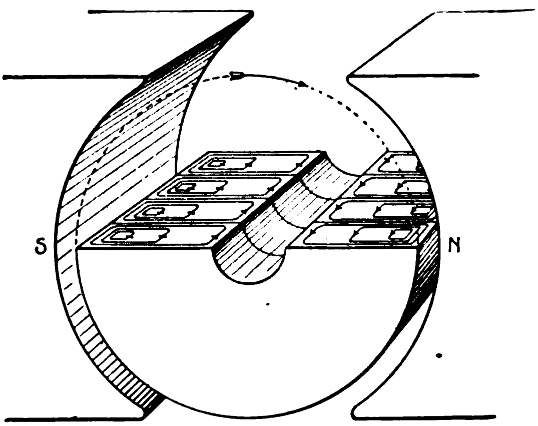


Fig. 86. Eddy Currents in Core-Discs.

Dead Turns. On account of the various internal reactions present in the armature, the terminal voltage is not quite proportional to the speed with constant field-current. Inasmuch as the machine acts as though some of its speed were ineffective, the name *dead turns* has been given to those revolutions by which the actual speed at any output exceeds that determined by strict proportionality.

Spurious Resistance. There is present in every rotating armature an apparent resistance proportional to the speed, due to the self-induction of the armature, as first pointed out by Cabanellas. It cannot be reduced by dividing the armature conductors into a greater number of segments, but can be made less by decreasing the number of conductors and increasing the cross-section of iron in the magnetic circuit. Its value is lessened by the introduction of a counter-e. m. f. aiding the commutation of the current, as previously explained.

Eddy Currents. In discussing the magnetic circuit, it was shown that parasitic currents may be produced in the iron parts

* By *apparent lines per square centimeter in the teeth* is meant the flux-density which would be present in the teeth if all the flux issuing from the poles entered the armature core through the teeth.

of generators if any of these parts form closed electrical circuits and cut flux. In the armature, the iron core rotates in a magnetic field;

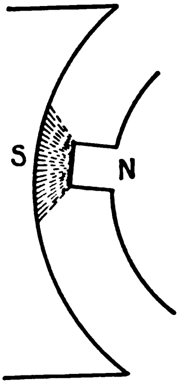


Fig. 87.

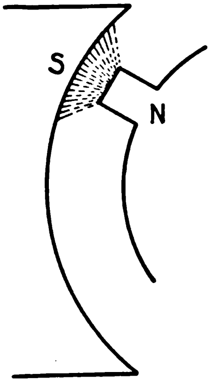


Fig. 88.

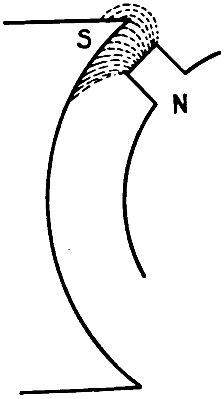


Fig. 89.

Alteration of Magnetic Field Due to Movement of Mass of Iron in Armature.

eddy currents are set up in this core, as shown in Fig. 86, and unless prevented from flowing, these currents will lower the efficiency of the machine. Eddy currents will also be produced in the pole-faces,

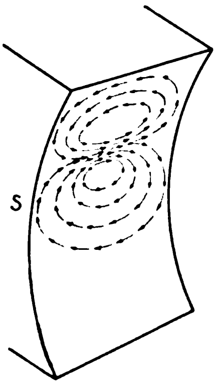


Fig. 90.

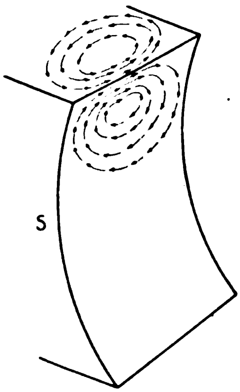


Fig. 91.

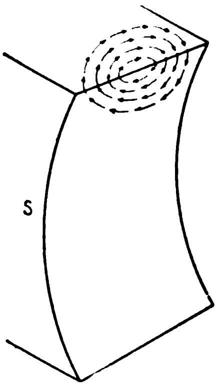


Fig. 92.

Eddy Currents Induced in Pole-Pieces by Movement of Masses of Iron.

due to the variation of the magnetic flux, as shown in Figs. 87–92; and they may in addition manifest themselves in the armature conductors if the latter are large.

In all cases where eddy currents are likely to be large, the circuits affected are laminated so that the plane of lamination cuts across the path of this parasitic current.

Drag on Armature Conductors. A conductor carrying a current is surrounded by a magnetic field, as shown on page 2. If, now, such a conductor be placed in a uniform magnetic field—as, for example, between a large north pole and a large south pole—a compound field will result, having the distorted appearance shown in Fig. 93. The direction of the mechanical force exerted may be determined by supposing that the flux acts as a bundle of elastic cords tending to

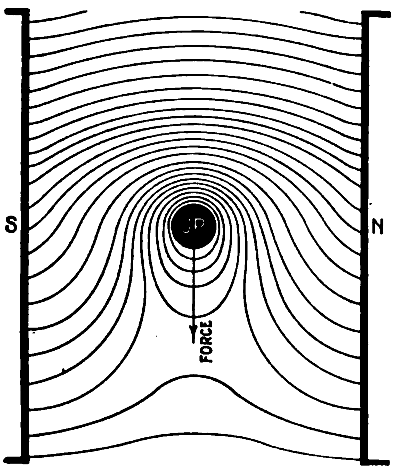


Fig. 93. Magnetic Lines Due to Conductor Carrying Current Placed in Magnetic Field.

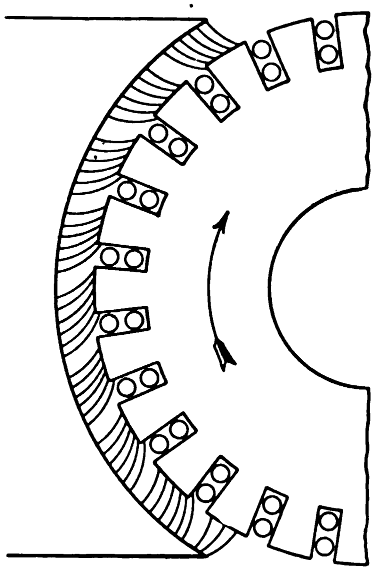


Fig. 94. Magnetic Field of Slotted Armature.

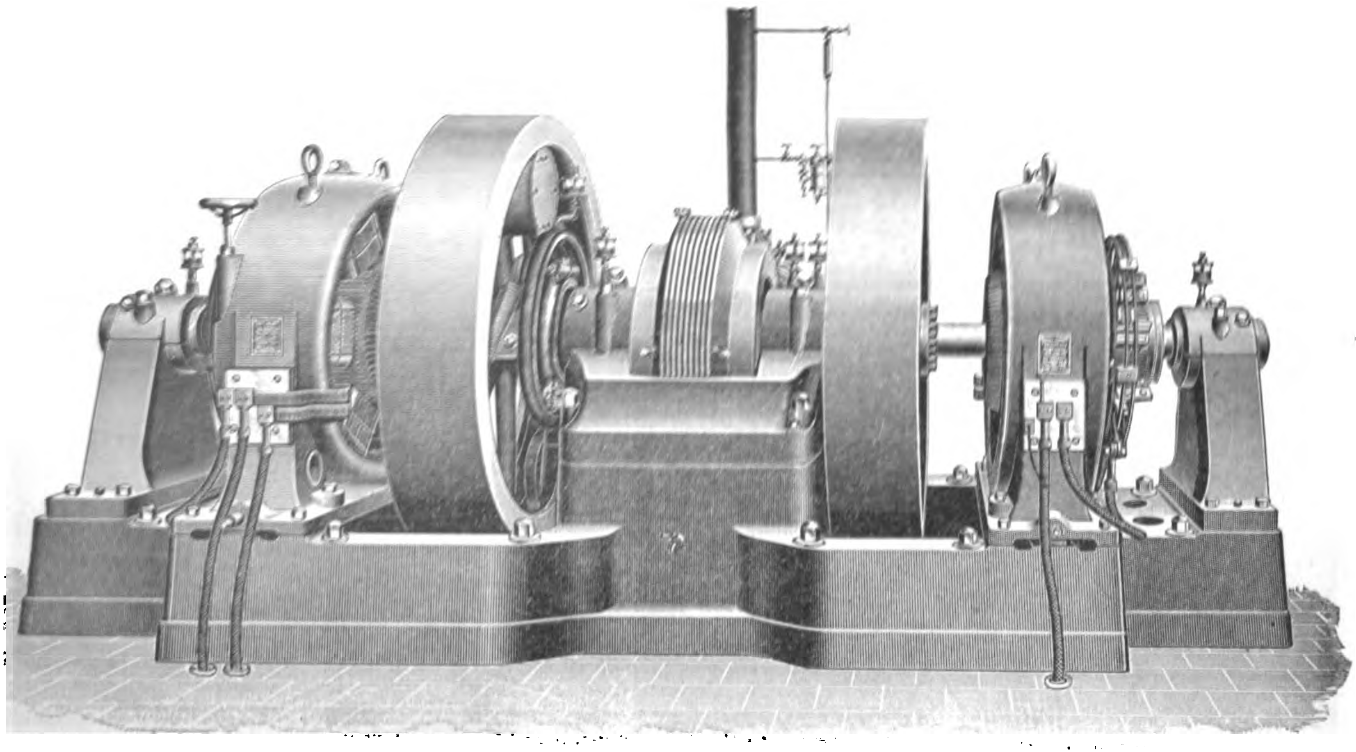
shorten themselves. As a matter of fact, there is tension in the direction of the flux, and stress at right angles to it, proportional at every point to the square of the flux-density. A conductor in which current is supposed to be flowing toward the observer will therefore be urged in the direction of the arrow, Fig. 93; so that in every dynamo-electric machine the current generated produces a mechanical reaction which tênds to stop the motion producing them.

If the conductors are imbedded in slots or holes in the armature core, Fig. 94, it is found that the drag comes upon the iron, the magnetic field being distorted as shown. In fact, the flux no longer directly cuts the conductors, but, as it were, flashes from tooth to tooth. In addition to thus relieving the conductors of the drag effect, the teeth permit a much smaller air-gap to be used, sometimes reducing it to a mere mechanical clearance.

Stray-Power. In all practical machines there is a difference between the input and the output. In electrical machines, this discrepancy is caused by the following reactions:

1. Armature-resistance drop producing I^2R effects.
2. Friction of bearings and brushes.
3. Air-friction of the rotating armature.
4. Hysteresis in the armature core.
5. Eddy currents in the armature core, conductors, and polar projections.
6. Energy is also consumed in the field winding, due to I^2R effects.

Nos. 2, 3, 4, and 5 are grouped under the head of *stray power losses*, being from 40 to 60 per cent of the total loss. No. 3 is small, except in those cases where the armature spider is provided with fans to aid ventilation, and where special ventilating ducts are provided in the armature, as in most modern machines. No. 4 is by no means negligible, but never adds more than 1 per cent to the driving power. No. 5 is the most important of all, especially in large machines. It makes its presence felt even in the metal of the shaft, and there will be power wasted if flux leaks through this portion.



ENGINE DIRECT-CONNECTED WITH TWO WESTINGHOUSE GENERATORS.
Ames Iron Works.

DYNAMO-ELECTRIC MACHINERY

PART II

CALCULATIONS AND CHARACTERISTIC CURVES OF CONTINUOUS-CURRENT GENERATORS

Symbols. The symbols used in the discussions now to be taken up, are as follows:

b – Number of external wires in a section of the armature.
c – Number of circuits in parallel through an armature.
E – Entire e. m. f. generated in an armature, in volts.
e – Lost volts, or potential drop in volts, of armature.
η – Commercial efficiency.
η_1 – Economic coefficient, or electrical efficiency.
η_2 – Gross efficiency, or efficiency of conversion.
F – Force—*i.e.*, push or pull—in pounds' weight.
ϕ – Flux per pole.
I – Current in external circuit, in amperes.
I_a – Current in armature circuit, in amperes.
I_{sh} – Current in shunt field-exciting coil, in amperes.
I_{se} – Current in series field-exciting coil, in amperes.
K – Number of commutator segments.
L – Coefficient of self-induction, or inductance, in henrys
λ – Angle of lead of brushes.
M – Volts per revolution per second.
μ – Magnetic permeabilty.
n – Revolutions per second.
ν – Coefficient of magnetic dispersion, or leakage coefficient
p – Number of poles.
q – Ampere conductors per inch of periphery of curvature.
R – Resistance of external circuit, in ohms.
r – Total internal resistance of generator, in ohms.
r_a – Total resistance of armature *coils*, in ohms.
r_{sh} – Resistance of shunt field-exciting coils, in ohms.
r_{se} – Resistance of series field-exciting coils, in ohms.
r.p.m. – Revolutions per minute.
ψ – Angle of pole span.
σ – Space-factor.
T – Number of turns.

T_{sh} — Number of field-exciting turns in shunt with armature.
T_{se} — Number of field-exciting turns in series with armature.
t — Time in seconds.
V — Volts at terminal of a generator.
v — Velocity in feet per second.
W — Power in watts.
ω — Angular velocity in radians per second.
y — Winding pitch.
y_f — Forward winding pitch.
y_b — Backward winding pitch.
Z — Number of conductors on the armature, counting all around periphery.

Fundamental Equation. We have seen on page 17 that an e. m. f. of one volt is generated when 10^8 lines are cut per *second*. Now, as most armatures have more than one conductor cutting the field flux, the e. m. f. generated will be a direct function of the number of conductors connected in series.

Assuming that the sections of the armature winding equal in number the commutator bars (K), the external conductors all around the armature will be bK. The total number of conductors that are in series with each other electrically from brush to brush is $\frac{bK}{c}$ or $\frac{Z}{c}$. If, now, the armature speed of rotation is given in r. p. m., then the revolutions per second $(n) = \frac{\text{r. p. m.}}{60}$.

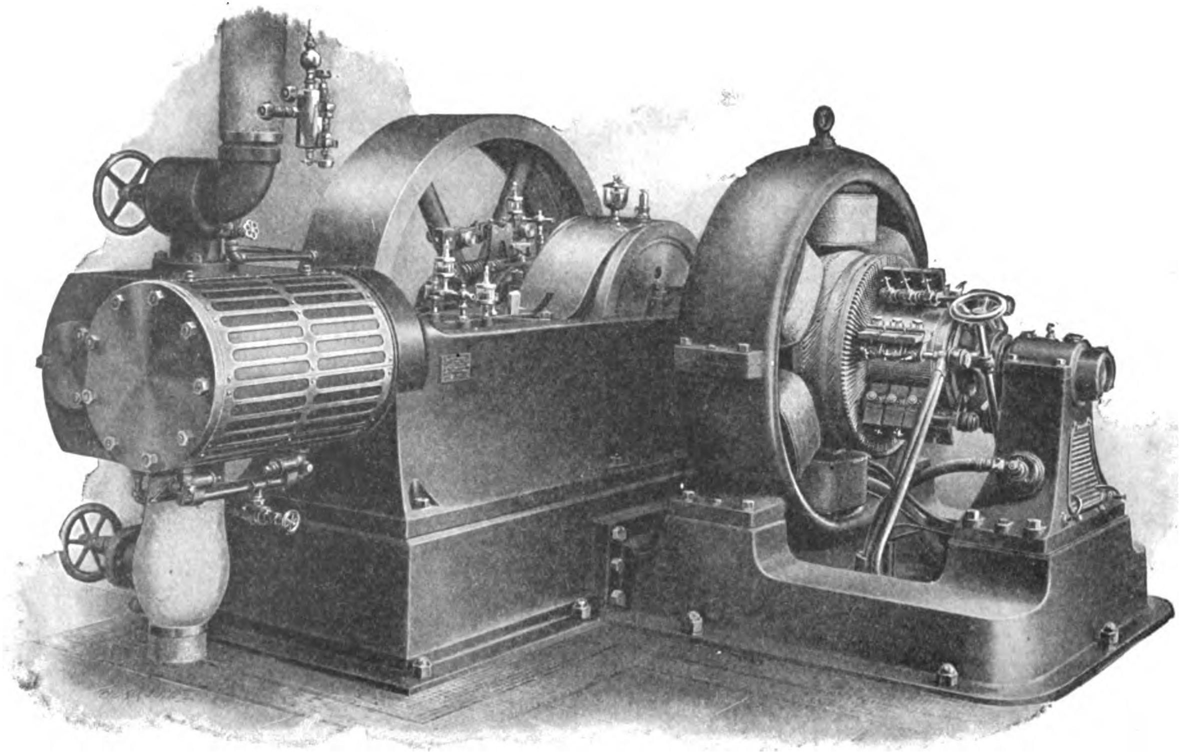
In order to compute the e. m. f. generated, we have:

Number of lines cut by one external wire in one revolution .... $= p\phi$
Number of lines cut by 1 external wire in 1 second .... $= np\phi$
Number of lines cut by $\frac{Z}{c}$ external wires in series in 1 second .... $= np\phi Z \div c$
Average e. m. f. generated, in C.G.S. units .... $= nZ\phi\frac{p}{c}$
Average e. m. f. generated, in volts .... $= \frac{nZ\phi}{10^8}\frac{p}{c}$
Average e. m. f. generated, in volts .... $= \frac{\text{r. p. m.} \times Z\phi p}{60 \times 10^8 \times c}$ **(1)**

If the number of circuits through the armature is equal to the number of poles in the field, we may write:

$$(\text{Average})\ E = \frac{\text{r. p. m.} \times Z\phi}{10^8 \times 60} = Mn \qquad (2)$$

It must be remembered that this e. m. f. is an average, and that it



HORIZONTAL ENGINE DIRECT-CONNECTED TO GENERATOR.
New York Safety Steam Power Company.

depends upon the construction of the armature how much fluctuation takes place during a rotation, as shown on page 22.

Example. Assume a 4-pole machine with a 4-circuit armature winding; the flux per pole, 2,000,000 lines of force; the total number of inductors in the armature, 600; and the speed of the machine, 1,200 r. p. m. Determine the generated voltage.

Substituting in Equation 1, we have;

$$E = \frac{1,200 \times 600 \times 2,000,000 \times 4}{60 \times 10^8 \times 4} = 240 \text{ volts.}$$

Efficiency of a Generator. The efficiency of a generator is defined to be the ratio of the mechanical power applied to the rotation of the armature of the generator at any given load, to the electric power output at that load. The mechanical power expended in turning the armature against the resisting forces may be measured mechanically by a dynamometer, or by taking indicator cards at the engine and allowing for friction. By far the best method is the electrical one, of using an electric motor, which has been carefully calibrated, to determine the mechanical power required to operate the generator at any given load. The Hopkinson or so-called *pumping-back* arrangements are even more commonly adopted, especially for large units.

The electrical power is expressed as the product of amperes of current and volts difference of potential between the two terminals of that part of the circuit in which the energy is being expended. This product, measured by suitable instruments, expresses the power or energy expended per second in the circuit in watts, the electrical unit of power. The mechanical unit of power (that is, the horse-power, h. p.), is practically equal to 746 watts*. We may therefore write,

$$\text{h.p.} = \frac{W}{746} = \frac{I \times V}{746} \quad \text{(3)}$$

The electrical efficiency or economic coefficient of a generator is defined to be the ratio between the electrical power utilized in the external electrical circuit and the electrical power developed in the armature. So that if, through an armature there are flowing I_a amperes due to a generated e. m. f. (E), the electrical activity expressed in watts will be EI_a.

* 1 h. p. = 745.560 watts exactly (Henry's *Conversion Tables*).

If the voltage at the terminals of the generator be V volts, and the current through the external circuit be I amperes, the useful power in watts will be $V \times I$.

Therefore the *economic coefficient* of the machine will be:

$$\eta_1 = \frac{\text{Useful electrical power}}{\text{Total electrical power}} = \frac{V \times I}{E \times I_a}.$$

The efficiency of electric conversion is defined as the ratio of the power developed in the armature to the mechanical power expended in producing it. This may be written:

$$\eta_2 = \frac{EI_a}{746 \times \text{h. p.}}.$$

Hence the commercial or true efficiency of the generator becomes:

$$\eta = \eta_1 \times \eta_2 = \frac{VI}{746 \times \text{h. p.}}.$$

It may also be obtained by taking the ratio between the output in watts, and the sum of the output and losses in watts; that is,

$$\eta = \frac{VI}{VI + \Sigma W'};$$

in which $\Sigma W'$ represents the sum of the mechanical and electrical losses in the generator. By multiplying the right-hand member of this last equation by 100, the commercial efficiency is obtained as a percentage.

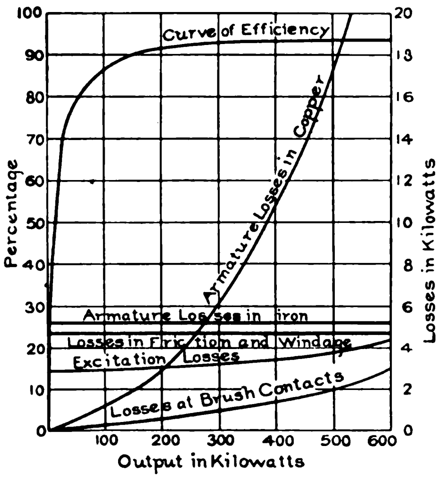


Fig. 95. Typical Curve of Efficiency.

The efficiency of a generator is by no means constant throughout all ranges of loading. On the contrary, because of the variation of the generator losses with the current through the armature, the efficiency curve takes some such form as that shown in Fig. 95. Here it is seen that the efficiency increases very rapidly from 0 to about 80 per cent at 80 kilowatts output, beyond which it increases slowly until it reaches a maximum value at about 550 kw. From this point it decreases slowly; and with still further increase in load, the efficiency would continue to decrease, but more and more rapidly. This is made clear when the curves representing the variation of the losses with load are examined. Assuming speed and voltage constant, it is seen that the friction, windage, and iron losses increase very slowly with output. The copper losses in the armature and field, and the brush-contact losses, increase, however, as the square of the current, and thus at large overloads attain enormous proportions. By proper design, the efficiency curve may be made to take any desired form within certain limits, the maximum point being usually designed to occur at the normal load.

Magneto Generator. In this type of dynamo the flux through the armature is due to the permanent field magnets. Thus ϕ depends both upon their magnetic strength and upon the cross-section of iron core of the armature and the air-gaps. If the current drawn from the machine is sufficiently great, the reaction of the armature will diminish ϕ, and lessen the generated e. m. f. (assuming constant speed of rotation). If, however, the current drawn produces a negligible effect upon the flux through the armature, the voltage of any given magneto machine will be directly proportional to the speed of rotation, by Equation 1, page 62.

The voltage at the terminals of the magneto as well as other types of electric generators, is not equal to that generated in the armature conductors. The armature winding is always of appreciable resistance, so that the passage of any current through it produces a drop of potential, in addition to which there is also a drop due to the brush-contact resistance. It is convenient to have an expression for E in terms of the terminal voltage V and other measurable quantities, because E cannot be measured directly when any current is being drawn.

Let r be the total internal resistance of the armature of the generator, measured at the brushes; let R be the total external resistance; and let I be the current. Then by Ohm's law,

$$E = I(R + r) \qquad (4)$$

$$e = Ir$$

$$V = IR;$$

so that,

$$\frac{V}{E} = \frac{R}{R + r} \qquad (5)$$

and

$$E = V + Ir = V + e \qquad (6)$$

which means that the generated e. m. f. is equal to the sum of the terminal voltage and the armature-resistance drop. This latter increases directly with the armature current, but in well-designed machines is arranged so as not to exceed 2 or 3 per cent at rated load.

On page 64 the economic coefficient was shown to be

$$\eta_1 = \frac{VI}{EI_a}.$$

In the magneto machine, $I = I_a$; so that, from Equation 5,

$$\eta_1 = \frac{V}{E} = \frac{R}{r+R}. \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

This equation shows that as the resistance of the armature is decreased, the economic coefficient of the machine increases, the *theoretical* maximum of unity being attained when the armature resistance is *nil.* This is true for all electrical machines.

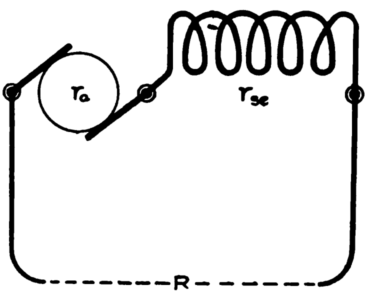


Fig. 96. Diagrammatic Representation of Series Generator.

Separately-Excited Generator. For this type of dynamo the same formulæ hold as for magneto generators. In this case, however, the flux per pole ϕ depends upon the strength of the field-exciting current secured from an independent source. In estimating the commercial efficiency, this fact must be taken into account, the power thus spent being usually from 1 to 3 per cent of the output of the machine, the larger figure relating to the smaller machines.

Series Generator. The series generator, shown diagrammatically in Fig. 96, has but one circuit and one current (I), whose strength depends upon the generated e. m. f. (E) and the total resistance in the circuit. Using the notation previously adopted, we have by Ohm's law:

$E = I(R + r_a + r_{se})$; and $V = IR$. Hence

$$V = E - (r_a + r_{se})\, I.$$

The economic coefficient will be:

$$\eta_1 = \frac{\text{Useful power}}{\text{Total power}} = \frac{I^2 R}{I^2 (R + r_a + r_{se})} = \frac{R}{(R + r^a + r_{se})} = \frac{V}{E} \quad \ldots\ldots (8)$$

This is obviously highest when r_a and r_{se} are *both* very small. They are usually about equal.

Shunt Generator. In the shunt dynamo, Fig. 97, the field and the external circuits are in parallel, so that we have two circuits to consider.

Let I = the current in the external circuit;
I_a = the current in the armature;
I_{sh} = the current in the shunt field-circuit.

Then,

$$I_a = I + I_{sh};$$

for it is clear that the current produced in the armature divides between these two parts of the circuit only.

Calling that part of the armature current which passes through the shunt winding and is consequently not available in the external circuit, the *lost amperes** = I_{sh}, we have the resistance of the shunt coils,

$$r_{sh} = \frac{V}{I_{sh}}.$$

In modern machines, r_{sh} is so proportioned that the shunt field amperes constitute from 1 to 3 per cent of the whole current output of the machine, the larger value being for the smaller generators.

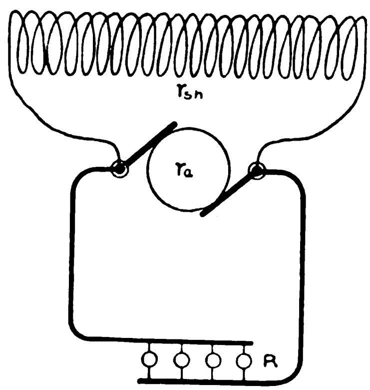


Fig. 97. Shunt Dynamo Showing Main and Shunt Circuits.

Example: In a standard Crocker-Wheeler 85 kw. shunt generator, 3.3 amperes was required in the field-exciting circuit, the generator giving 370 external amperes at 230 volts. Thus the resistance of the field winding was 69.7 ohms, the armature current was 373 amperes, and the shunt field current was about 1 per cent of the rated load current.

We may now compute the economic coefficient of a shunt-wound generator as follows:

The total watts produced in the armature of the machine are:

$$W = EI_a \quad \text{.......... (9)}$$

*S. P. Thompson's *Dynamo-Electric Machinery*, N. Y., 1904, Vol. I, Page 300.

and the watts delivered to the external circuit are

$$w = V I \qquad (10)$$

We also have

$$E = V + I_a r_a = V + (I + I_{sh}) r_a, \qquad (11)$$

since

$$I_a = I + I_{sh}$$

Substituting these values in Equation 9, we obtain:

$$\begin{aligned} W &= (V + Ir_a + I_{sh} r_a)(I + I_{sh}) \\ &= VI + VI_{sh} + (I + I_{sh})^2 r_a \\ &= VI + VI_{sh} + I_a^2 r_a \qquad (12) \end{aligned}$$

which reads: The watts produced in the armature are equal to the sum of the watts delivered to the external circuit, the watts wasted in the shunt field, and the watts dissipated in heating the armature conductors. Considering, then, the purely electrical efficiency of a shunt-wound generator, the iron losses, friction, windage, and other mechanically supplied losses not being present in Equation 12, we have,

$$\eta_1 = \frac{w}{W} = \frac{VI}{VI + VI_{sh} + I_a^2 r_a} \qquad (13)$$

In order that this ratio may approach unity, its limit, the sum of the losses must approach zero. Writing the latter as a fraction of the output, we have,

$$\begin{aligned} \frac{1 - \eta_1}{\eta_1} &= \frac{V I_{sh} + I_a^2 r}{VI} \\ &= \frac{I_{sh}}{I} + \frac{I_a r_a}{V} \qquad (14) \end{aligned}$$

which shows that the two terms are of equal importance, assuming that $I_a = I$, *i.e.*, that the shunt-exciting current is negligible, as in practice it rarely exceeds 2 to 3 per cent of the rated current.

Equating these two terms, and inserting for I_{sh} its value $V \div r_{sh}$, there is obtained,

$$\frac{I r_a}{V} = \frac{V}{I r_{sh}} \qquad (15)$$

that is

$$\frac{V}{I} = \sqrt{r_a r_{sh}} = R \qquad (16)$$

showing that the external resistance is a geometric mean between the armature resistance and the resistance of the shunt-field winding.

Substituting in Equation 14, for I and V, their values in terms of resistances as given above, we have,

$$\frac{1-\eta_1}{\eta_1}=\frac{R}{r_{sh}}+\frac{r_a}{R} \quad\quad (17)$$

from which it is obvious, that for the percentage of losses to be small, the shunt-winding resistance must be large in comparison with the armature resistance.

It must be clearly borne in mind throughout the preceding discussions, that the *commercial efficiency* is always lower than the so-called "electrical efficiency," since the latter does not include the mechanically supplied losses due to friction, windage, hysteresis, and eddy currents. The economic coefficient, or electrical efficiency,

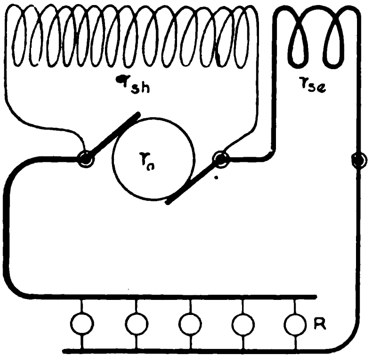


Fig. 98. Short-Shunt Method of Connecting Shunt-Coils to Dynamo.

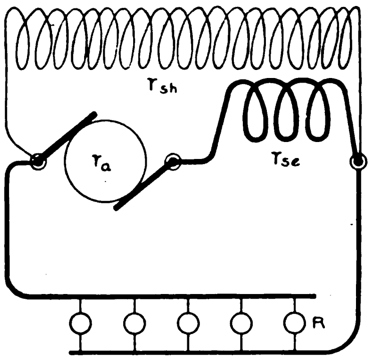


Fig. 99. Long-Shunt Method of Connecting Shunt-Coils to Dynamo.

may be used to compare various types and to show the conditions for best electrical working; but the commercial efficiency is the true and final test for any given machine.

Compound-Wound Generator. Under this head will be considered that type of compound dynamo in almost universal use at the present time. This may be regarded as either a shunt machine in which series turns have been added to the field winding in order to compensate for the drops due to armature resistance and armature reactions; or as a series generator to which shunt windings have been added in order to produce an initial magnetization. In either case, there are two possible ways of connecting the terminals of the shunt coils to the source of voltage, known respectively as the *short-shunt* and *long-shunt* methods.

In the short-shunt method, the shunt coils are connected directly across the brushes of the machine, Fig. 98; while in the long-shunt arrangement, Fig. 99, the shunt coils may be considered as a shunt to the external circuit. In the former method the voltage applied to the terminals of the shunt windings is not a constant, but increases with load if the generator be assumed to be compounded to give a constant or increasing terminal voltage with load. In the long-shunt method, the voltage at the terminals of the shunt coils will be the same as that impressed upon the external circuit; and if the generator is compounded to give constant terminal voltage, the arrangement becomes analogous to the case of a machine with one field-exciting winding supplied from an independent source at constant potential, and a second field-exciting winding in series with the external circuit.

The calculations for both long- and short-shunt arrangements are practically the same; but, on account of greater simplicity, those for the former, with the generator assumed to be compounded for constant terminal voltage, will be given.

We have from page 62, $E = M\,n$; also, $V = E - (r_a + r_{se})\,I_a$. Since the flux depends upon the ampere turns of excitation

$$M = M_o + M_x = u\,(I_{sh}\,T_{sh} + I_{se}\,T_{se}), \qquad (18)$$

in which u is a variable quantity representing, at various stages of the magnetization, the numerical relation between the flux and excitation of the magnetic circuit for a particular dynamo. Consequently, when the external current is zero, we have:

$$M_o = u_o\,I_{sh}\,T_{sh}.$$

M is proportional to the flux entering the armature from one pole, which in compounded machines is not a constant quantity. It is due to the combined effects of the shunt and series ampere-turns; that is, $M = M_1 + M_x$, in which M_1 is proportional to the shunt ampere-turns, and M_x is proportional to the series ampere-turns.

From pages 10, 61, and 62, it is clear that,

$$M_x = \frac{0.4\pi\,I_{se}\,T_{se}}{\Sigma \dfrac{l}{\mu A}} \cdot \frac{Z\,p}{10^8 . c},$$

and

$$M_1 = \frac{0.4\pi\,I_{sh}\,T_{sh}}{\Sigma \dfrac{l}{\mu A}} \cdot \frac{Z\,p}{10^8 . c},$$

where μ is the *average* value of the gross permeability (iron and air together), between its two extreme values—that is, when I = zero, and I = maximum.

Adding the two preceding equations, we have:

$$M = M_e + M_x = \frac{Z\, p\, 0.4\, \pi}{10^8 c\, \Sigma \frac{l}{\mu\, A}} (I_{se}\, T_{se} + I_{sh}\, T_{sh}).$$

Replacing the factor $\dfrac{Z\, p\, 0.4\, \pi}{10^8\, c\, \Sigma \frac{l}{\mu\, A}}$ by u, the result is:

$$M = u\, (I_{sh}\, T_{sh} + I_{se}\, T_{se}), \text{ as above.}$$

Substituting the values of E and M, there is obtained:

$$V = n\, u\, I_{sh}\, T_{sh} + n\, u\, I_a\, T_{se} - (r_a + r_{se})\, I_a.$$

Inspecting this equation, we note that it is composed of three terms. The first contains as variable factors the speed of rotation and the shunt current, which latter may be kept constant if the terminal voltage can be made constant. The second and third terms contain as a variable factor, the current I_a, while the second contains also the speed as a variable. It is noted, however, that the algebraic signs of the second and third terms are opposite, and that, if the speed of rotation is constant, the latter terms contain the only variables. Therefore, in order that V may remain constant throughout all changes of load within the rating of the machine, these terms must cancel. That is, $n\, u\, T_{se} = r_a + r_{se}$ is an equation of condition for constant V at constant n. Dividing both sides by $n\, u$, or by $u\, T_{se}$, there results:

$$T_{se} = \frac{r_a + r_{se}}{n} \cdot \frac{1}{u}\ ; \text{ or, } n = \frac{r_a + r_{se}}{T_{se}} \cdot \frac{1}{u}. \qquad (19)$$

When the external current is zero,

$$V = n\, M_o - (r_a + r_{se})\, I_a\ ;$$

and assuming the drops due to the resistances of the armature and series field-windings to be zero (since they are negligibly small when the external current is zero), we have:

$$V = n\, u_o\, I_{sh}\, T_{sh} = I_{sh}\, r_{sh}.$$

Substituting value of n from Equation 19, we have:

$$\frac{r_{sh}}{T_{sh}} \cdot \frac{1}{u_o} = \frac{r_a + r_{se}}{T_{se}} \cdot \frac{1}{u}\ ; \text{ or, } \frac{T_{sh}}{T_{se}} = \frac{r_{sh}}{r_a + r_{se}} \cdot \frac{u}{u_o} \qquad (20)$$

which is the final equation of condition that V shall be constant.

As u_0 is proportional to μ_0, the permeability of the magnetic circuit when the external current is zero, and as u is proportional to μ, the average permeability over the working range, it follows that if there were no alteration due to saturation, we should have $u = u_0$.

Thus far we have assumed that the difference between the generated e. m. f. and the terminal voltage of the machine was dependent upon the resistances of the armature and series-field windings; but, as we have seen on page 49, there is also a drop due to the armature demagnetizing action. In order to take account of this, we must remember that if the angle of lead of the brushes be λ, the demagnetizing conductors will be confined within a belt 2λ (*i.e.*, $Z\lambda \div 90°$). Then, if the number of paths through the armature be c, each conductor will carry $I_a \div c = I_1$ amperes; and the number of demagnetizing ampere-turns will be $2DI_1$, where D is the number of armature conductors within the angle λ. In order to compensate for this action, a number of turns must be added to the series regulating turns, such that the m. m. f. produced by the external current flowing through them shall be exactly equal but opposed to that produced by the demagnetizing tendency of the armature. That is, the compensating turns must be at least,

$$\frac{2 I_1 D}{I} = \frac{2 D}{c}.$$

Owing, however, to the effect of magnetic leakage, the total m. m. f. of this compensating winding will not be sufficient to void the armature demagnetizing effect. This leakage may be provided for by multiplying $2 D \div c$ by ν, the coefficient of magnetic leakage. Hence we must substitute for T_{se} in Equation 20, $T_{se} - \frac{2 \nu D}{u}$, in order to compensate for these effects.

Should it be required to have the generator over-compound or under-compound, the additional series-turns will be either more or less than those given by the revised Equation 20, depending upon the amount of over- or under-compounding, examples of which will be considered under *Design*. In the above discussion, we tacitly assumed that the speed of rotation was maintained constant. This is in general not the case, however, the speed of the prime mover falling off as the load on the generator increases, producing a diminution in the generated e. m. f. In addition, the load is frequently remote from the dynamo, necessitating feeders between the machine and load, with a consequent drop in voltage. In order to compensate for these factors which tend to lower the voltage at the point of application of the power, it is customary to over-compound generators so that their terminal voltage at rated load is from 3 to 15 per cent in excess of the no-load value. The lower values are usual for generators supplying lighting circuits, while the higher ones are for those employed in railway systems.

CALCULATIONS OF THE MAGNETIC CIRCUIT

Forms of Field-Magnets.—*General.* Before discussing the application of the formulæ for the magnetic circuit, already given, to actual

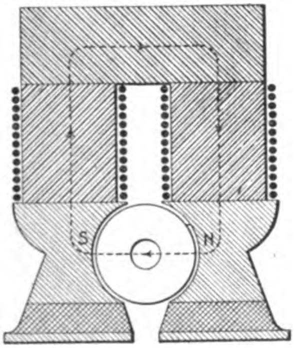


Fig. 100. Under-Type Bipolar Dynamo.

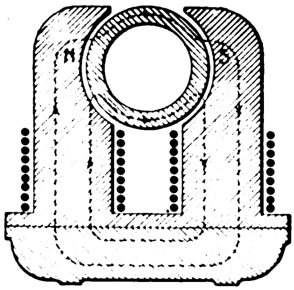


Fig. 101. Over-Type Bipolar Dynamo.

machines, let us consider the various shapes in which field-magnets and frames are usually found.

The form of a field-magnet depends primarily upon whether it is *bipolar* or *multipolar*. Prior to about 1890, the former type was in universal use for all direct-current machines, even up to large sizes; but now it is generally restricted to machines of less than 5 kilowatts output, larger sizes being made multipolar to save material, as explained later.

Bipolar field-magnets may be of the simple horseshoe type, placed as in the early Edison machines (Fig. 100); or may be turned with the pole-pieces upward, known as the *inverted* or *over-type* (Fig. 101); or the horseshoe may be laid on its side (Fig. 102). This latter type produces an unsymmetrical machine, and, in addition, the entire base and bearings are connected to one of the pole-pieces, exposing a large surface which materially increases the magnetic leakage. This type is interesting, however, from the fact that it has

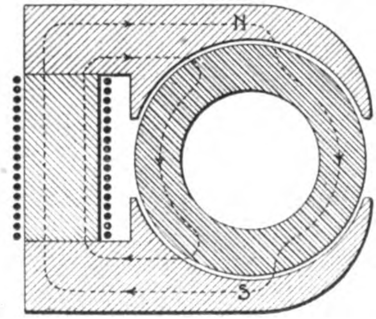


Fig. 102. Single Exciting-Coil Type Bipolar Dynamo.

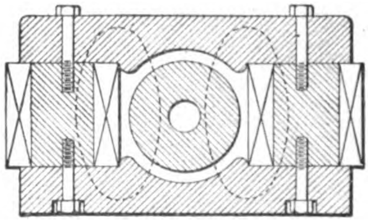


Fig. 103. Manchester Type of Field-Magnet.

but a single field-coil. The same form is also arranged with the core horizontal, the armature being either under or over the latter, in which case the supports for the bearings must be of some non-magnetic material such as brass, since they extend from one pole-piece to the other.

These forms, excepting the over-type, are open to the objection that, if set upon an iron base, the base would act as a magnetic short-

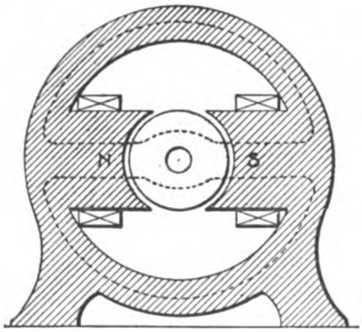


Fig. 104. Bipolar Ring Field-Magnet.

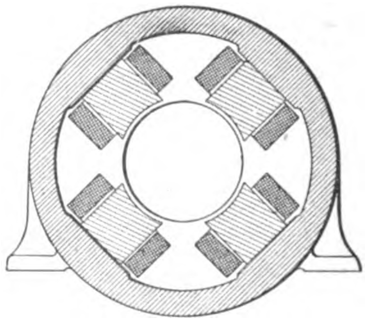


Fig. 105. Four-Pole Ring Field-Magnet.

circuit, and thus rob the armature of a considerable portion of the magnetic flux. In the Edison machines, this difficulty was partly overcome by interposing thick pieces of zinc between the pole-pieces and the base; but Hopkinson* found that even with this arrangement,

*Philosophical Transactions of the Royal Society, May 6, 1886.

the leakage through the base was over 10 per cent of the total flux. The over-type, on the other hand, has but small magnetic leakage of this character, since the pole-pieces are far removed from the base bearings or other magnetic conductors.

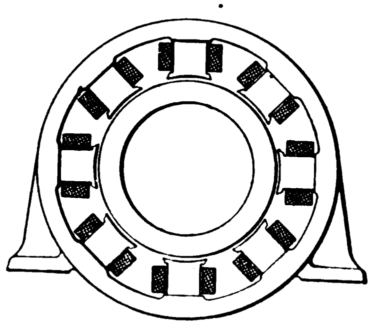


Fig. 106. Multipolar Ring Field-Magnet.

Fig. 103 represents a radically different form of bipolar magnet, called the *Manchester* type, from its place of manufacture in England. The construction is extremely solid, and offers good protection to the machine; but it has the undesirable feature of having two magnetic circuits in parallel, producing consequent poles and requiring the full number of ampere-turns for each circuit. Hence the total number is doubled; but each is only $\sqrt{\frac{1}{2}}$ times as long, because the cross-section of each core is one-half that of an equivalent single core. The required length of wire is thus $2 \times \sqrt{\frac{1}{2}} = 1.41$ times as great for the double magnetic circuit. This form also has considerable magnetic leakage, the entire base and bearings being connected to one of the pole-pieces.

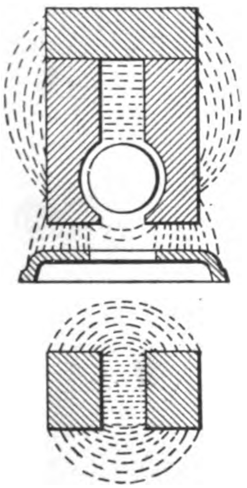


Fig. 107. Magnetic Leakage or Stray Flux in Bipolar Field.

The modern tendency has been to draw away from these early designs, and to adopt machines that are wholly or partially enclosed. Figs. 104, 105, 106 represent respectively the bipolar, four-pole and multipolar ring arrangements of present-day practice, the bipolar type being restricted to machines of small output, as noted above. This ring arrangement has the advantages of strength, simplicity, symmetrical appearance, and minimum magnetic leakage, since the pole-pieces have the least possible surface and the path of the magnetic flux is shorter, more symmetrical, and more natural.

Magnetic Leakage. The function of the field-magnet is, as we have seen, to produce a flux which the armature conductors cut in order to generate an e. m. f. This flux is called the *useful* flux. In addition to this useful flux, there is a *stray* flux from all parts of the field system (Figs. 107, 108), the m. m. f. of the exciting ampere-turns having to produce both these fluxes. If we call ϕ_m the flux in the magnet-core, ϕ_a the flux in the armature, and ϕ_s the flux which strays, we have:

$$\phi_m = \phi_a + \phi_s$$

The ratio between the total flux and the useful flux is called the *coefficient of magnetic leakage or dispersion*, that is,

$$\nu = \frac{\phi_m}{\phi_a}.$$

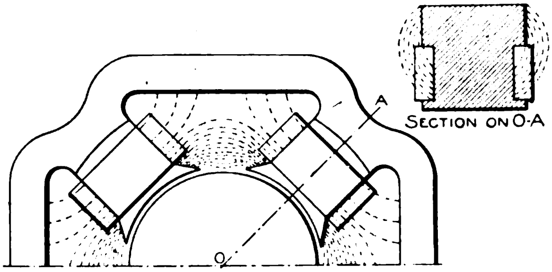


Fig. 108. Magnetic Leakage or Stray Flux in Four-Pole Field.

It is a number greater than unity, and varies in value from 1.15 in ring types (Figs. 104–106), to 1.7 in the Manchester and under-types (Figs. 100–103).

The magnitude of the stray field depends chiefly (*a*) upon the shape of the magnet-limbs; thus circular cores, for example, will have less leakage than those of rectangular cross-section, on account of the smaller area of the side flanks; (*b*) upon the length of the air-gap, because the higher the reluctance of the latter, the greater the tendency of the flux to take alternative paths; (*c*) upon the degree of saturation to which the field system is pushed, because the magnetic conductivity of the leakage paths in air is constant, while that of the iron cores decreases as the saturation point is approached It is evident, therefore, that the coefficient of dispersion not only varies with different types of machine, but is not generally constant even in a given machine, since it rises with the excitation. Moreover, when a large armature current flows, the demagnetizing action of the latter directly aids dispersion, as it usually produces a m. m. f. opposed to that of the main flux, which tends to blow aside the latter.

The only accurate method of determining the dispersion factor of any machine is by experiment.* For purposes of design, however,

*For various methods of procedure, see S. P. Thompson's *Dynamo-Electric Machinery*, Vol. I, p. 134, New York, 1901.

one must resort to the results of experiments performed on machines similar to the one being designed. Table II gives approximate values of dispersion coefficients for machines of the modern type (*i.e.*, multipolar frames), and — for comparison — values for corresponding machines of the other types mentioned.*

TABLE II

Dispersion Coefficients

Output in Kilowatts	Multipolar Type Figs. 104, 105, 106	Overtype Fig. 101	Undertype Fig. 100	Single-Magnet Type Fig. 102	Manchester Type Fig. 103
1	1.35				
2	1.25				
5	1.20	1.40	1.60	1.55	1.70
7	1.18				
10	1.16				
25	1.15	1.28	1.45	1.40	1.55
50	1.14				
100	1.12	1.22	1.35	1.32	1.45
200	1.11				
300	1.10		1.25		
500	1.09				
1,000	1.08				

It is seen that the magnetic dispersion is greater with the smaller sizes of machines, because the surfaces from which it occurs are relatively longer compared with the total flux. It is also greater with cast-iron magnets and pole-pieces and with smooth-core armatures.

It is theoretically possible to predetermine the dispersion of a given machine from the working drawings,† the calculations being based upon the principle that where a circuit offers alternative paths, the flux will divide itself between the paths in the proportion of their relative magnetic conductance or permeance. In fact, the theory of parallel electrical circuits is here applicable. Various rules have been devised for this purpose; but the manufacturers' designer usually contents himself with referring to tables such as that given above.

Exciting Ampere-Turns. The determination of the exciting ampere-turns for a machine is a simple matter if we know the dis-

* *Dynamo-Electric Machinery.* S. P. Thompson. New York, 1904, Vol. I, p. 138.
† *Dynamo-Electric Machines*, A. E. Wiener, 2d ed., p. 217.

persion coefficient and the magnetic properties (as shown by the B–H curve) of the materials forming parts of the magnetic circuit. See Fig. 112.

The simplest mode of procedure is to fix approximately the flux necessary to pass through the armature in order to produce the required e. m. f.* Knowing this value, and also the size of the machine, we may select from Table II a suitable dispersion coefficient, and thus find the flux required to be produced by the field winding. That is:

$$\phi_m = \nu \phi_a$$

The next step is to allow a sufficient cross-section of material in the various parts to carry this flux at a reasonable flux-density. Knowing the latter at once fixes the reluctance, and the necessary number of ampere-turns is found by solving the equation connecting the flux, m. m. f., and reluctance of each portion of the circuit, given on page 10. That is,

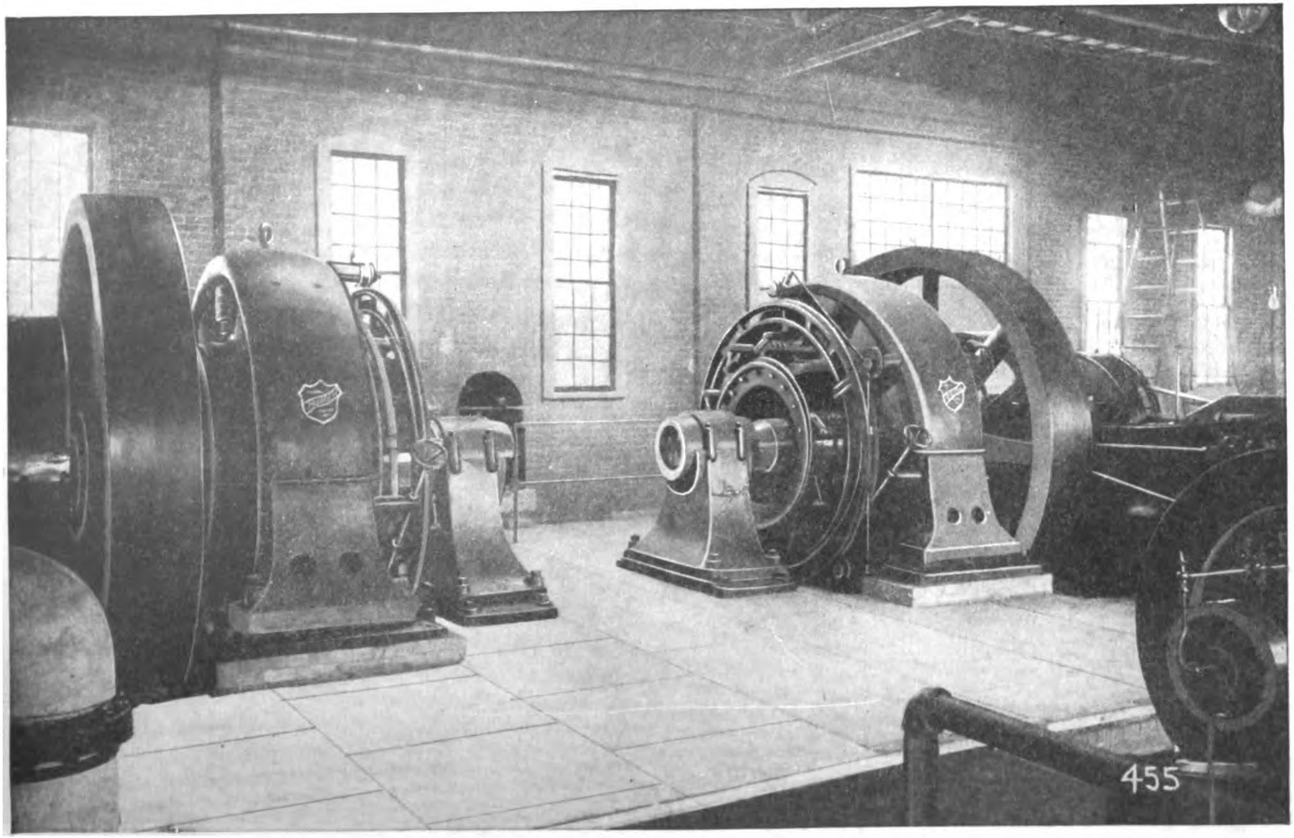
$$\text{Ampere-turns} = IT = \frac{\phi\, l}{1.257\, A\mu} = \frac{B\, A\, l}{1.257\, A\, \mu} = \frac{B\, l}{1.257\, \mu}.$$

Where B is the flux-density per square centimeter, and l the length of the part in centimeters, the sum of the ampere-turns required for the different parts will then give the total ampere-turns for that circuit. The magnetic path from one pole to its neighbor of opposite polarity and return, is alone considered as indicated in Figs. 104, 105, 106 (assuming a ring-type yoke). Hence the total ampere-turns for this circuit will be those necessary per pair of poles. In other words, each field-coil must have one-half of this total value.

As average values for the magnetic densities in the various parts of continuous-current generators, we may take the figures of Table III, departures from which are, however, often necessitated by circumstances.

If the particular solution thus arrived at is not suited to the various conditions, a slight change in the original assumptions will bring one nearer to the proper value. In fact, the more preliminary calculations that are made, the more nearly perfect and the more reliable will be the final figures; furthermore, it is always wise to make assumptions both sides of the accepted value, to make sure that it is right.

*See Equations 1 and 2, page 62.



ENGINE-TYPE GENERATORS

In Republic Rubber Works, Youngstown, Ohio.

Bullock Electric Manufacturing Co.

As these assumptions carry with them the selection of the magnetic dimensions of the machine, it will be well to consider these here.

TABLE III

Average Flux-Densities in Various Parts of Continuous-Current Generators

FLUX-DENSITY, IN:—	LINES PER SQUARE INCH	MATERIAL
Armature body	50,000 to 95,000	Soft sheet iron or mild steel
Armature teeth	125,000	Do.
Air-gap	40,000 to 55,000	Air
Magnet-cores	75,000 to 100,000	Cast steel or wrought iron
Magnet-yoke	70,000 to 90,000	If cast steel or wrought iron
	35,000 to 50,000	If cast iron

(*a*) *Yoke.* In all machines of the ring (yoke) type, the yoke carries only one-half the total flux, as can be seen by reference to Figs. 104 to 106. The magnetic length is the mean length of path.

(*b*) *Magnet-Cores.* As each core carries the whole flux for one pole-face, the entire section of one core is considered. The length of the magnetic path in the magnet-cores is, however, twice the length of one core.

(*c*) *Air-Gap.* Since slotted armatures are the type used almost exclusively at present, the magnetic area of this portion will be equal to the pole-face area. The total magnetic length of these gaps is taken as twice the distance from iron to iron, measured perpendicular to the armature periphery.

(*d*) *Armature Core.* Here, also, the magnetic flux divides into two or a multiple of two paths (for the ring-yoke design), so that the magnetic area carries only one-half the flux entering the armature from one pole-face. The magnetic section is also less than the gross section, on account of the insulation of the core-discs* and the presence of ventilating ducts.† If the latter are absent, it is usual to allow 10 per cent as space loss if the insulation is varnish, and 15 per cent if it is paper. When the air-ducts are present, 25 per cent may be assumed for preliminary calculations with varnish insulation, and 35 per cent with paper insulation. The magnetic length

* See page 14 for reason for laminating and insulating core-discs.

† See page 171 for design, etc., of ventilating ducts.

is the length of the mean path lying between the roots of the teeth and the periphery of the internal hole.*

(*e*) *Teeth.* The total length traversed by the flux in this portion of the circuit is equal to twice the depth of one tooth. The width of one tooth may be taken as the width at the root, the teeth being generally trapezoidal in shape. The number of teeth receiving the flux from one pole may be taken as the number lying immediately under the pole-face, *plus* one or two, depending upon the allowance for fringing.† The magnetic area of the teeth will therefore be the number so determined, *multiplied by* the product of the mean width of one tooth and the mean length of the armature, where the latter is the gross length *minus* the percentage allowed for insulation and air-ducts. Account must also be taken of the fact that when the teeth are operated at densities of 100,000 lines per square inch or more, part of the flux from the poles will take the alternative air-paths through the slots to the armature core, since at this high density their permeance is not insignificant compared with that of the teeth themselves. In other words, the ampere-turns calculated to force the flux through the teeth alone at high flux-densities would be in excess of the correct amount.

In order to find the true value of the flux-density in the teeth if we know the apparent flux-density, let us assume that:

α = Ratio of net length to gross length of armature core;
B_t = True value of the tooth flux-density;
b_t = Width of a tooth, at the root;
b_s = Width of a slot;
h = Height or depth of a slot;
l = Net length of the armature parallel to the shaft;
ϕ_a = Flux entering the armature from one pole;
ϕ_t = Flux actually carried by the teeth, from one pole.

We then have:

$$\text{Iron section of one tooth} = b_t \times l.$$

$$\text{Air section of one slot} = \frac{b_s \times l}{\alpha}.$$

The actual space forming an alternative path for the magnetic flux, per slot, will be given by the area of one slot (parallel to the pole-face) *plus* the area lost along one tooth by insulation and air-ducts; or,

---

*The "internal hole" is that portion of the armature between the center and inner edge of the core.

†"Fringing" means spreading of flux issuing from a pole-shoe.

$$\text{Section of air-space per slot} = \frac{b_s \times l}{\alpha} + (1 - \alpha)\frac{b_t \times l}{\alpha}$$
$$= \frac{l\,(b_t + b_s - \alpha\, b_t)}{\alpha}.$$

Since the flux entering the armature from one pole will divide between the two paths inversely as the reluctance of the two, we have, as the flux in the air-space,

$$(\phi_a - \phi_t) \propto \frac{l\,(b_t + b_s - \alpha\, b_t)}{\alpha\, h};$$

and the true flux in the teeth,

$$\phi_t \propto \frac{b_t\, l\, \mu}{h},$$

in which μ is the actual permeability of the teeth when transmitting the flux ϕ_t.

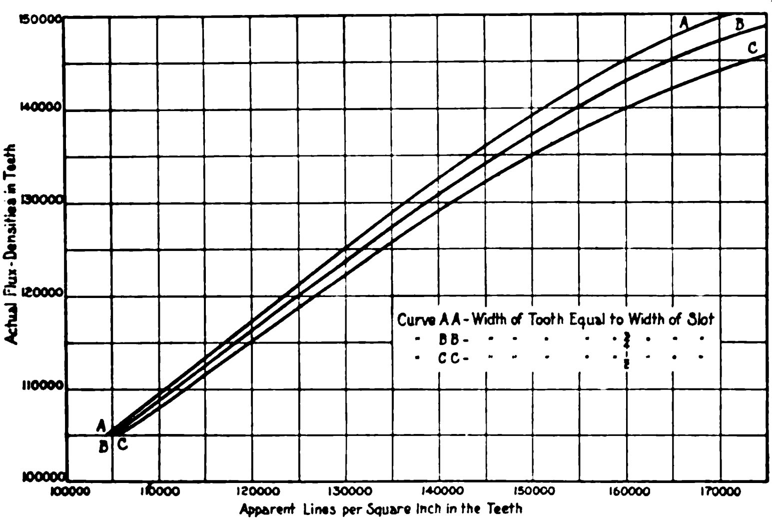


Fig. 109. Apparent and Actual Flux-Densities in Teeth.

Dividing the second equation by the first, we obtain,

$$\frac{\phi_t}{\phi_a - \phi_t} = \frac{\alpha\, b_t\, \mu}{b_t + b_s - \alpha\, b_t};$$

$$\phi_t\,(b_t + b_s - \alpha\, b_t + \alpha\, b_t\, \mu) = \phi_a\, \alpha\, b_t\, \mu$$

$$\frac{\phi_t}{\phi_a} = \frac{\alpha\, b_t\, \mu}{b_t + b_s - \alpha\, b_t + \alpha\, b_t\, \mu} = \frac{B_t}{B_a}.$$

Taking this last equation, and substituting for α 0.75 (a common value), and various ratios for $b_t \div b_s$, we obtain the curves given in Fig. 109, by assuming various values for B_t, finding the corresponding values of the permeability from Fig. 110, and then calculating B_a. If other values of α are used and greater accuracy is desired, where the actual B–H curve of the material of the teeth is known, these new quantities should be placed in the equation given above, and new curves drawn.

Example of Calculation. In order that the foregoing rules may be clearly understood, and to exemplify the use of the curves and the method of calculation, we shall take a concrete case of dynamo design. In Fig. 111 is given a dimensioned sketch of a modern six-pole continuous-current generator having a capacity of about 200 kw. Assuming that 12,500,000 lines are required to produce the rated e. m. f. in the armature, let us calculate the ampere-turns per pair

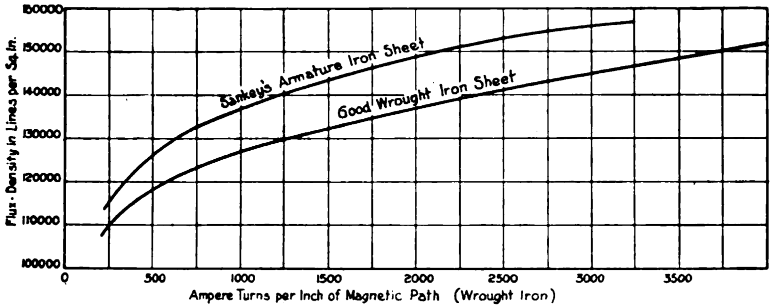


Fig. 110. Magnetization Curves at Very High Densities.

of poles to produce this flux in the armature. From Table II, $\nu = 1.11$ approximately, and the data of the magnetic circuit around path A or path B is:

Part	Material	Total Flux
Yoke	Cast steel	6,937,500
Pole-cores	Cast steel	13,875,000
Pole-shoes	Cast steel	13,875,000
Air-gap	Air	12,500,000
Armature teeth	Sheet steel	12,500,000
Armature core	Sheet steel	6,250,000

We now estimate the magnetic lengths and areas as follows:

Yoke. From Table III, we assume the flux-density = 65,000; hence the cross-section of the yoke is

$$6,937,500 \div 65,000 = \text{approximately } 105 \text{ sq. in.} = A_y.$$

Consequently the dimensions of the yoke would be, say, 6 in. by 17.5 in., making the actual flux-density in the yoke,

$$B_y = 6,937,500 \div 105 = 65,200 \text{ lines per sq. in.}$$

The length of magnetic path, scaled off from the drawing, is

$$l_y = 55 \text{ in.}$$

Magnet-Cores. Assuming, from Table III, the flux-density in the teeth as 85,000 lines per sq. in., we have as the required area of cross-section of the magnet-cores,

$$13,875,000 \div 85,000 = 163.2 \text{ sq. in.}$$

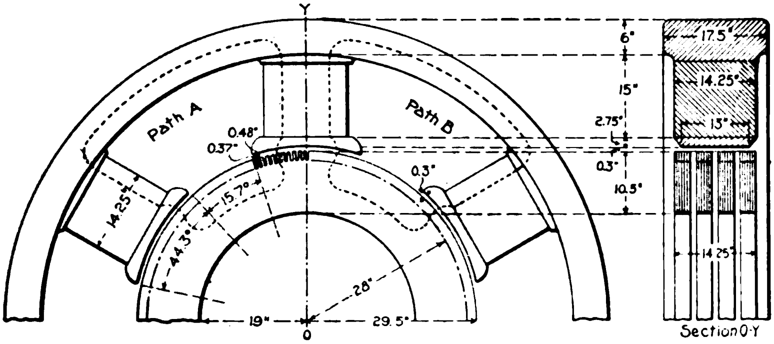


Fig. 111. Part of Magnetic Circuit of a Six-Pole Machine.

Selecting a circular section for the pole-cores, let us assume a diameter of, say, 14.25 inches, as giving an area of cross-section nearest to that above computed. This gives:

$$A_m = 159.5 \text{ sq. in., and}$$

$$B_m = \frac{13,875,000}{159.5} = 87,000 \text{ lines per sq. in.}$$

The length of magnetic path in the pole-cores is twice the length of one; so that,

$$l_m = 2 \times 15 = 30 \text{ in.}$$

Pole-Shoes. These are cast-steel extensions affixed to the magnet-cores to increase the air-gap area. The mean area of each shoe is,

$$A_s = 197.5 \text{ sq. in.;}$$

so that,

$$B_s = \frac{13,875,000}{197.5} = 70,400 \text{ lines per sq. in.}$$

The mean length of magnetic path per shoe is 2.75 in. Hence we have,

$$l_s = 2 \times 2.75 = 5.5 \text{ in.}$$

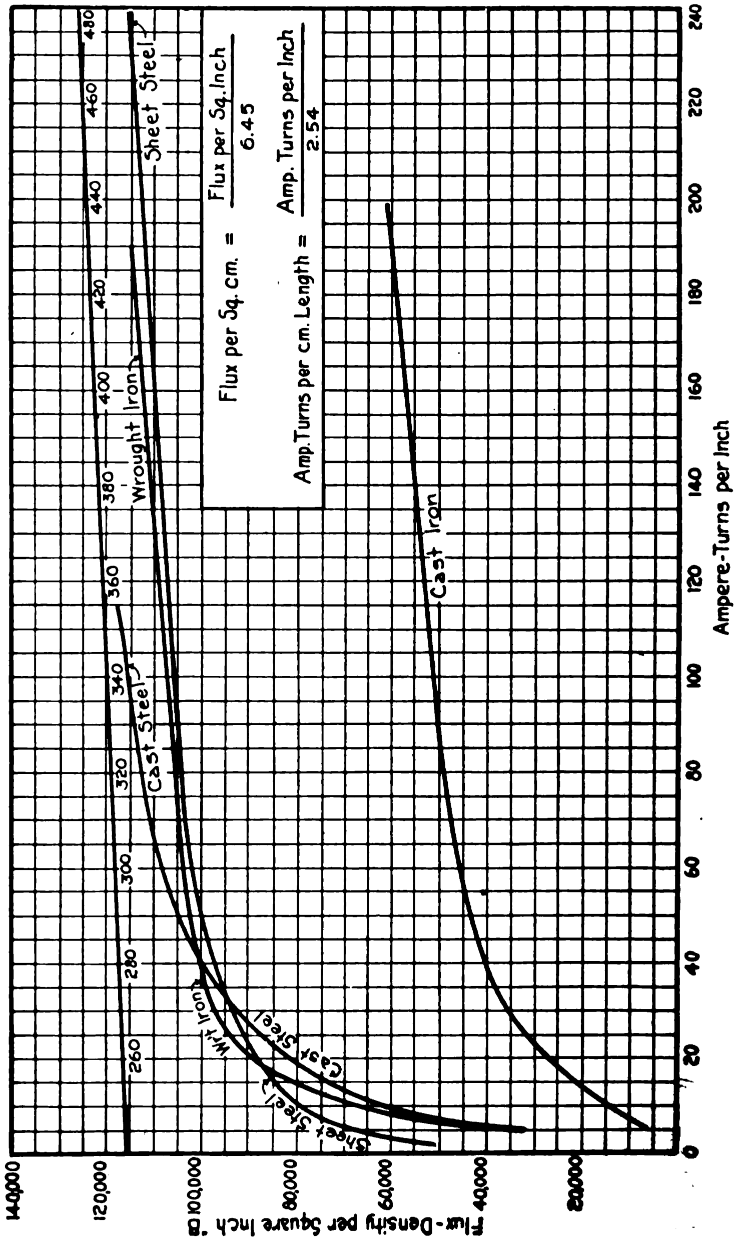


Fig. 112. Magnetization Curves of Irons and Steels.

Air-Gaps. The magnetic area of the air-gap being the area of the pole-face, we have it equal to 300 sq. in. Hence

$$B_g = 12{,}500{,}000 \div 300 = 41{,}700 \text{ lines per sq. in.}$$

The magnetic length through air in path *A* or *B* is twice the length of an air-gap; that is,

$$l_g = 2 \times 0.3 \text{ in.} = 0.6 \text{ in.}$$

Armature Teeth. The iron area of the 28 teeth acted upon by one pole, if the width of one tooth at its root is 0.326, is:

$$A_t = 0.326 \times 28 \times 14.25 \times 0.75 = 97.4 \text{ sq. in.}$$

Therefore,

$$B_t = \frac{12{,}500{,}000}{97.4} = 128{,}500 \text{ ``apparent'' lines per sq. in.}$$

Referring to Fig. 109, we see, since a tooth is as wide as a slot, that $B_t = 124{,}200$ actual lines per square inch in the teeth.

For the magnetic length, we have,

$$l_t = 2 \times 1.5 = 3.0 \text{ in}$$

Armature Core. The magnetic area is

$$A_c = 9 \times 14.25 \times 0.75 = 96.3 \text{ sq. in}$$

Hence,

$$B_c = \tfrac{1}{2} \times \frac{12{,}500{,}000}{96.3} = 65{,}000 \text{ lines per sq. in.,}$$

as the flux divides and takes two paths through the armature core.

The mean length of the magnetic path as obtained from the drawing, is:

$$l_c = 33 \text{ in.}$$

The preceding data may now be tabulated as follows:

Part	Material	Magnetic Area in Sq. In.	B in Lines per Sq. In.	Length of Path in In.
Yoke	Cast Steel	105	65,200	55
Pole-core (1)	" "	159.5	87,000	15
Pole shoe (1)	" "	197.5	70,400	2.75
Air-gap (1)	Air	300	41,700	0.3
Arm. Teeth	Sheet steel	97.4	128,500	1.5
Arm. Core	" "	96.3	65,000	33

By reference to the magnetization curves (Fig. 112), the ampere-turns per inch of length for the various materials at the flux-densities determined may be found, and the ampere-turns for total length of path computed. The results may then be tabulated as follows:

Part	Flux-Density in Lines per Sq. In.	Ampere-Turns per In. Length of Magnetic Path	Length of Path in Inches	Ampere-Turns for Total Path
Yoke	65,200	12	55	661
Pole-cores (2)	87,000	21.5	30	645
Pole-shoes (2)	70,400	13.5	5.5	75
Air-gaps (2)*	41,700	13,080	0.6	7,745
Arm. Teeth (2)	128,500	589	3	1,767
Arm. Core	65,000	8	33	264
		Ampere-turns per pair of poles,		11,157

Coil Winding Calculations. In series field-coils the whole of the external current, or a definite part of it, is used for the production of a m. m. f., so that the number of turns of wire or strip is found by dividing the requisite number of ampere-turns at any given load by this current. Furthermore, this wire or conductor must be of sufficient size to carry safely, efficiently, and without overheating, the given current. The series-wound generator is at present in general use for arc-lighting machines; and as the current in this case is usually about 10 amperes, it has been found by experience that, depending upon the depth of the winding, No. 10 or No. 8 B. & S. gauge wire are the correct sizes to use.

If the machine were to be separately excited, it is probable that the e. m. f. of the exciter would be specified, and we should have practically the shunt case. If, however, the current were given, the determination would be the same as in the case of the series winding above.

Shunt Winding Calculations. The determination of the best size of wire for a shunt winding is far more difficult than for a series one, in that merely the ampere-turns and the voltage applied to the terminals of the coil are given, while the space allotted to the winding and the heating limits must be kept within definite bounds. Various methods have been suggested, but none are very satisfactory. One of the simplest is as follows: The temperature of the field coils for

*In computing ampere-turns per inch length of the air-gap, it must be remembered that for air $\mu = 1$; so that in inch-units we have,

$$IT_g = 0.3133 \times B_g \times l_g .$$

The number 0.3133 is called the *gap-coefficient*, and represents the number of ampere-turns per inch length of path, requisite for a flux-density of one line per square inch in air.

continuous operation at rated load may be assumed to be 75° C.—that is, a 50° C. rise above a room temperature of 25° C. At this temperature the resistance of a mil-foot of copper wire (that is, a wire one foot long and 0.001 inch in diameter) is 12.56 ohms. Hence,

$$R = \frac{12.56 \times l}{\text{Circ. mils}},$$

in which l is the length of the conductor in feet, and "Circ. mils" is the area of cross-section in circular mils, which is equal to the diameter in mils squared. The current traversing the wire when a voltage V' is applied at its terminals, is,

$$I = \frac{V' \times \text{Circ. mils}}{12.56 \times l}.$$

It is also evident that the ampere-turns in any winding are numerically equal to the amperes that would result if a single turn of wire were supposed to be subjected to the given voltage, because two turns would have twice the resistance and would take one-half the current; and so on for any number. Hence,

$$\text{Ampere-turns} = \frac{V' \times \text{Circ. mils}}{12.56 \times l},$$

in which l represents the mean length of one turn in feet. By transposition we obtain the cross-section of the wire required—that is:

$$\text{Circ. mils} = \frac{\text{Ampere-turns} \times l \times 12.56}{V'}.$$

Example. An 8-pole 150 kw. shunt generator required 808 ampere-turns per pair of poles when its terminal voltage was 115. The poles were 9¼ inches wide, and 10 inches long parallel to the shaft. Allowing a depth of winding of about 2 inches and a spool thickness of about ½ inch, the mean length of one turn would be nearly 50.5 inches, the poles being rectangular. Then, at rated voltage, V' per pair of field-exciting coils is 115 ÷ 4 = 28.75 volts, and we have:

$$\text{Circ. mils} = \frac{808 \times 50.5 \times 12.56}{28.75} = 17,850.$$

Referring to a wire-gauge table, we see that the wire having an area of cross-section in circular mils nearest this figure is No. 7 B. & S., for which circ. mils = 20,820.

In applying the above formula to the shunt winding for a dynamo, allowance must be made for the resistance of the rheostat which is usually put in the shunt circuit to regulate the e. m. f.

This resistance will consume from 20 to 30 per cent of the no-load voltage; and the value of V' to be substituted in the formula should therefore be a corresponding amount lower, unless the rated load voltage be used. In this case the resistance of the rheostat is determined by the resistance which it is necessary to add to that of the field-winding in order to keep the generated e. m. f. at the proper point for all other loads.

Space-Factor. In all cases where insulated conductors, whether strip or wire, are used, the space taken up by the conductor proper is always a fraction of the whole space occupied by the entire winding. This fraction will obviously depend upon the shapes of the conductors and the space set apart for the winding, and also upon the thickness of the insulation. The ratio of net cross-sectional

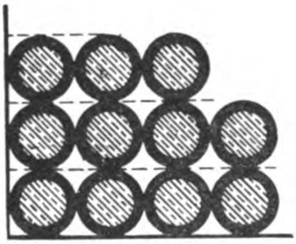


Fig. 113. Square Order of Bedding.

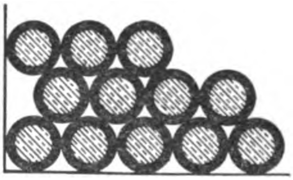


Fig. 114. Hexagonal Order of Bedding.

area of copper in any such space to the gross section, is called the *space-factor.*

In winding bobbins for field-magnet coils, the space-factor depends largely upon whether square or round wire is used. If the former, the space wasted is less, and the heating of the coil is reduced (for a given number of turns carrying a given current, etc.), since there is less cross-section filled with air or insulation, either of which is a bad conductor of heat. If round wires are used (as is generally the practice), the space-factor will be determined chiefly by the ratio between the relative thicknesses of the wire and its insulation, and also by the partial bedding of one layer of wires between those of the layer below.

Suppose the round wires to be wound so as to lie in the square order without any bedding, as in Fig. 113. Then, if the diameter of the bare wire is d, and the insulated diameter is d_1, the ideal space-factor would be:

$$\sigma = 0.7854 \frac{d^2}{d_1^2}, \quad \text{.......................} (21)$$

because the area of each small circle is $\pi \frac{d^2}{4} = 0.7854\ d^2$, and the area of the small square enclosing each outer circle is d_1^2. Suppose, however, an extreme case of bedding, as in Fig. 114, where the wires lie in hexagonal order. By similar reasoning, the space-factor would then be:

$$\sigma = 0.906 \frac{d^2}{d_1^2}.$$

If rectangular strip is used, there is no bedding, and no wasted space except where the end of one layer of a coil extends to the layer above. If the area of cross-section of the bare conductor is ab, and the area of the same, insulated, is $a'\,b'$, the space-factor is simply $ab \div a'\,b'$. In practice it has been found that edge-wound strip gives the highest space-factor, ranging from 0.83 to 0.93.

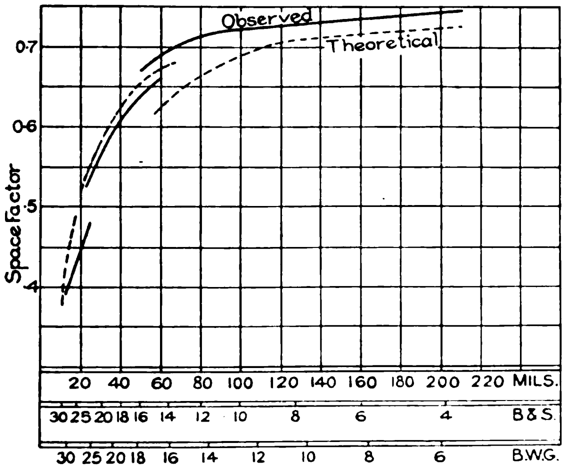


Fig. 115. Curves Showing Space-Factors for Round Wires of Various Gauges.

In practice, with round wires, it is found, however, that even the most experienced winders produce a bedding of seldom over 3 per cent; so that the safest course is to assume no bedding, and to take the space factor as given above unless it is actually known.

Some actual figures have been put into graphical form by Dr. S. S. Wheeler, and these are given in Fig. 115. Here the full lines represent the values by the formula assuming the square order; and the broken lines, the observed values. It is seen that the larger sizes of wire do actually bed a little, while with smaller sizes the bedding is negative.

Connections of Exciting Coils. It is the almost invariable custom to connect all the field-magnet exciting coils of the same type in series with each other, so that the magnetizing current is the same throughout. Then, if the number of turns per spool is the same, the flux per pole will be uniform. They must also be connected up so as to produce alternate north and south poles, so that if all the coils are wound in the same direction, and similarly placed, the connections will come alternately at the yoke-end and the pole-face end of the bobbin, as in Fig. 116.

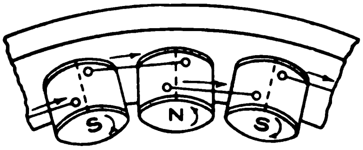


Fig. 116. Connections of Field-Magnet Coils.

Excitation Losses. Having computed the resistance of the shunt winding (r_{sh}) by the previously explained method, we have $\frac{V}{r_{sh}} \times V = \frac{V^2}{r_{sh}}$ as the watts actually expended in the shunt field-coils, V being the terminal voltage of the generator. To this loss must be added the one in the shunt-regulating resistance, and also the loss in the series-regulating coils, if any, in order to give the total watts required in excitation. For shunt-wound machines, the watts required in excitation vary in practice from 1 to 8 per cent or more of the output, depending upon the capacity of the machine. As a guide in this direction, Table IV has been constructed, giving the *maximum permissible* excitation losses.

TABLE IV

Excitation Losses

Output of Machine in Kilowatts	Excitation Losses in per cent of Rated Load Output
5	6
10	5
20	4
30	3.5
50	3.0
100	2.75
200	2.50
300	2.25
500	2.00
1,000	1.75
2,000	1.50

Heating of Magnet-Coils. The heat developed in field-magnet coils is dissipated in two ways: It is either carried by conduction through the copper and the insulation, and then by radiation and convection to the outer air, or it is conducted to the iron portions of the machine nearby and radiated off by these. In either case the amount of heat produced in the coil is equal, in watts, to the product of the resistance and the square of the current, while the rate at which the heat is lost cannot be very accurately calculated.

In order to compute the temperature which a field-coil finally reaches, let w_m = watts wasted in field-coils at rated load of machine;

A'_m = Radiating area of all the bobbins, in square inches:

θ_m = Final temperature rise above surrounding air (usually 50° C.).

Then

$$\theta_m \propto w_m,$$

$$\theta_m \propto \frac{1}{A'_m}.$$

So that,

$$\theta_m \propto \frac{w_m}{A'_m};$$

or,

$$\theta_m = h\frac{w_m}{A'_m},$$

where h is a constant depending upon the depth of the winding, upon the cooling action due to the armature rotation, and upon the condition of the surrounding air. It is the temperature above that of the sorrounding air to which the coil would be raised if radiating 1 watt per square inch.

Experience has shown that a certain rise in temperature is allowable, this being usually put at 50° C. or 90° F. above the temperature of the surrounding air. Tests have also demonstrated that this rise in temperature is not usually exceeded if a certain surface of coil is allowed for each watt converted into heat. The difficulty in fixing this is due to the way in which the heat is dissipated, as before noted. Also, authorities differ in regard to what surface shall be considered as radiating, in some cases going so far as to count only the external cylindrical surface of the coil. As a matter of fact, the internal surface of the coil, next to the poles, usually dissipates more heat in a given time than the external surface, so that the total area should be reckoned. This may be done by assuming a proper

TABLE V

Specific Temperature Increase in Magnet-Coils of Various Proportions at Unit Energy Loss per Sq. In. of Core Surface

Cylindrical Magnets								Rectangular and Oval Magnets	
					Increase of Magnet Temperature for Each Watt per Square Inch of Core Surface				
					Radiating Surface Consisting of				
Ratio of Winding Depth to Core Diameter	Winding Depth in Parts of Core Diameter	Ratio of External Coil Surface to Core Surface	Ratio of Cylindrical Surface plus One End Surface of Coil to Core Surface	Ratio of Cylindrical Surface and Both End Surfaces of Coil to Core Surface	Cylindrical Coil Surface	Cylindrical Surface plus One End Surface	Cylindrical Surface and Both End Flanges	Ratio of Radiating Surface to Core Surface	Temperature Increase for Unit Energy Dissipation
1 : 100	.01	1.02	1.03 to 1.05	1.04 to 1.07	75°	74° to 72°	73° to 71°	1.02	75°
1 : 50	.02	1.04	1.05 " 1.10	1.07 " 1.12	73	72 " 69	71 " 68	1.05	72
1 : 30	.033	1.067	1.07 " 1.15	1.10 " 1.20	71	70 " 65	69 " 63	1.1	69
1 : 20	.05	1.1	1.12 " 1.20	1.15 " 1.30	69	68 " 63	65 " 58	1.25	60
1 : 15	.067	1.133	1.15 " 1.25	1.20 " 1.40	67	65 " 60	63 " 53.5	1.5	50
1 : 12	.083	1.167	1.20 " 1.30	1.25 " 1.45	65	63 " 58	60 " 51.5	1.75	43
1 : 10	.1	1.2	1.25 " 1.40	1.30 " 1.55	63	60 " 53.5	58 " 48	2	37.5
1 : 9	.11	1.22	1.28 " 1.45	1.35 " 1.60	61.5	59 " 51.5	55.5 " 47	2.25	33
1 : 8	.125	1.25	1.30 " 1.50	1.40 " 1.70	60	58 " 50	53.5 " 44	2.5	30
1 : 7	.143	1.286	1.35 " 1.55	1.45 " 1.80	58.5	55.5 " 48.5	51.5 " 41.5	3	25
1 : 6	.167	1.33	1.40 " 1.60	1.50 " 1.90	56.5	53.5 " 39.5	50 " 39.5	3.5	21.5
1 : 5	.2	1.4	1.50 " 1.75	1.60 " 2	53.5	50 " 43	47 " 37.5	4	19
1 : 4	.25	1.5	1.65 " 2	1.80 " 2.5	50	45.5 " 37.5	41.5 " 30	5	15
1 : 3	.33	1.67	1.85 " 2.5	2 " 3	45	40.5 " 30	37.5 " 25	6	12.5
1 : 2	.5	2	2.25 " 3	2.5 " 4	37.5	33 " 19	30 " 19	8	9.5
1 : 1	1	3	3.5 " 5.5	4 " 8	25	21.5 " 13.5	19 " 9.5	10	7.5
3 : 2	1.5	4	5 " 8.5	6 "12	19	15 " 9	12.5 " 6	12	6
2 : 1	2	5	6.5 "12	8 "18	15	11.5 " 6	9.5 " 4	15	5

value of h, which, according to W. B. Esson, is about 55 and according to Esterline 83, for ordinary bobbins; or by relying upon the experimental results given in Table V. Esson, in using this figure, counts as radiating surface only the external heat-radiating area, and not the end flanges and internal surfaces. Esterline includes in the radiating surface the external and internal areas and the flanges, counting the last two as radiating only one-half as much as a corresponding external area.

ARMATURE WINDINGS

Armature conductors—or *inductors*, as they are sometimes called—are almost universally made of copper. Their arrangement upon the armature, and the order in which they are connected together to form a complete winding, constitute one of the most involved subjects in the design of dynamo-electric machinery.

Classification. Armature windings may be classified according to the way the conductors are placed upon the armature core, as follows:

Ring Windings, in which the conductors are placed upon a ring-shaped core, passing through the interior of the ring in the form of a helix, and hence sometimes called *helical windings*.

Drum windings, having the conductors wound entirely upon the surface, or in slots upon the surface, of a cylindrical core.

Disc windings, where the conductors are arranged in a plane like the spokes of a wheel, the connections being similar to those in drum armatures.

Of all these types, the drum is almost exclusively used at the present time for the armature windings of continuous-current machines, since, in contradistinction to the ring winding, there are no internal return conductors to increase the amount of armature copper needed, and for the greater reason that formed coils are applicable, greatly reducing the first cost and facilitating insulation and repairs. A drum armature partly wound with formed coils is illustrated in Fig. 117.

Besides this grouping, we may also divide windings into *closed-coil* and *open-coil* types, depending upon whether the winding constitutes a closed or an open circuit. Closed-coil armatures are in almost general use for direct-current machines, since they give a steadier current and spark considerably less than the open-coil type.

The latter are used for direct-current arc-lighting machines and for star-wound alternators.

Armature Coil.—*Element of Winding.* A *winding element, section,* or *coil* is that portion of an armature winding which terminates at two commutator bars. In its simplest form it consists of two armature conductors (in drum windings), with the necessary end connections, so that the maximum number of armature coils is equal to one-half the number of armature conductors. In ring windings, an element may consist of only one armature conductor, the internal return portion being inactive (that is, cutting no flux) and therefore

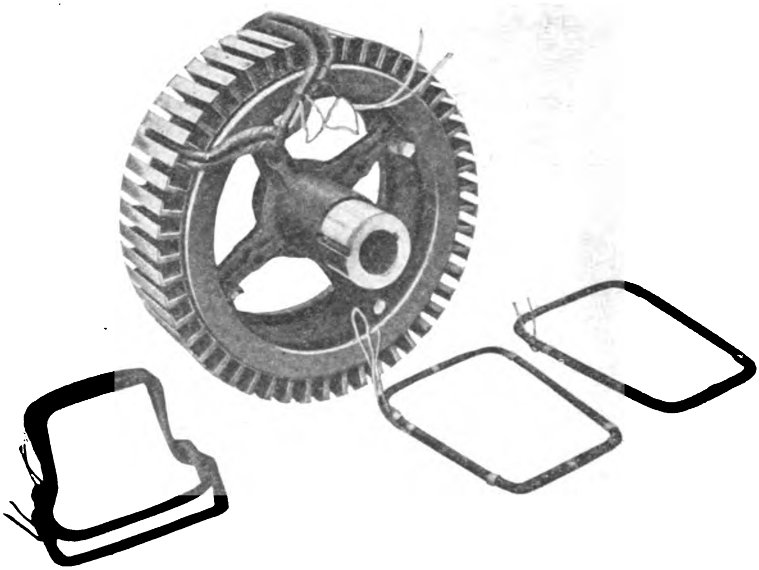
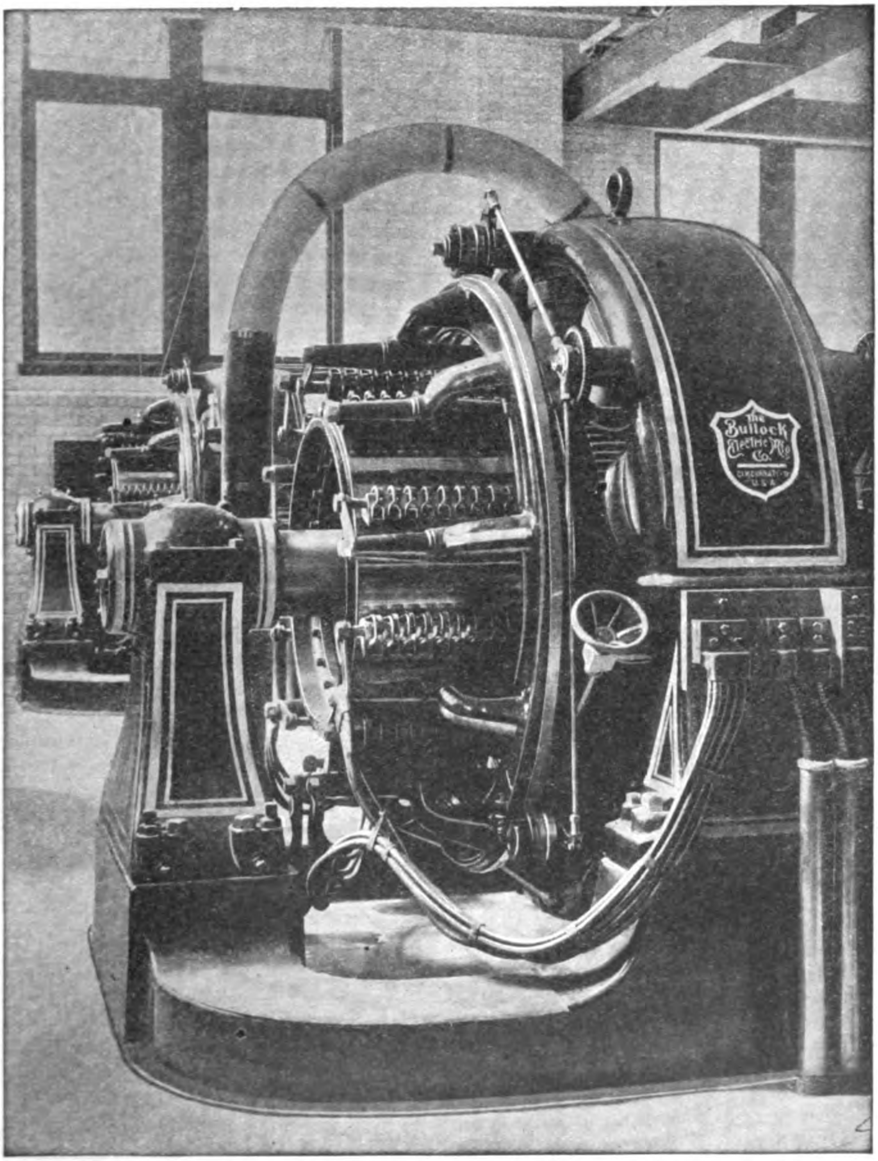


Fig. 117. Showing Method of Winding and Applying Formed Coils for an Armature Core.

serving as an end connector. Such an element may also consist of 2 or $2n$ armature conductors in series for drum windings, or of n armature conductors in series for ring windings, where n is an integer; but this affects only the e. m. f. generated by the coil, the end connections of the section as a unit remaining unchanged. Similarly, the resistance of an element may be reduced by connecting several conductors in parallel; but this also does not affect the end connections of the coil as an element of winding; it merely increases the current-carrying capacity. In either case the *method* of winding



250 K.W. ENGINE-TYPE GENERATOR
at Prudential Life Building, Newark, N. J.
Bullock Electric Manufacturing Co.

is not altered by putting more turns of wire in series or in parallel in each section.

The whole theory of armature winding may therefore be said to resolve itself into a study of end connections; and in discussing drum windings, we shall consider an element consisting of two armature conductors with their end connections only.

Possible Number of Commutator Bars. We have seen that at each end of a section of winding there is a commutator bar. In the simplest form of ring-wound armature, each element of the winding contains only one armature conductor, so that the maximum number of commutator bars is Z, the rest of each element being equivalent to an end connection. The number of commutator bars in a ring winding may also be less than Z (where Z = the number of armature conductors); but in any case it is $\frac{Z}{m}$, where m is 1 or an integer factor of Z.

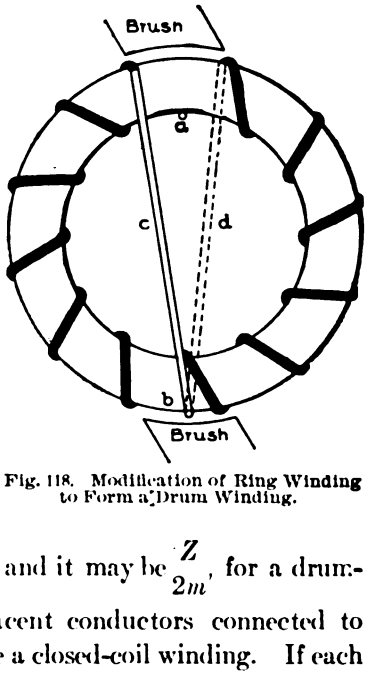


Fig. 118. Modification of Ring Winding to Form a Drum Winding.

In closed-coil drum windings, K, the number of commutator bars, has for its maximum value $\frac{Z}{2}$, and it may be $\frac{Z}{2m}$, for a drum-wound armature cannot have adjacent conductors connected to separate commutator segments and be a closed-coil winding. If each alternate armature conductor in a drum winding be considered as the return of its neighbor, the equivalent ring winding would be as indicated by coil in Fig. 118, and we then see that the armature would be short-circuited.

Field Step. In ring windings, the coils are wound around the armature core, so that they pass through its interior; but in drum windings the armature conductors are laid in slots on the surface of the core, and do not pass through the interior. It is plain, in the latter case, that unless one of the conductors of a section is cutting flux under a south pole at the same time that the other armature conductor of the same section is cutting flux under a north pole, either the coil will not be working at maximum efficiency (in which case only one conductor will be cutting flux), or both armature conductors will be under poles of like polarity at the same instant so that the e. m. f. generated in one will tend to equalize that in the other. Hence, in practice, we have one conductor of an element under a south pole at the instant that the other is under a north pole, in which case the e. m. f.'s generated by the two coils are additive. It is also universal to have the step or spacing from one armature conductor to the next of that section, nearly equal to the distance between the centers of adjacent unlike poles; but windings could be devised in which the step so made from one conductor to the next would be to the region of a more distant pole; in that case, however, the end connections would be unduly long.

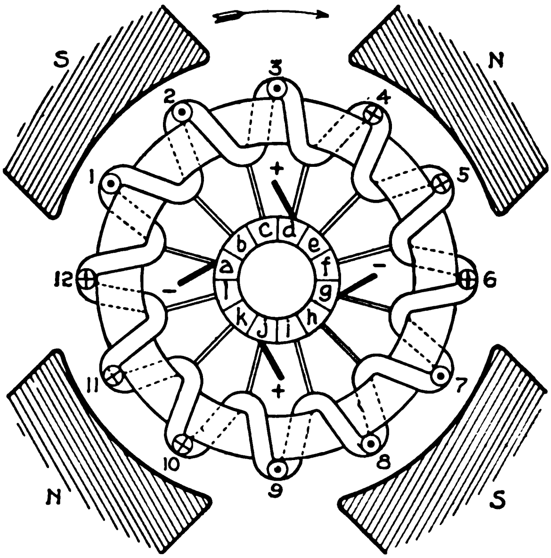


Fig. 119. Ring Winding for 4-Pole Machine.

Pitch of Winding. The pitch or spacing of a winding denotes the distance from one inductor of the winding to the next inductor in the succession; and it is usual to express it in terms of the number of inductors spanned over. In order to see more clearly what

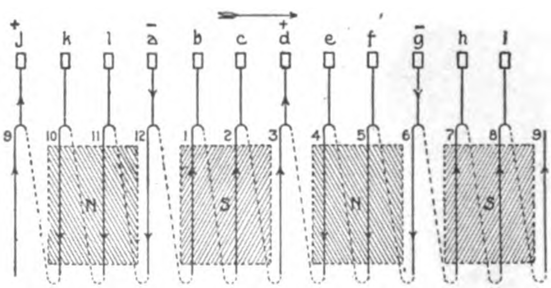


Fig. 120. Development of Ring Winding for 4-Pole Machine.

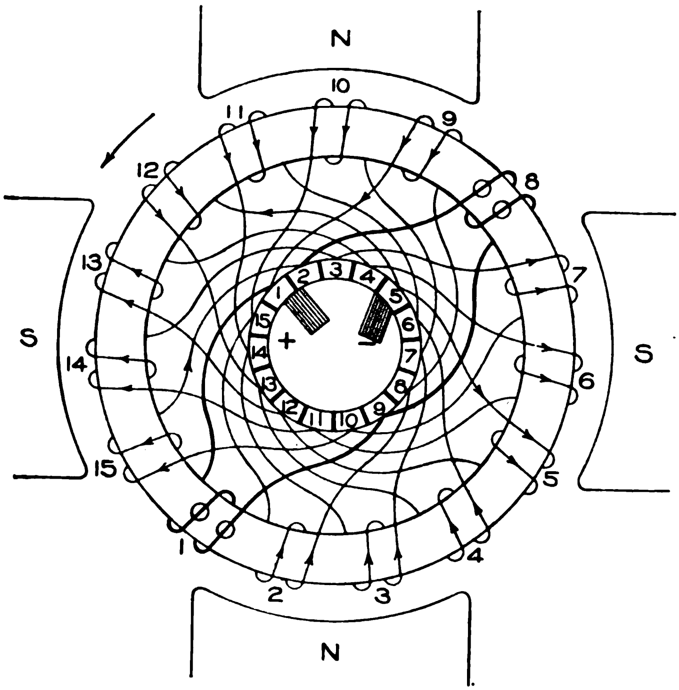


Fig. 121. Series-Connected Wave-Wound Ring Armature.

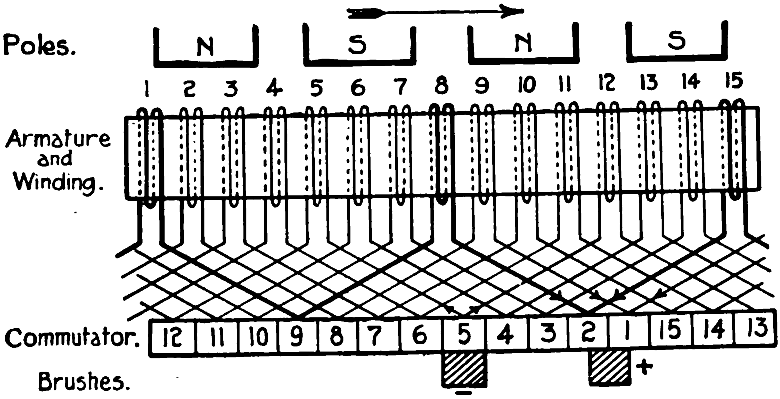


Fig. 122. Development of Winding Shown in Fig. 121.

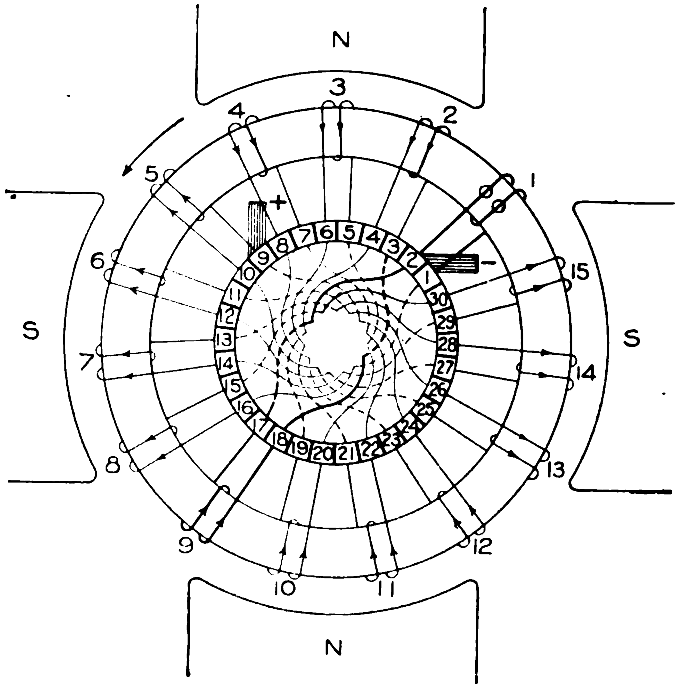


Fig. 123. Series-Connected Multipolar Ring Armature.

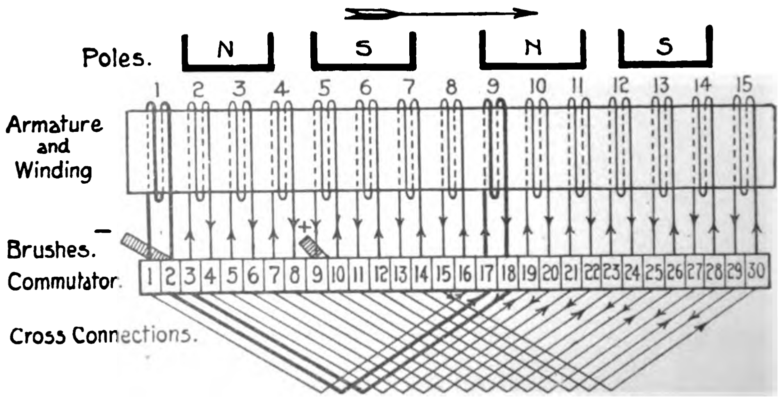


Fig. 124. Development of Winding Shown in Fig. 123.

is meant, let us suppose that the inductors around a certain drum winding are numbered consecutively from 1 up. If it is further assumed that inductor 1 is joined at the front end to inductor 16 to form a loop, and that 16 is joined at the rear to 31 to form a similar loop, the pitch at both ends would be 15. Had 1 been joined to 18 at the front end, and 18 to 3 at the rear end, then 3 to 19 at the front end, the front pitch would be $y_f = +17$, the back pitch $y_b = -15$, the average pitch 16, and the resultant pitch 2.

Ring Windings. Ring windings may be divided into two classes; the *spirally wound* ring, shown in Figs. 119 and 120, and the *series-connected wave-wound* ring, shown in Figs. 121, 122, 123, and 124 for two methods.

The first type, forming in itself a single closed helix, is unaffected by the number of poles; by merely placing $2p$ sets of brushes on the surface of the commutator at equal distances apart, the winding is at once divided into as many equal and symmetrical paths through the armature, and we have $c = p$. A multipolar armature is thus obtained, having as many parallel circuits and as many points of collection of the current as there are poles. The equation of the e. m. f. of such a *multipolar parallel-wound* or *multiple-circuit* armature is similar to that for a bipolar machine; that is,

$$E = \frac{Z \times p\,\phi \times \text{r. p. m.}}{60 \times 10^8 \times c} = \frac{Z \times \phi \times \text{r. p. m.}}{60 \times 10^8},$$

since $c = p$. This multipolar winding has greater current-carrying capacity than the bipolar, since there are more paths in parallel, the multipolar winding being therefore equivalent to several bipolar dynamos in parallel, just as the bipolar machine was shown to be equivalent to two sets of cells in parallel (Fig. 48).

As in a bipolar machine, there are two points on the commutator where the e. m. f. is zero—*i.e.*, where proper commutation may occur—so there will be p points in a multipolar parallel-connected ring winding where the current is commutated, and p brushes will be needed. If, however, the increased number of points of collection be regarded as a disadvantage, they may again be reduced to two, by joining all commutator bars which are situated $360 \div \frac{p}{2}$ degrees apart, so that sectors which are at any moment at the same voltage are connected together. Thus, in a four-pole machine, each commutator bar must be connected to that which is diametrically opposite, and there is a choice between two positions for the brushes at right angles to one another. In a six-pole machine, each cross-connection must unite three sectors situated 120° apart, and the brushes may be either 60° or 180° apart; in an eight-pole machine, four sectors 90° apart must be joined, and the brushes may be either 45° or 135° apart. Thus we see that in general the angle between the brushes of unlike sign may be $180° \div \frac{p}{2}$ or any uneven multiple of this angle. The commutator connections for a four-pole cross-con-

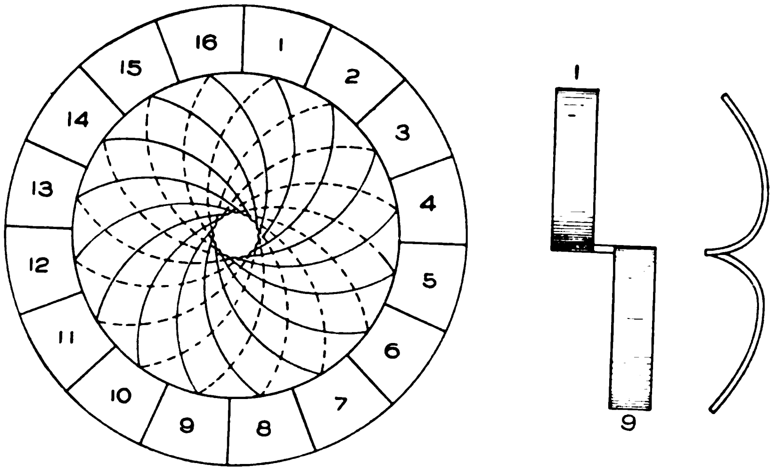


Fig. 125. Commutator Connections for a 4-Pole Cross-Connected Winding.

nected winding of the type described, are shown in Fig. 125, while Fig. 126 illustrates the same for a six-pole machine. When thus cross-connected, the commutator must be made $p \div 2$ times as long as before, in order to provide sufficient surface of contact to collect the current by the two sets of brushes; also, the number of commutator segments must be divisible by p.

In the multipolar ring winding of Fig. 119, each pole corresponded to one circuit through the armature, the total number of circuits being therefore equal to the number of poles. It is also possible to add together the inductive effects of two or more poles, so that the e. m. f.'s produced by one-half the inductors on the armature are summed up in series. The winding will then have two paths in parallel, whatever the number of poles. This is called a *series-wound* or *two-circuit* armature. Ring windings of this kind are not used in practice, so that they need not be further considered. Series-wound or two-circuit drum windings are of practical importance, and will be described later.

Forms of Drum Windings. Closed-coil drum windings are of two forms, known as *lap windings* and *wave windings* respectively, and so called from the manner of connecting the ends of the inductors to form a section. In the bipolar type, there is no essential difference

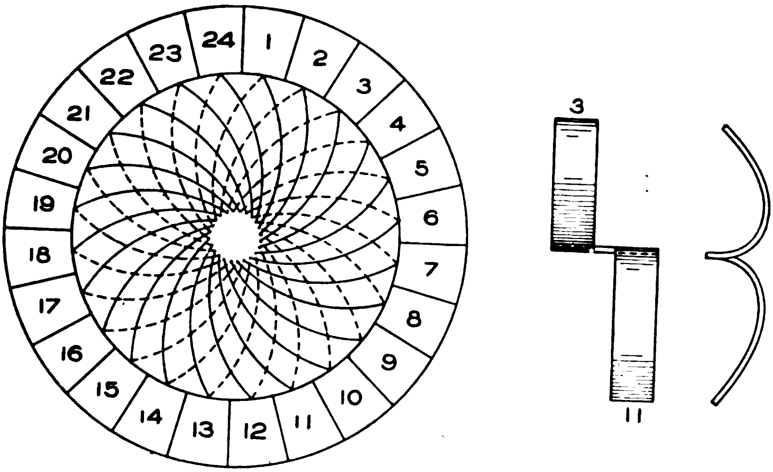


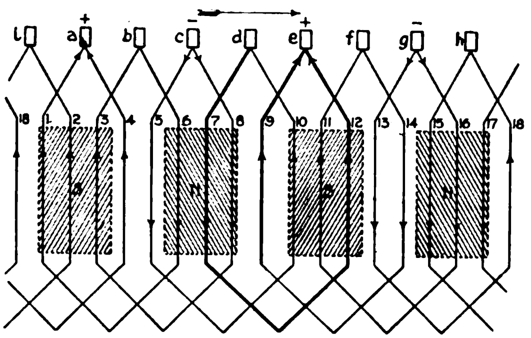
Fig. 126. Commutator Connections for a 6-Pole Cross-Connected Winding.

between the two forms; but when applied to multipolar machines, the divergence is marked.

A simple (simplex) lap winding, Fig. 127, gives as many circuits through the armature as there are poles, whence it is similar to a parallel-wound ring armature. On the other hand, a simplex wave winding, Fig. 128, always gives 2 paths through the armature, irrespective of the number of poles.

It is seen, therefore, from the fundamental formula for the e. m. f. of a dynamo (page 62), that, for a given number of armature inductors, a wave winding will give more voltage than a lap winding in a multipolar field. The latter, however, will give a greater number of paths in parallel through the armature, thus increasing its current capacity.

The distinction between the two windings arises in the following manner. Since the inductors that are passing a north pole generate an e. m. f. in one direction, and those passing a south pole are generating an e. m. f. in the opposite direction, it is clear that an inductor in one of these groups should be connected to one in a nearly corresponding position in one of the other groups, so that the current may flow down one and up the other in agreement with the directions of the e. m. f.'s. If, now, we examine Fig. 127, we see that at the back of the armature—that is, the end distant from the commutator—each inductor is connected with the one five spaces



F		B	F
+ a	1	6	b
b	3	8	c
− c	5	10	d
d	7	12	e
+ e	9	14	f
f	11	16	g
− g	13	18	h
h	15	2	i
i	17	4	a

Fig. 127. Typical Simplex Lap Winding, and Winding Table for Same.

further on, or the pitch at the back is 5. At the front end of the winding, after winding one element—as, for instance, *e*–9–14–*f*—a second element *f*–11–16–*g* is formed, which laps over the first; and so on completely around the winding. In the wave winding illustrated in Fig. 128, however, the case is different. The connections at the rear end remain as in the preceding winding; but at the commutator end, instead of lapping back toward the point from which it started, the connection turns the other way—as, for example, *c*–5–10–*h*. This results in a winding that advances in a sort of zigzag path; hence its name.

Lap Windings. Fig. 127 illustrates a simplex or single lap winding, since the terminals of an element are connected to adjacent commutator bars. Following through this winding and starting at segment *a*, we pass along conductor 1 to the rear of the armature, then by an end connection skip over to conductor 6, which leads to commutator bar *b*. From that point, conductor 3 leads again to the rear, and is there connected to 8, which brings us back to bar *c*. Following on in this manner to bar *i* by conductor 2, and from here *via* conductor 17, we finally reach bar *a* through 4, thus closing the winding on itself without traversing each conductor more than once. Calling the interval between the conductors connected at the rear of the armature the *back pitch* (y_b), and the interval between those connected together at the front end the *front pitch* (y_f), we see that for this winding, $y_b = +5$; and $y_f = -3$. The average pitch, being half the arithmetical sum of the front and back pitches, is $y_{av} = 4$; while the resultant pitch is $y_r = +2$, being the algebraic sum of the front and back pitches.

Considering only the case in which each element or section of the winding is a single loop, the number of such sections will be $Z \div 2$; the number of sections (which is the same as the number of resultant steps if multiplied by the length of each resultant step) will equal the total travel of the winding. This will be equal to Z if the whole winding must be traversed before closing upon itself. If, however, only one-half or one-third of the winding had to be traversed before the start was reached, the total travel would be UZ, where U is the number of times the winding must be traversed before finally closing on itself. We have, therefore, for the first condition controlling a lap winding,

$$\frac{Z}{2}(y_b + y_f) = U\,Z; \text{ so that } U = \frac{y_b + y_f}{2},$$

where U may be any whole number. Hence it follows that the sum of the front and back pitches must in every case be an even number.

There is also the condition that no conductor shall be encountered twice; that is, no number of steps whatever, however often repeated, shall make $y_b + y_f$ equal to y_f. Or, taking m as any whole number,

$$y_f \gtrless m\,(y_f + y_b);$$

whence,

$$y_f \div y_b \gtrless m \div (1-m).$$

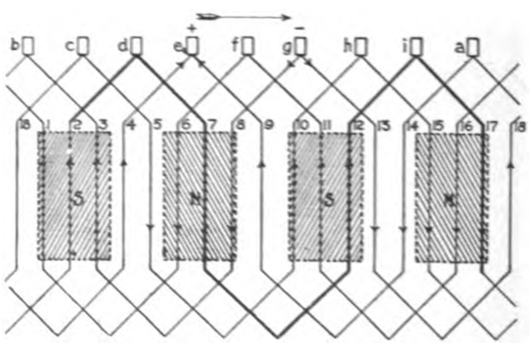
It follows from this inequality, that y_f and y_b cannot possibly have any common factor; and as their difference must be even, it is evident that both must be odd numbers. Also, to make the winding lap back, it is necessary that one of them should be a negative number.

Wave Windings. The winding illustrated in Fig. 128 is called a *simplex wave winding*. Starting at bar *a*, we pass along conductor 1 to the back of the armature, thence by a connector to conductor 6, and then ahead to bar *f*. From here we follow along conductor 11, and then 16 to *b*, whence we are led along 3 and 8 to *g*. Following through the complete winding, we arrive at bar *a* by way of conductor 14, after having traversed each conductor once. Thus the winding closes upon itself after passing through $p \div 2$ winding elements.

For this winding, then, we have,

$$y_f = +5; \; y_b = +5; \; y_{av} = 5; \; y_r = +10.$$

The resultant step is $y_f + y_b$ as before; and the number of such



F	B		F
a	1	6	f
f	11	16	b
b	3	8	g
−g	13	18	c
c	5	10	h
h	15	2	d
d	7	12	i
i	17	4	e
+e	9	14	a

Fig. 128. Typical Simplex Wave Winding, and Winding Table for Same.

steps being $Z \div 2$, and the total travel through the winding being U, we have;

$$\frac{Z}{2}(y_f + y_b) = U\,Z; \quad \text{whence} \quad U = \frac{y_f + y_b}{2}.$$

In order that no conductor be encountered twice in traversing the winding, it must not be possible, by any number of repetitions of the step $y_f + y_b$, to recur to the step y_f beyond any previous number of repetitions of the resultant step. Hence, if m and n are any whole numbers, $m\,(y_f + y_b)$ must not equal $n\,(y_f + y_b)$ steps plus y_f. That is,

$$m\,(y_f + y_b) \gtrless n\,(y_f + y_b) + y_f.$$

It follows in this case, also, that y_f and y_b cannot have any common factor; and as their sum must be even, both of them may be odd, since U may be any number. They may, however, be equal to one another, and this is commonly the case.

General Formulæ for Drum Windings. In general, if y stands for the complete step from the first conductor of any group to the first conductor of the next group, m for the field step, and G for the total number of groups in the winding, we shall have, from the previous deductions:

$$mZ = mgG = \frac{1}{2} p\, y \pm c\,,$$

when

$$Z = \frac{p\, y \pm 2\, c}{2m}\,;\ \text{and}\ y = \frac{2\, m\, Z \mp 2\, c}{p}\,,$$

which are the general formulæ for symmetrical windings, where g is the number of conductors per group.

For *lap windings* we have $m = 0$, so that,

$$y = \mp \frac{2\, c}{p}\,.$$

We may separate y into two parts y_f and y_b, of which either is negative, and either slightly less than or equal to $Z \div p$, and which differ from one another by $2c \div p$.

In *lap windings* the step of the winding at the commutator is related to the winding pitch by the simple rule:

$$y_k = y \div g.$$

Thus, in a simple winding of this type where $y = 2$, and where each element of the winding is a simple loop of two conductors so that $g = 2$, we would have $y_k = 1$.

For *wave windings*, $m = 1$, so that,

$$y = \frac{2Z \mp 2\, c}{p}\,;$$

and if this complete step is made up of equal front and back pitches, we shall have:

$$y_f = y_b = \frac{Z \mp c}{p}\,.$$

Re-entrancy of Windings. A winding which closes upon itself is called a *closed-coil winding*, as heretofore noted; also, because it re-enters upon itself, it is known as a *re-entrant winding.*

If the *whole* winding must be traversed before the first inductor is reached or re-entered, the winding is said to be *singly re-entrant.* If one-half the winding need be traversed before the inductor from which the start is made is again encountered, the winding is said to be *doubly re-entrant;* and so on for triply and other multiply re-entrant windings. The number of times the drum is passed *around* is of no consequence when considering the re-entrancy of a drum winding. For example, in Fig. 129, the drum is passed around 25 times before the conductor from which the start is made is reached, yet the winding is singly re-entrant, as shown by the winding table accompanying it.

Multiplex Windings. An armature may be wound with two or more independent windings, each of which may be singly re-entrant,

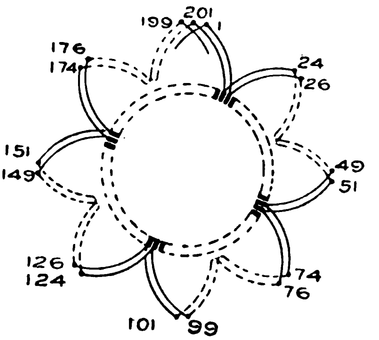


Fig. 129. Wave Winding. 8-Pole, 2-Circuit, Singly Re-entrant. (See Winding Table on Page 107.)

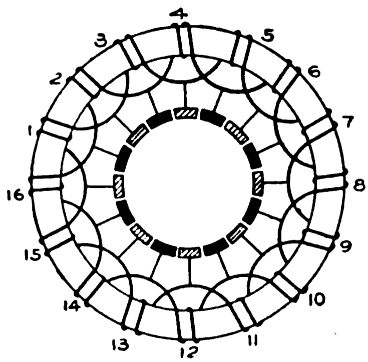


Fig. 130. Duplex Winding Consisting of Two Singly Re-entrant Ring Windings.

as shown in Fig. 130. These two windings might be furnished with two independent commutators situated at each end of the armature; but usually there is one with the number of its segments doubled, the two sets of bars being alternated between one another. In this case the brushes must be made broad enough to overlap at least two and one-half commutator bars, so as to collect current from both windings simultaneously. Such a winding is known as a *duplex singly re-entrant winding. Triplex-wound armatures* have three independent windings, with three sets of commutator bars similarly arranged.

The advantage of multiplex windings is that sparking at the brushes may be considerably lessened, for the coils are short-circuited a much shorter length of time and there is a longer brush-resistance path. Hence multiplex windings are much used in machines intended to supply large currents at small voltages, such as generators for electrolytic work.

WINDING TABLE FOR 8-POLE DRUM ARMATURE; 202 CONDUCTORS; TWO-CIRCUIT, SERIES-PARALLEL GROUPING; BRUSHES (±) 135° APART.

F	B	F	B	F	B	F	B	F

D	U	D	U	D	U	D	U
1	26	51	76	101	126	151	176
201	24	49	74	99	124	149	174
199	22	47	72	97	122	147	172
197	20	45	70	95	120	145	170
195	18	43	68	93	118	143	168
193	16	41	66	91	116	141	166
191	14	39	64	89	114	139	164
189	12	37	62	87	112	137	162
187	10	35	60	85	110	135	160
185	8	33	58	83	108	133	158
183	6	31	56	81	106	131	156
181	4	29	54	79	104	129	154
179	2	27	52	77	102	127	152
177	202	25	50	75	100	125	150
175	200	23	48	73	98	123	148
173	198	21	46	71	96	121	146
171	196	19	44	69	94	119	144
169	194	17	42	67	92	117	142
167	192	15	40	65	90	115	140
165	190	13	38	63	88	113	138
163	188	11	36	61	86	111	136
161	186	9	34	59	84	109	134
159	184	7	32	57	82	107	132
157	182	5	30	55	80	105	130
155	180	3	28	53	78	103	128
153	178	1					

Paths in Parallel and Conductors in Series between Brushes. In a simplex lap winding there will be p paths in parallel between the brushes, and $Z \div p$ conductors in series. In a simplex wave winding, there will always be 2 paths in parallel through the armature, and each path will consist of $Z \div 2$ conductors in series.

A multipolar lap winding is often called a *parallel-grouped winding*, on account of the number of parallel paths through the armature. Sometimes it is called a *multiple-circuit winding* for the same reason. Similarly, a simplex wave winding is called either a *two-circuit winding* or a *series winding*.

Combining simplex windings to give a multiplex winding adds to the number of paths in parallel through the armature, but not the generated e. m. f. The latter is increased by multiplying the number of turns per coil, or the number of coils in series; but having a great number of turns per section (that is, element of the winding) aggravates the tendency to spark, as already shown (page 46).

Number of Brush Sets Required. Where there are p points around the commutator at which the voltage is zero (see page 35 for method of measuring potential around a commutator), p sets of brushes may be used in any case. In a lap winding, simplex or multiplex, p sets must be used in order to collect the full armature current; while in wave windings, simplex or multiplex, 2 sets of brushes are sufficient, though any number up to p may be used in order to insure sparkless collection of the armature current. For, by referring to Fig. 131, it is seen that if six brushes were placed around the commutator 60 degrees apart, the extra ones might be considered as cross-connections introduced to reduce the armature I^2R loss.

Conditions to be Satisfied by a Closed-Coil Drum Winding. A drum winding cannot have an odd number of inductors. Both the front and back pitches must be odd in simplex windings, for the odd-numbered conductors may be regarded as the returns for even-numbered ones.

Both the front and back pitches must be approximately equal to $Z \div p$, in order that conductors moving simultaneously under poles of opposite polarity should have their generated e. m. f.'s additive. The smallest pitch meeting this condition would stretch completely across a pole-face, while the largest would stretch from the given pole-tip to the next pole-tip of like polarity. When the front and back pitches differ considerably from $Z \div p$, the winding is called a *chord winding*, the name being due to the appearance of the end-connections. As we have seen, this method possesses the advantage of cutting down the demagnetizing effect of the armature; but it has the disadvantage that the two edges of any section are not both passing at the same time into a commutating field, so that it is not suitable for handling large outputs of current.

For a given number of inductors, the front and back pitches must be chosen so as to comply with the following conditions:

(*a*) All winding elements must be similar mechanically and electrically, and must be symmetrically placed upon the armature.

(*b*) In a simplex winding, every inductor must be passed over once only, and the winding must close upon itself, or be re-entrant.

(*c*) In a multiplex winding, each simplex element must comply with condition (*b*).

(*d*) A multiplex winding not consisting of complete and independent simplex windings (called a *singly re-entrant multiplex winding*), must as a whole satisfy condition (*b*).

(*e*) In a *two-layer winding* (that is, one where the conductors are placed one on top of another in a slot), it is usual to give the upper ones odd numbers, and the lower ones even numbers.

In addition to these conditions for drum windings in general, lap windings must also comply with the following:

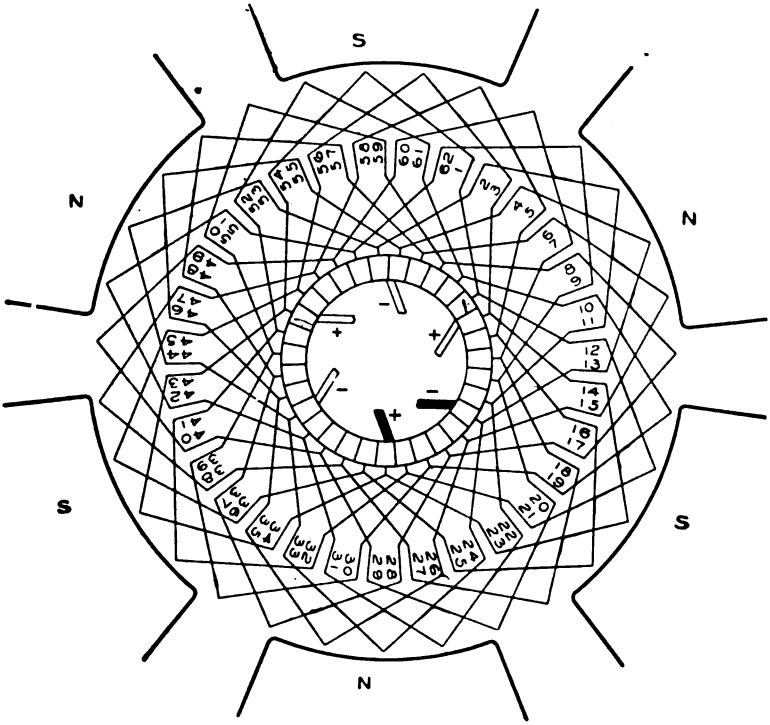


Fig. 131. Six-Pole Drum Simplex Wave Winding, Singly Re-entrant.

(*a*) Front and back pitches must be opposite in sign.

(*b*) The front and back pitches must be unequal, otherwise the coil would be short-circuited upon itself.

(*c*) In a simplex lap winding, the front and back pitches differ by 2; that is $y_b = y_f \pm 2$.

(*d*) In a multiplex lap winding, the front and back pitches differ by $2x$, where x is the number of component simplex windings.

(*e*) Z may be any even number; and in slotted armatures, it must also be a multiple of the number of slots; the latter may be even or odd.

Wave windings must similarly comply with the following conditions:

(*a*) Front and back pitches must be alike in sign.

(*b*) Front and back pitches may be equal, or differ by any multiple of two. Usually they are both equal nearly to $Z \div p$, although one may be less, and the other greater.

(*c*) In simplex windings, $Z = p\,y_{av} \pm 2$.

(*d*) In multiplex windings, $Z = p\,y_{av} \pm 2x$.

Resumé of Winding Formulæ. In Table VI will be found formulæ covering most of the types of ring and drum windings which are now used. The symbols in the columns have the same significance as those used in the text.

Equipotential Connections. As the armature in practice is not always centered exactly with respect to the pole-pieces—and, further, since the conductors are not equidistant from the latter, because of winding inequalities—the generated e. m. f. of the various sections will not be exactly equal. Hence there will be cross-currents internal to the armature, which increase sparking at the commutator and heating of the armature. In wave windings, the conductors are connected in series and so distributed as to have no perceptible tendency to produce cross-currents; but in lap windings, inaccurate centering may lead to the production of large local currents. In order to reduce their production as much as possible, it is customary, in large generators or in others liable to be so affected, to connect through low-resistance leads, the bars, or conductors at the same voltage. These connections are called *equipotential connections;* and although they reduce the sparking tendency due to local currents in the armature, they add a little to the heating of the armature.

Examples of Armature Windings. On the following pages will be found examples of windings in common use. In Figs. 131 to 137 inclusive, the short, radial, numbered lines represent the conductors; the crossed lines outside of the circle of conductors represent the connections at the back end of the armature; and the crossed lines between the circle of conductors and the commutator at the center, represent the connections at the front end of the armature. For the sake of simplicity, only a few conductors are shown in these examples; and it should be noted that in actual designs, their number Z attains a much greater value.

Fig. 132 represents a six-pole drum simplex singly re-entrant lap winding, with 60 conductors, a front pitch of −11, and a back pitch of + 9. In this particular case the general progression of the winding is around the drum in an anti-clockwise direction, and on this account it is sometimes called a *retrogressive* winding to distinguish it from a clockwise one, which is called a *progressive* winding. The winding here shown has a commutator pitch of –1, and there are six paths in parallel through the armature, necessitating six brush sets unless the winding or commutator is cross-connected (see Fig. 125).

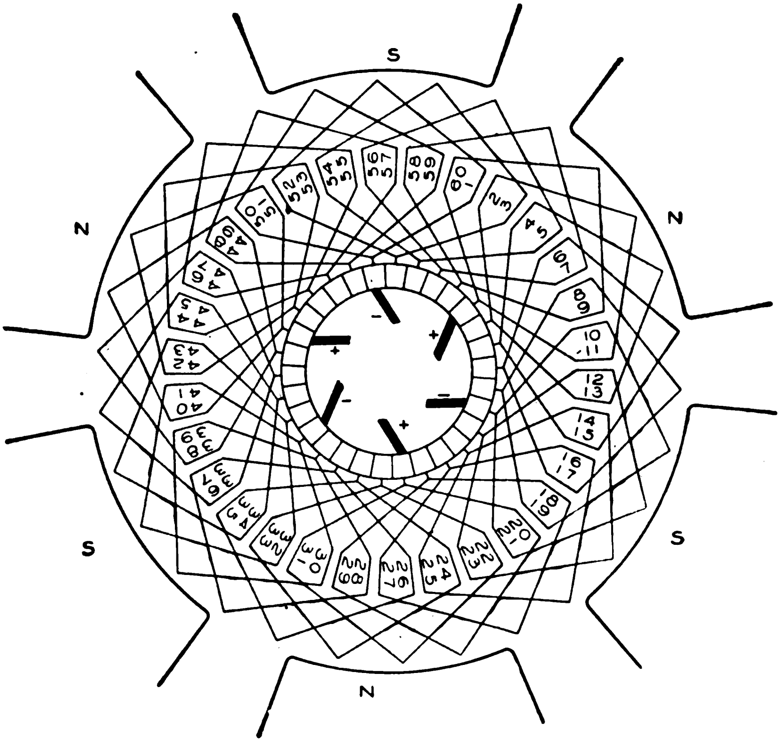


Fig. 132. Six-Pole Drum Simplex Lap Winding, Singly Re-entrant.

Fig. 131 illustrates a six-pole drum simplex singly re-entrant wave winding of 62 inductors. It has a front pitch of +11, and a back pitch of +9, giving an average pitch of 10, and a commutator pitch of 10 also. This winding has two paths in parallel through the armature, so that only two brush sets are required. The locations of the other brush sets, which may be added if large currents are to be collected, are also indicated by dotted lines.

Fig. 133 shows a six-pole drum duplex doubly re-entrant lap winding composed of 60 inductors with a front pitch of –11, a back

TABLE VI.

Formulæ for Ring and Drum Windings

RING WINDINGS

Types of Winding	No. Circuits in Parallel through Arm. = c	No. Circuits in Parallel per Winding = c_1	No. Separate Windings = x	Field Step = m	No. Conductors = Z	Resultant Pitch = y	Commutator Pitch = y_k	Conductors in Series between Brushes	No. Brush Sets	Angle between Brush Sets	Figs. Illustrating Winding
A*	ϕ	ϕ	1	0	$= g\,G = g\,K$	$\pm g$	$\pm g$	Z+p	p	360°+p	....
B	2	2	1	1	$= \frac{g\,p\,y \pm 2}{2}$ and $= g\,G = g\,K$	$\frac{2\,Z \mp 2}{p}$ and must be odd	$\frac{2\,K \mp 2}{p}$	Z+2	Min. 2 Max. p	360°+p or any odd multiple	....
C	4, 6, 8, or any other even number > 2	c	1	1	$\frac{p\,y \pm c}{2}$	$\frac{2\,Z \mp c}{2}$	$\frac{2\,K \mp c}{p}$	Z+c	p	360°+p	....
D	$x\,p$	p	2, 3, 4, or any other whole number	0	$= x\,g\,b = x\,g\,k$	$\pm g\,x$	$\pm g\,x$	Z+xp	p	360°+p	....
E	$2\,x$	2	do	1	$\frac{g\,n\,p\,y \pm 2\,n}{2}$	$\frac{2\,Z \mp 2\,x}{x\,p}$	$\frac{2\,K \mp 2\,x}{p}$	Z+2x	Max. p Min. 2	360°+p or any odd multiple	....
F	$x\,c_1$	4, 6, 8, or any other even number > 2	do	1	$\frac{g\,n\,p\,y \pm 2\,n\,c_1}{2}$	$\frac{2\,Z \mp 2\,x\,c_1}{x\,p}$	$\frac{2\,K \mp 2\,x\,c_1}{x\,p}$	Z+x c_1	p	360°+p	....

LAP-WOUND DRUM WINDINGS

Types of Winding	No. Circuits in Parallel through Arm. = c	No. Conductors in Series between Brushes	No. Separate Windings = x	No. Circuits in Parallel per Winding = c_1	Field Step = m	No. Armature Conductors = Z	Resultant Pitch = y	Forward Pitch = y_f	Backward Pitch = y_b	Commutator Pitch = y_k	No. Brush Sets	Angle between Brush Sets	Figs. Illustrating Winding
G*	p	$Z \div p$	1	p	0	$Z = 2\,g\,G = 2\,g\,Z$, i. e., any even number	± 2	Equal to or less than $\frac{Z}{p}$, and must be odd	$-(y_f \pm 2)$	1	p	360°+ p	132
H	$p\,x$	$Z \div p\,x$	2, 3, 4, or any other whole number	p	0		$\pm 2\,x$		$y_f - 2\,x$	$\pm x$	p	360°+ p	....
J	4, 6, 8, or any other even number > 2	$Z \div c$	1	4, 6, 8, or any other even number > 2	0		$\pm c$		$y_f - c$	$\pm \frac{1}{2}\,c$	ϕ	360°+ p	135
K	$x\,c_1$	$Z \div x\,c_1$	2, 3, 4, or any other whole number	do x p	0		$\pm x\,c_1$		$y_f - x\,c_1$	$\pm \frac{1}{2}\,x\,c_1$	p	360°+ p	133

WAVE-WOUND DRUM WINDINGS

Types of Winding	No. Circuits in Parallel through Arm. $= c$	No. Conductors in Series between Brushes	No. Separate Windings $= x$	No. Circuits in Parallel per Winding $= c_1$	Field Step $= m$	No. Conductors $= Z$	$y_t = y_b$	Commutator Pitch $= y_k$	No. Brush Sets	Angle between Brush Sets	Figs Illustrating Winding
L*	2	$Z \div 2$	1	2	1	$p\,y_{av} \pm 2$	$\frac{Z \mp 2}{p}$ must be odd and have no common factor with Z	$\frac{2K \mp 2}{p}$	Min. 2, Max. p	$360° \div p$, or any odd multiple	132
M	$x\,c_1$	$Z \div x\,c_1$	2, 3, 4, or any other whole number	2	1	$x\,p\,y_{av} \pm 2x$	$\frac{Z \mp 2x}{x\,p}$ where y_{av} is even y_t may $= y_{av} + 1$, y_b may $= y_{av} - 1$	$\frac{2K \mp 2x}{x\,p}$	Min. 2, Max. p		137
N	4, 6, or any other even number > 2	$Z \div c$	1	4, 6, 8, or any other even number > 2	1	$p\,y_{av} \pm c$	$\frac{Z \mp c}{p}$	$\frac{2K \mp c}{p}$	Min. 2, Max. p		136
P	$x\,c_1$	$Z \div x\,c_1$	2, 3, 4, or any other whole number	2, 4, 6, or any other even number	1	$x\,p\,y_{av} \pm x\,c_1$	$\frac{Z \mp x\,c_1}{x\,p}$	$\frac{2K \mp x\,c_1}{x\,p}$	Min. 2, Max. p		134

* Key to Special Types of Ring, Lap, and Wave Windings is given below:

KEY TO TABLE VI

Following is a key to the special types of Ring, Lap, and Wave Windings for which formulæ are given in Table VI:

RING WINDINGS

A—Parallel Grouping (Simplex).

B—Series Grouping (Singly Re-entrant).

C—Series-Parallel Grouping (Simplex Doubly or Multiply Re-entrant).

D—Duplex or Multiplex Parallel Grouping.

E—Duplex or Multiplex Series Grouping.

F—Duplex or Multiplex Series-Parallel Grouping.

LAP-WOUND DRUM WINDINGS

G—Simplex Singly Re-entrant (Parallel) Lap Winding.

H—Duplex or Multiplex (Parallel) Lap Winding.

J—Simplex (Series-Parallel) Doubly or Multiply Re-entrant Lap Winding.

K—Duplex or Multiplex (Series-Parallel) Doubly or Multiply Re-entrant Lap Winding.

WAVE-WOUND DRUM WINDINGS

L—Simplex Singly Re-entrant (Series) Wave Winding.

M—Duplex or Multiplex (Series) Wave Winding.

N—Simplex Doubly or Multiply Re-entrant (Series-Parallel) Wave Winding.

P—Duplex or Multiplex Doubly or Multiply Re-entrant (Series-Parallel) Wave Winding.

pitch of +7, a commutator pitch of −2, and 12 paths in parallel through the armature. This winding is also retrogressive, and composed of two complete but distinct simplex singly re-entrant lap windings, each having 30 inductors. One set is represented by the full lines, the other by the broken lines, their respective commutator segments being unshaded and shaded. It should be noted that with

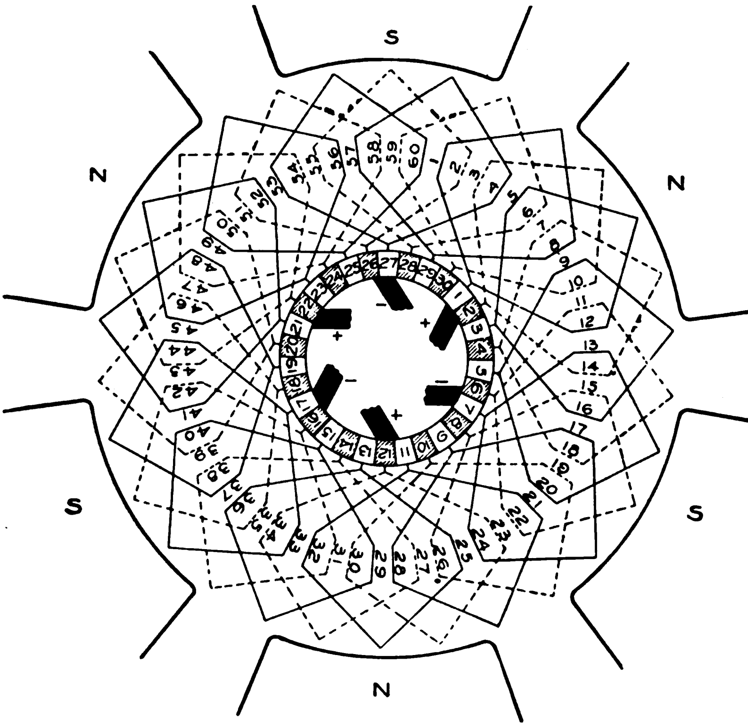


Fig. 133. Six-Pole Drum Duplex Lap Winding, Doubly Re-entrant.

a duplex or any other multiplex winding, the brushes must be wide enough to cover at least as many segments as there are windings. Here the brushes cover two segments.

Fig. 134 represents a six-pole drum duplex doubly re-entrant wave winding, consisting of 64 inductors, having a front pitch of +9, a back pitch of +11, and a commutator pitch of 10. The average pitch is 10, and there are four paths in parallel through the armature. Nevertheless only two brushes are required to collect the current, although others may be added as indicated, if desired. It consists of two complete simplex singly re-entrant wave windings; hence its appellation, *duplex doubly re-entrant.*

Fig. 135 represents a four-pole drum simplex doubly re-entrant lap winding having 34 inductors. In this case the front pitch is +9, the back pitch is −5, and the commutator pitch is +2, while there are 8 paths in parallel through the armature. Four brushes only are required, and inspection shows this to be a progressive winding.

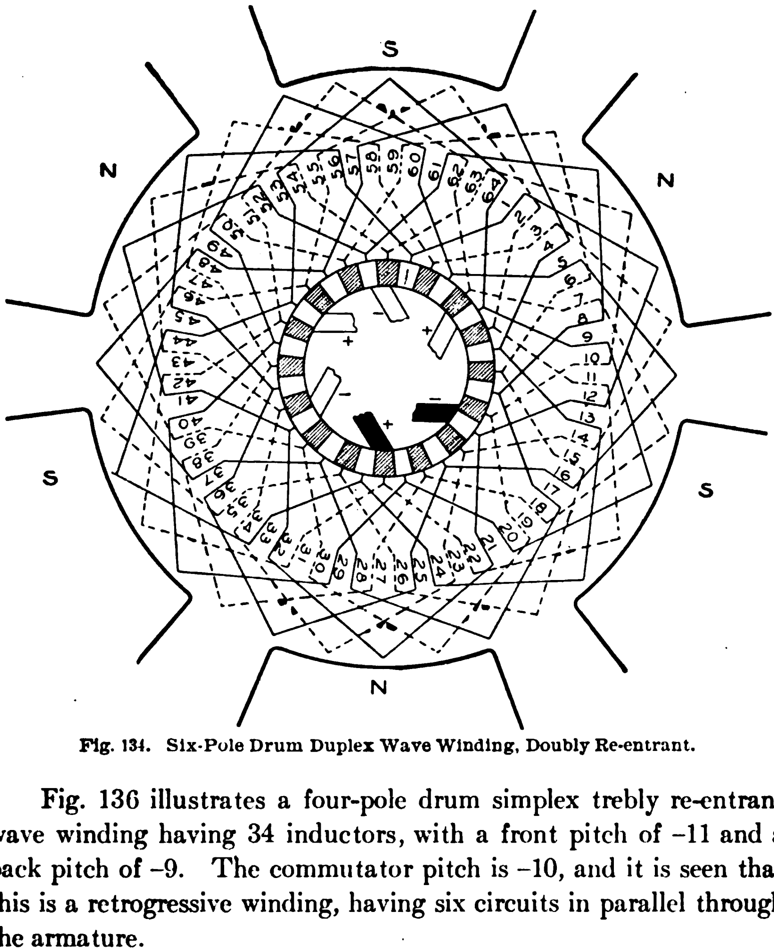


Fig. 134. Six-Pole Drum Duplex Wave Winding, Doubly Re-entrant.

Fig. 136 illustrates a four-pole drum simplex trebly re-entrant wave winding having 34 inductors, with a front pitch of −11 and a back pitch of −9. The commutator pitch is −10, and it is seen that this is a retrogressive winding, having six circuits in parallel through the armature.

In Fig. 137 we have a six-pole drum duplex singly re-entrant wave winding, with a back pitch of 11, a front pitch of 9, an average pitch and a commutator pitch of 10. It has two paths in parallel through the armature; and although only two brushes are required, six sets may be used if desired, as indicated. It is a progressive winding.

Length of Armature Winding. The length of wire in an armature winding depends upon the particular type of winding employed. Determination of this length is necessary in the design of

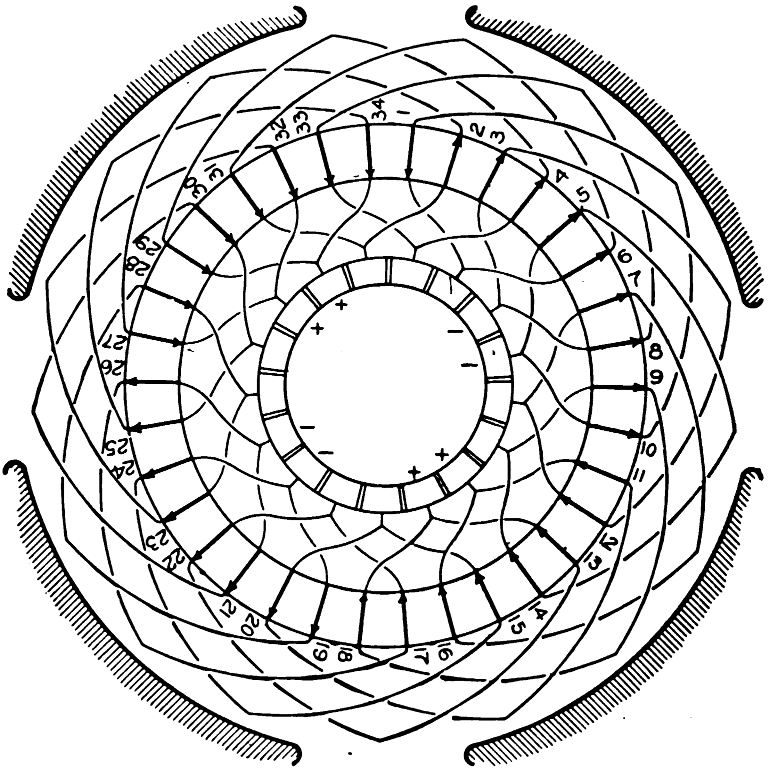


Fig. 135. Drum Simplex Doubly Re-entrant Lap Winding.

dynamo-electric machinery in order to compute the armature resistance and the resulting regulation of the machine. G. Simonds,* J. Dalemont,** H. M. Hobart,† and A. I. M. Winetraub†† have given methods for computing the lengths of winding necessitated by the different types; but the method usually employed by manufac-

*Electrical World, March 3, 1900.
** Bulletin of the Institute Montefiore, ii, 428, 1902.
† Traction and Transmission, V, 239, 1902.
††Electrical World, August 25, 1906.

turers consists simply in drawing the armature to scale, and laying off thereon a section of the winding, the requisite length of wire being then determined by actual measurement. In particularly important cases—for example, when a new type of machine is to be built in large numbers or sizes—a portion of a dummy armature core is made of wood and wound with the correct size of wire. The length thus em-

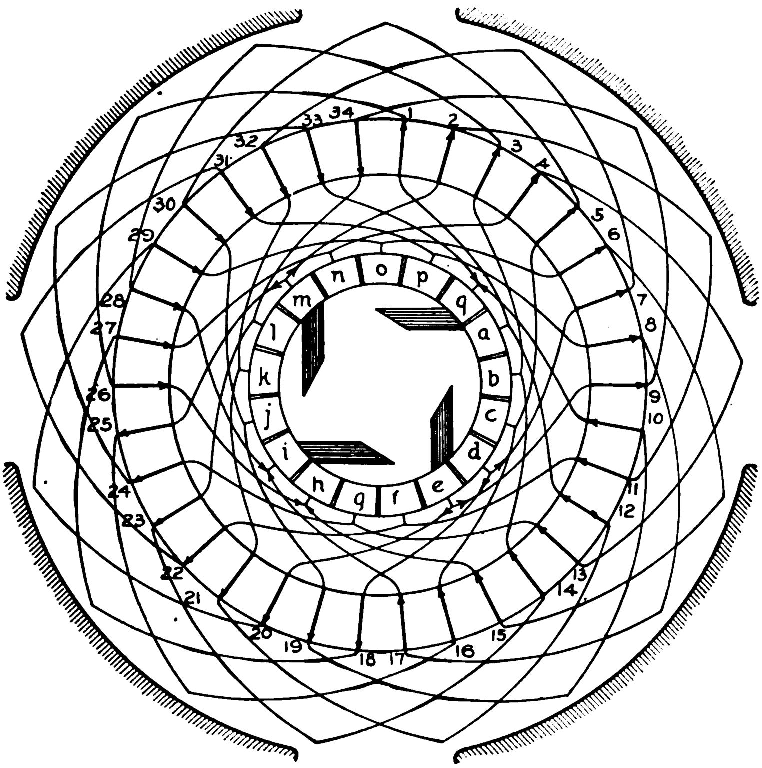


Fig. 136. Six-Circuit Drum Simplex Trebly Re-entrant Wave Winding.

ployed for one section is then multiplied by the number of sections to obtain the total length of wire required.

Armature Resistance. Having obtained the length of wire required for the winding, the resistance of the armature may be calculated from the formula,

$$r_a = \frac{\rho\, l}{c^2\, s},$$

wherein ρ is the resistance of a unit-length of copper of unit cross-section; l is the total length of the armature winding in the same linear units as ρ; c represents the number of circuits in parallel through the armature; and s is the cross-sectional area of the conductor in the same units as that upon which the value of ρ is based.

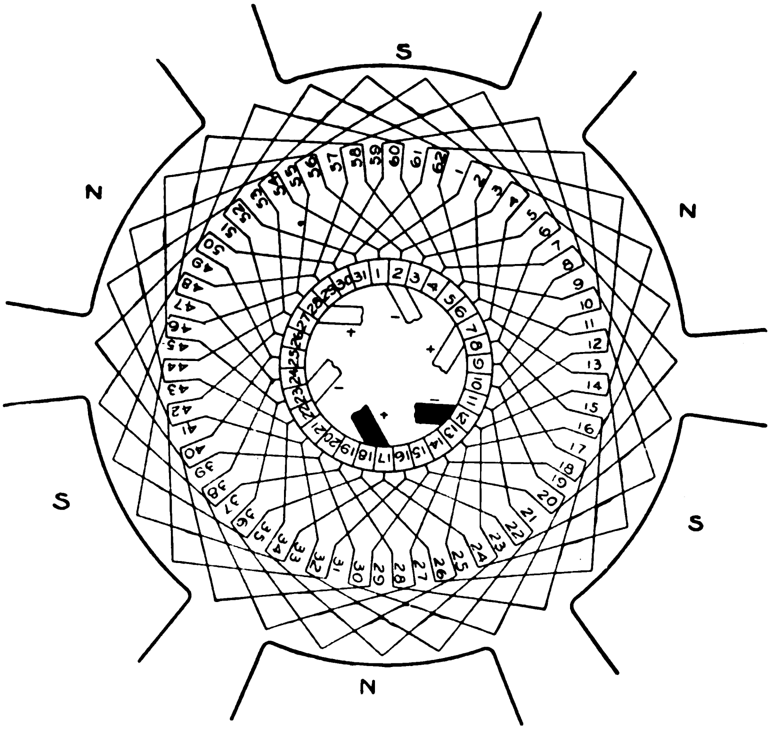


Fig. 137. Six-Pole Drum Duplex Wave Winding, Singly Re-entrant.

A circular conductor one foot long and one mil (0.001 inch) in diameter is called a *circular mil foot;* and if composed of standard copper, it has at 20° Centigrade a resistance of 10.35 ohms, and at 0° Centigrade a resistance of 9.55 ohms. At any other temperature t, the resistance R_t is:

$$R_t = 9.55 (1 + 0.0042t).$$

If we take as our basis of calculation a square conductor, the cross-section being a square each of whose sides is one mil long, we have a *square mil foot,* which has an area $4 \div \pi$ times that of a circular mil foot. Hence its resistance is $\pi \div 4$, or 0.7854 of that of a circular mil foot. Hence the resistance of a square mil foot of copper wire at 20° C. is 10.35 × 0.7854 = 8.15 ohms, and at 0° C. it is 9.55 × 0.7854 = 7.5 ohms.

The resistance of any copper conductor, the cross-section of which is given in circular mils, is at 20° C. equal to $\frac{10.35 \times l}{d^2}$, where l is the length of the conductor in feet, and d^2 is the cross-section in circular mils (that is, the square of the diameter in mils).

Example. 1,200 feet of copper wire 0.1 inch (100 mils) in diameter is required for a certain six-circuit armature winding. Substituting in the equation $r_a = \frac{\rho\, l}{c^2\, s}$, we have for the resistance of the armature:

$$r_a = \frac{10.35 \times 1{,}200}{36 \times 10{,}000} = 0.0345 \text{ ohm at } 20°\text{C.}$$

Armature Losses. The losses in the armature may be divided into those due to the resistance of its winding, and those due to the hysteresis and eddy currents in its iron core.*

Under the preceding heading, a method of finding the resistance of the armature winding was given; hence the copper loss in the armature due to the resistance of its winding is:

$$w_{cu} = I_a^2\, r_a.$$

For calculating the hysteresis loss w_h in the armature, we may use the formula and curves given on page 14, or may refer to a curve obtained by test upon the iron to be used. Similarly, the eddy-current loss w_e may be computed from the formula given on page 15, or from the graphs of Fig. 17. The total iron loss in the armature is therefore:

$$w_i = w_e + w_h.$$

It is found, however, by tests upon actual machines, that the iron losses thus computed are considerably lower than the true values. This is no doubt due to unequal distribution of flux in the various parts of the magnetic circuit subject to a varying flux-density; also to the departure from the ideal conditions in the matter of dispersion, and to the presence of wasteful currents in other parts of the machine. Prof. J. Epstein† gives curves, Fig. 138, showing that the calculated losses of a machine based on any of the heretofore standard

* Windage due to the rotation of the armature will be dealt with under a later heading.

† Proceedings of the Institution of Electrical Engineers of Great Britain, Nov. 11, 1906.

data would be low; hence the actual commercial efficiency is lower than the computed.

In addition to the calculated iron and copper losses, there may be a loss in the armature conductors due to eddy currents, and another loss if for any reason the current does not distribute itself evenly through the conductor. Also, if the division of current between the parallel circuits of the armature winding is not uniform,

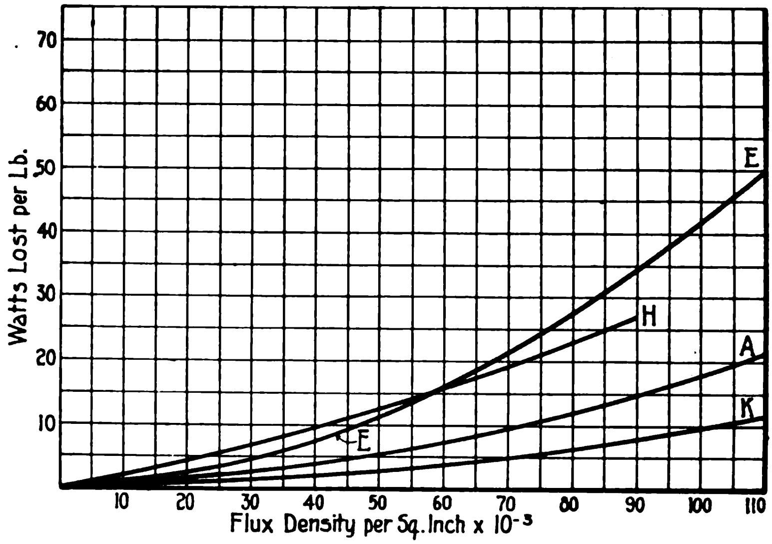


Fig. 138. Standard Iron-Loss Curves at 30 Cycles per Second.
E—Prof. Epstein; *H*—Hobart, "Electric Motors;" *A*—Prof. Arnold, *Die Gleichstrommaschine*; *K*—G. Kapp, *Gleichstrom und Wechselstrom.*

and equalizing connections are not provided, an additional loss results. These are so obscure as to baffle computation; and as their value is small, they may be neglected.

Heating of Armatures. The amount of heat which will be dissipated by a unit-surface of a moving armature depends upon:

(1) Resistance, eddy-current, and hysteresis losses in the armature.

(2) Heat-radiating surface of the armature.

(3) Peripheral speed of the armature.

(4) Proportion, within limits, of the ratio of the radiating surface to polar surface.

(5) Temperature of the radiating surface.

The first of these is dependent upon the internal actions of the armature, and represents the total heat which must be dissipated.

The surface exposed to the cooling action of the air is somewhat indefinite, but in most cases the total peripheral surface of the armature is assumed as radiating surface, and to this may be added one-half the surface of the ends of the armature.

As the peripheral speed of the armature becomes greater, it is found that the radiating capability of its surface increases, though not in direct proportion.

Messrs. A. H. and C. E. Timmerman* found by actual test that the effect of pole-faces above a surface is to interfere with the radiation of heat. As the proportion of surface covered by the pole-faces became larger, the amount of heat radiated per degree rise in temperature became less. They also found that elevation in temperature of a surface caused an increase in the radiation of heat per degree rise in temperature, but that this rate diminished as the temperature rose.

Various formulæ may be given for estimating the ultimate rise in temperature of armatures; but as most of them are empirical and clumsy, the curves of Fig. 139 have been substituted. With their aid, we may determine the temperature-rise in degrees Centigrade of an armature at any usual peripheral speed, if we know the total radiating surface and the total armature losses.

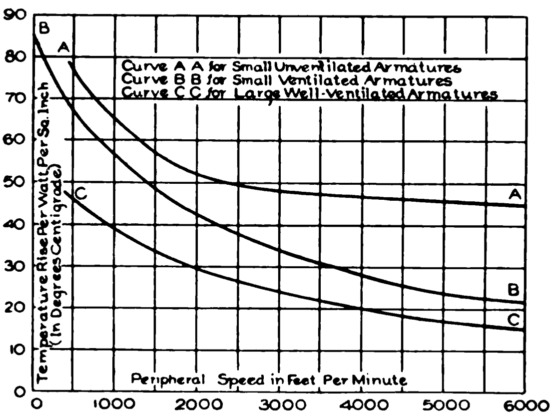


Fig. 139. Curves for Estimat ng Temperature-Rise.

Example. In a 480-kilowatt generator, the heat-radiating surface of the armature was computed to be about 5,000 square inches, while total losses in the armature were found to be 12,330 watts by calculation. Hence the watts wasted per square inch of heat-radiating surface are 12,330 ÷ 5,000 = 2.46.

As the peripheral speed of the armature in this instance was 4,500 feet per minute, we see by reference to the curves of Fig. 139, that there will be a rise of 19° C. for each watt per square inch. Hence the temperature-rise of this armature will be approximately:

$$\theta_a = 2.46 \times 19 = 47° \text{ C.}$$

* Transactions of the American Institute of Electrical Engineers, Vol. X, 1893.

Commutator and Brush Calculations. Commutators for continuous-current machines may be divided into two classes, depending upon whether they are for *open* or *closed-coil* armature windings. In the former special case, used for arc-lighting generators, the commutator has a small number of segments separated from each other by an air-gap, and each covering a considerable angle. With closed-coil windings, ordinarily used for direct-current lighting and power, in which case the terminal voltage is kept comparatively constant (in contradistinction to series arc-lighting machines, for which the current is constant), the commutator is of the original Pacinotti type —that is, consisting of a considerable number of parallel bars or segments separated by strips of insulation, usually mica. In both cases the completed commutator presents a cylindrical surface against which the brushes press.

Number of Segments. The number of segments depends upon the number of sections of the winding, as shown on page 95. We have also seen (page 49) that increasing the number of commutator segments reduces the tendency to spark at the brushes. This increase is limited, however, by the matter of cost, and the fact that the number of sections in a drum-wound armature can never exceed one-half the number of inductors, while, in a ring-wound armature, the number of sections can never be greater than the number of inductors.

The proper number of segments is therefore determined by the winding of the armature, which depends upon the voltage and output of the machine. If by experience the suitable number of average volts per segment e_k of the commutator be known, then K, the number of segments, may be readily computed from the following formula:

$$K = E c \div e_k.$$

Experience shows that the values of e_k indicated in Table VII, may be chosen, although the matter is influenced by the current to be collected. If the latter be less than 100 amperes, then the value of e_k may be increased, but in no case should it exceed 25 volts.

Arnold has given the rule that the number of commutator segments must *never be less than* from 0.037 to 0.04 times the product of the number of armature inductors into the square root of the current carried by one circuit of the armature. This rule is an empirical one based on observations with regard to sparking; nevertheless it has been found that good machines were built in which the constant was slightly less than 0.037.

Example. A 1,000-kilowatt generator having 16 paths in parallel through its armature produced 500 volts at its terminals. The number of armature conductors was 2,304. Hence, according to Arnold's rule, K must not be less than $0.037 \times 2{,}304 \sqrt{2{,}000 \div 12} = 956$. As a matter of fact, 1,152 segments were taken for this machine, making the number of segments equal to one-half the number of conductors.

TABLE VII

Voltage and Number of Segments

For Machines Working at	Average Volts per Segment $= e_k$	Average Segments per Pole or Circuit
500 to 650 volts	5 to 12	40 to 150 or more
200 to 250 volts	3 to 8	25 to 75
100 to 130 volts	2 to 4	20 to 50

Size of the Commutator. The size of the commutator depends upon the number of segments, their thickness and that of the insulation between them, and the length of the segments parallel to the shaft. The diameter is limited by the peripheral speed allowable. The length depends upon the amount of current to be collected, a density of 50 amperes per square inch being as much as should be allowed for the contact area between a carbon brush and the bar. Bars are rarely ever thinner than 0.2 in., or with insulation say 0.3 in., and the peripheral speed of a commutator seldom exceeds 2,500 feet per minute; so that by keeping within these limits good results may be expected. A favorite size for commutator diam-

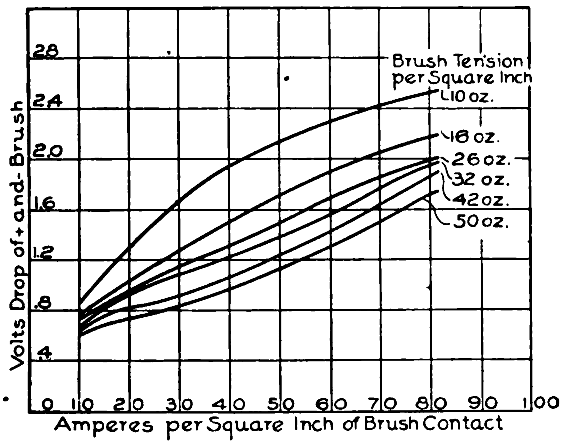


Fig. 140. Curves Showing Average Brush Drop with Various Brush Tensions and Current-Densities.

eters is ¾ that of the armature diameter, which serves as another guide.

Commutator Losses. The losses which the commutator surface must take care of may be divided into those arising from the resistance, or more properly the voltage drop, of the brush contact, and from the friction of the brushes against the rotating commutator. The former depends mainly upon the following factors:

(1) Material of the brushes.

(2) Pressure of the brushes upon the commutator.

(3) Peripheral speed of the commutator.

(4) Current-density in the brush.

(5) Condition of the commutator and brushes.

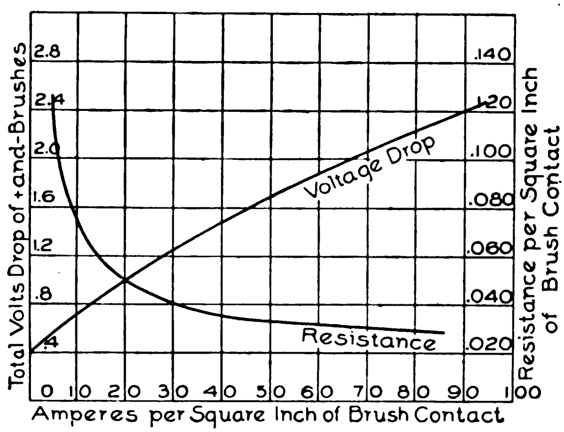


Fig. 141. Curves Showing Average Brush Drop and Contact Resistance at Various Current-Densities for Several Standard Grades of Carbon and Graphite Brushes.

The loss due to friction of the brushes upon the commutator varies with:

(1) Pressure of the brushes.

(2) Peripheral speed of the commutator.

(3) Coefficient of friction between commutator and brushes.

Fig. 141 shows the effect of various current-densities with various grades of brushes; and this may be taken as illustrating the influence of the material of the brush upon its contact resistance. Fig. 140 shows how the pressure of the brushes affects the voltage-drop; while Fig. 142 indicates the effect of peripheral speed of the commutator upon this drop, if we divide the watts loss by the amperes per square inch of brush contact; and Fig. 141 illustrates the relation between the current density in the brush and the voltage-drop across both positive and negative brushes. The influence of the condition of the commutator and brushes upon contact resistance cannot be stated exactly; but it is a fact that if either be in bad condition, the losses at the commutator may be increased many fold.

Multiplying the volts drop obtained from Fig. 141, by the current per brush set, we obtain the energy loss due to brush-contact resistance. For example, if we design the brushes so that the current-density in them is 35 amperes per square inch at rated load, we have a drop over the contact surfaces of both positive and negative brushes of 1.35 volts; and multiplying the total current output by 1.35 gives the watts lost.

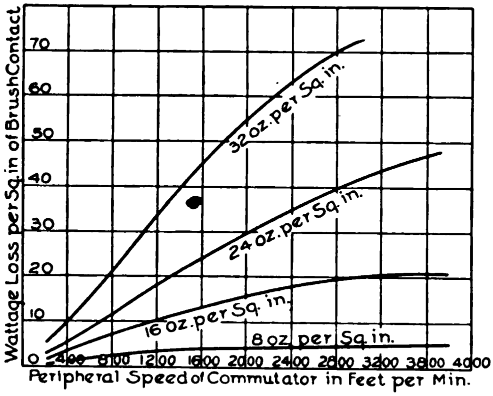


Fig. 142. Curves Showing Average Friction Loss per Square Inch of Brush Contact at Various Speeds and Brush Tensions.

Example. In a 100-kilowatt machine of one of the large manufacturing companies, the current collected by the brushes amounted to 415 amperes. If the current-density in the brushes had been 35 amperes per square inch, the loss due to contact resistance would have been:

$$1.35 \times 415 = 560 \text{ watts.}$$

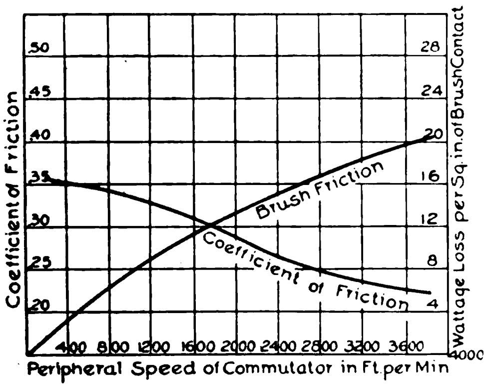


Fig. 143. Curves Showing Average Coefficient of Friction and Brush-Friction Loss for Different Grades of Brushes at Various Commutator Speeds, with Brush Tension of 1 lb. per Square Inch.

The variation of friction losses (which the surface of the commutator must radiate as heat) with peripheral speed of the commutator at various pressures, is shown graphically in Fig. 142; while the dependence of the coefficient of friction upon the commutator peripheral speed is indicated by Fig. 143 for carbon brushes in good condition.

To compute the watts lost through brush friction, multiply the total area of brush contact by the stress—*i.e.*, the pressure per unit area—to get the total pressure in pounds. Then multiply this value by the coefficient of friction and peripheral speed in feet per minute of the commutator, which gives the losses in foot-pounds per minute. Dividing by 33,000 to convert this value into horse-power, and multiplying by 746, we convert the result thus obtained into watts.

Example. Taking the same machine as just above mentioned, let us assume the brush pressure as 1.5 pounds per square inch, the total brush area as 23.7 sq. in., the peripheral speed of the commutator as 2,500 feet per minute, and the coefficient of friction as 0.27. We have the friction loss:

$$23.7 \times 1.5 \times 0.27 \times 2{,}500 \times 746 \div 33{,}000 = 543 \text{ watts (nearly).}$$

Commutator Heating. The final temperature which the commutator surface will attain depends upon the total losses to be radiated by it and the radiating surface, together with the peripheral speed. According to tests made by Prof. E. Arnold, the final rise in temperature of the commutator in degrees Centigrade will be:

$$\theta = \frac{46.5 \times w_c}{A_c\,(1 + 0.005\,v)},$$

in which w_c represents the total commutator losses, electrical and mechanical, in watts; A_c represents the radiating surface of the commutator in square inches; and v represents the peripheral speed of the commutator in feet per minute.

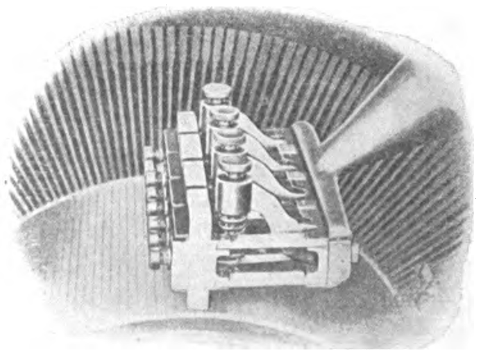
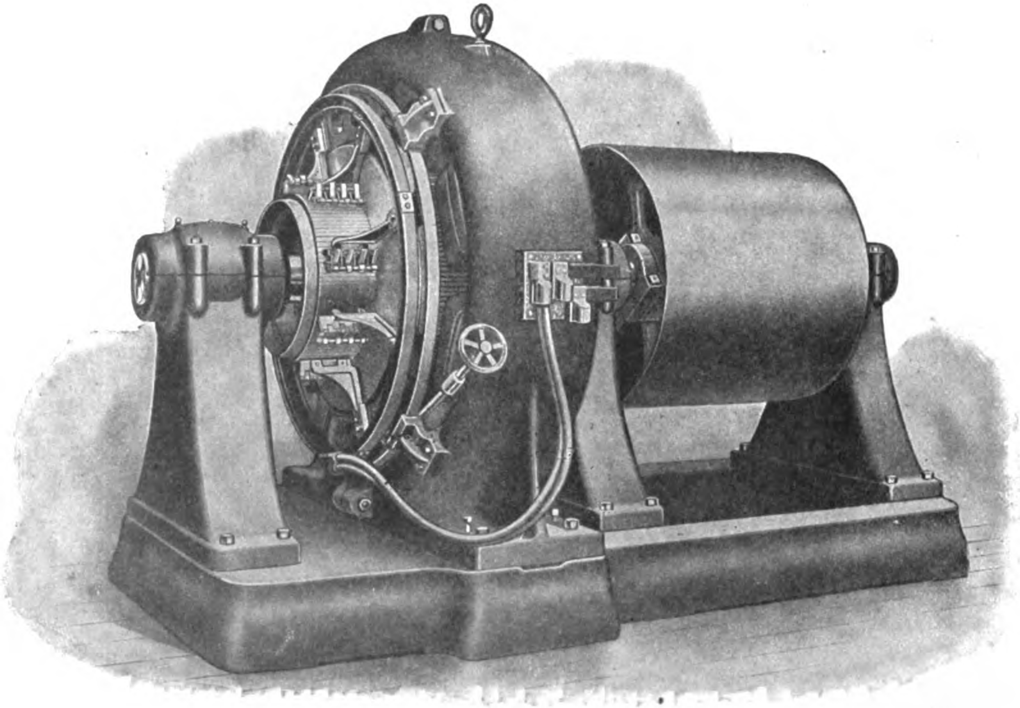


Fig. 144. Parallel-Movement Brush-Holder. Crocker-Wheeler Company.

According to Messrs. Parshall and Hobart, the rise in temperature of the commutator will seldom exceed 20° C. with one watt per square inch of peripheral radiating surface at a peripheral speed of 2,500 ft. per minute, a figure which may be much improved upon with ventilated armatures.

Number and Size of Brushes. The total number of brush sets is usually fixed by the type of armature winding, as previously stated; but this criterion gives us no clew to the number of brushes per set. In all but the smallest machines, it is usual to place at least two brushes exactly similar, side by side (Fig. 144 shows four), instead of one broad brush, thus allowing one brush to be removed for trimming or



360 K.W. 350 R.P.M. THREE-BEARING BELTED GENERATOR.

Triumph Electric Company.

renewal while the machine is running. The contact between the brushes and the commutator is made much better by this subdivision, for a slight inequality at one point of the latter may slightly raise one brush of a set at each revolution, without much harm, while, with one broad brush, the entire brush would be lifted, causing bad sparking. Subdivision of the brush also tends to equalize the wear upon the commutator, each brush being separately held against the commutator, and the gap between two adjacent brushes of the same set being bridged by the brushes of the other set or sets. The number of individual brushes in each group depends upon the current capacity and size of machine and the judgment of the designer, and varies from two to eight or more.

The proper thickness for carbon brushes cannot be stated definitely, but they are usually made to span 2½ bars in armatures having simplex windings. For armatures with duplex and triplex windings, thicker brushes must necessarily be used. The usual thickness of metal brushes spans about 1½ commutator bars.

Table VIII gives standard sizes of carbon brushes employed by most manufacturing companies; and in designing a generator or motor it is best to select one of these sizes that most closely approximates the requirements.

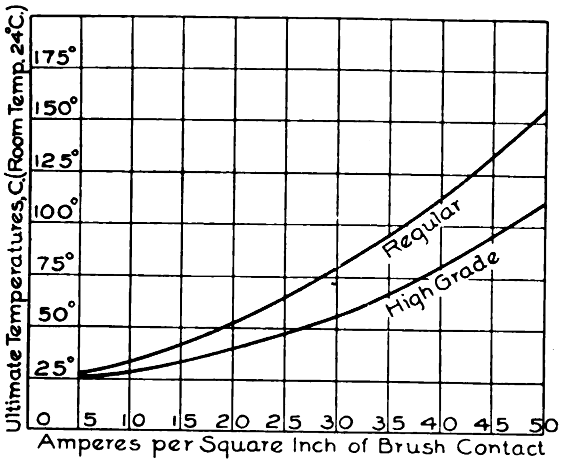


Fig. 145. Average Temperature Curves of Standard Grades of Carbon or Graphite Brushes.

Heating of Carbon Brushes. Fig. 145 gives the variation of the temperature-rise of two well-known grades of carbon brushes with increase in the current-density employed. The room temperature at the time of the test was about 24° C., so that the values on the curves represent final or total temperatures. It is therefore necessary to deduct 24 from the values given by these curves, to realize the actual temperature-rise.

TABLE VIII

Standard Sizes of Carbon Brushes

Length Width Thickness	Length Width Thickness	Length Width Thickness	Length Width Thickness	Length Width Thickness	Length Width Thickness	Length Width Thickness
2½x2¼x ¼	3 x 1 x ¼	3½ x 1 x ¼	4 x 1 x ¼	5 x 1 x ¼	6x1½x ½	7x1½x ½
2½x2¼x ½	3 x 1 x ½	3½ x 1 x ½	4 x 1 x ½	5x1½x ¼	6x1½x ¾	7x2 x ½
2½x2¼x ¾	3 x 1 x ¾	3½ x 1 x ¾	4 x 1 x ¾	5x1½x ½	6x1½x1	7x2¼x ½
2½x2¼x1	3 x 1 x 1	3½ x 1 x 1	4 x 1 x 1	5x1½x ¾	6x1½x1¼	7x2½x ½
2½x2 x ½	3x1½x ¼	3½ x 2 x ¼	4x1½x ¼	5x1½x1	6x1½x1½	7x2½x ⅜
2½x2½x ¼	3x1½x ½	3½ x 2 x ½	4x1½x ½	5x1½x1½	6 x 2 x ½	7x2½x ⅝
2½x2½x ½	3x1½x ¾	3½ x 2 x ¾	4x1½x ¾	5 x 2 x 1	6x2½x ¾	7x2¼x ⅜
2½x2½x ¾	3x1½x1	3½ x 2 x 1	4x1½x1	5 x2 x 1¼	....	7x2¼x ⅝
2½x2½x1	3 x 2 x ¼	3½ x 3 x ¼	4 x 2 x ¼	5x2½x ¼	....	7x2¼x ¾
....	3 x 2 x ½	3½ x 3 x ½	4 x 2 x ½	5x2½x ½	....	7x2¼x ⅞
....	3 x 2 x ¾	3½ x 3 x ¾	4 x 2 x1⅛	5x2½x1	....	7x2¼x1
....	3 x 2 x 1	3½ x 3 x 1	....	....	....	7x2¼x1½
....	3 x 3 x ¼	3½x3½x ¼	....	....	....	....
....	3 x 3 x ½	3½x3½x ½	....	....	....	....
....	3 x 3 x ¾	3¼x3½x ¾	....	....	....	....
....	3 x 3 x 1	3½x3½x 1	....	....	....	....
....	....	3½x3½x1½	....	....	....	....

CALCULATIONS OF MECHANICAL PARTS

General. The almost invariable practice is to have the magnet-yoke of a generator or motor serve as a frame for all the remaining parts, except in larger sizes, for which independent bearings are used. The strength of the material used in the field-ring is great, and as its bulk is large in comparison with the load sustained, it is rarely that mechanical calculations are made. In the case of the armature shaft, the arms or spokes for the spider, and the bearings, however, calculations are necessary, which will now be briefly considered.

Armature Shafts. The shafts of armatures are usually made of mild steel; and for their design, reference may be made either to standard works on machine design or to the formulæ below, based on the usual methods employed in that class of work, and modified to meet the requirements of electrical machinery. Shafts for the latter are generally made somewhat larger than for other machines, on account of the magnetic pull which comes upon the shaft when the armature is even slightly out of center of the poles, as already noted.

The diameter of that portion of the shaft within the armature core, Fig. 146, may be found from the following expression,

$$d_c = k_1 \sqrt[4]{\frac{W}{\text{r. p. m.}}},$$

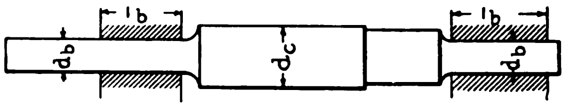


Fig. 146. Dimensions of Armature Shaft.

in which

d_c = Shaft diameter within the core, in inches;

k_1 = A constant depending upon the output of the machine as given in Table IX;

W = Output of the machine in watts.

The shaft diameter in the bearing or journal, may be computed from the following formula,

$$d_b = k_2 \sqrt{W} \sqrt[4]{\frac{1}{\text{r. p. m.}}}$$

in which

d_b = Diameter of the shaft in the bea ing;

k_2 = A constant depending upon the speed of the machine (see Table X).

TABLE IX

Value of Constant in Formula for Diameter of Core Portion of Shaft

Capacity of Machine (in Kilowatts)	Value of k_1
Up to 1 kilowatt	1
1– 5 "	1.1
5– 10 "	1.2
10– 50 "	1.3
50– 100 "	1.4
100– 200 "	1.5
200– 500 "	1.6
500–1,000 "	1.7
1,000–2,000 "	1.8

TABLE X

Value of Constant in Formula for Diameter of Shaft in Bearing

Type of Armature	Value of k_2
High-speed drum armature	0.0025
High-speed ring armature	0.003
Low-speed drum armature	0.004
Low-speed ring armature	0.005

Armature Spider Spokes. Drum armatures in which the core consists of a ring of iron supported by means of a skeleton pulley or spider attached to the shaft, the winding being placed in slots in the circumference of the core, are called *ring-core* armatures, to distinguish them from *ring-wound* armatures such as shown in Fig. 30. Fig. 147 represents a ring-core, drum-wound armature in process of construction. In both cases the driving of the armature is effected by a number of spokes which respectively form part of the spider itself (Fig. 148) or of a separate frame keyed to the skeleton pulley (Fig. 149). The spokes are usually elliptical in cross-section, and are generally made of cast iron or steel. They should be designed adequately to support and drive the armature.

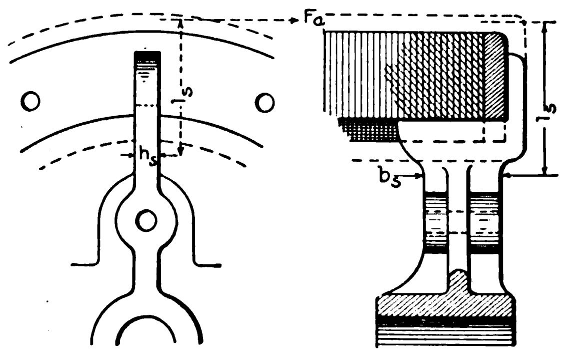


Fig. 147. Ring-Core Drum-Wound Armature in Process of Construction.

From a consideration of the bending and shearing moments acting upon such an arm or spoke (Fig. 149), it may be shown* that:

$$\frac{\pi\, b_s\, d_s^2}{32}\text{†} \leq \frac{100\, w\, l}{r\, n_s\ \text{r. p. m.}} \cdot \frac{1}{f_t}\ ;$$

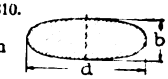
and,

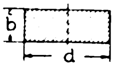
$$b\, d \leq \frac{100\, w\, l}{r\, n_s\ \text{r. p. m.}} \cdot \frac{1}{f_s}\ ,$$

in order that the safe working stresses of the material utilized may not be exceeded. In these formulæ,

b = Breadth of an arm parallel to the shaft, in inches;

*See "The Dynamo," by Hawkins & Wallis, New York, 1903; p. 310.

† $\frac{\pi b_s d_s^2}{32}$ is known as the *modulus of resistance* of the section 

For the section  it is $\frac{b_s d_s^2}{6}$; for the section  it is $\frac{\pi d^3}{32}$; and if any one of these sections be used, the corresponding section modulus should be substituted in the formula.

f_s = Safe working stress of the material for shearing, in lbs. per sq. in., which, for cast iron, is 5,000, and for cast steel 15,000;

f_t = Safe working stress of the material for tension or compression, in lbs. per sq. in., which is 1,250 for cast iron, and 5,000 for cast steel;

d = Thickness of the arm, in inches;

l = Distance from the tip of section whose breadth is b_s and whose thickness is d_s.

n_s = Number of spokes or arms;

r = Radius of an arm, in inches.

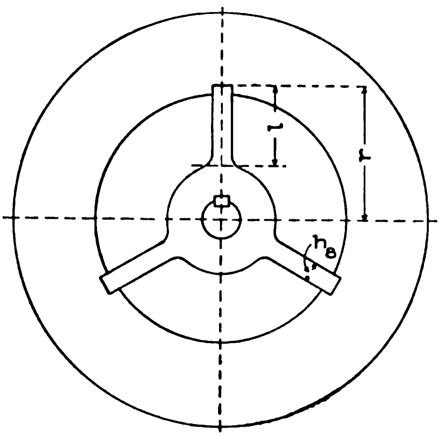


Fig. 148. Armature Driven by Spokes Forming Part of Spider.

Armature Binding Wires. In the case of toothed armatures, the conductors must be held in the slots. For this purpose it is customary to use wedges driven in under the tops of the teeth, or, in the case of straight teeth, to use a number of external bands known as *binding wires*. These must be strong enough to resist the centrifugal forces, and yet at the same time occupy very little radial depth, that they may not interfere with the clearance between the armature and the pole-faces. The almost invariable practice is to use a tinned wire of hard-drawn brass, phosphor-bronze, or steel, which, after winding, can be sweated together into a solid band. The ultimate tensile strength of phosphor-bronze is from 65,000 to 120,000 pounds per square inch, while that of steel wire varies from 120,000 to 250,000 pounds per square inch, the larger figures relating to the smaller sizes of wire.

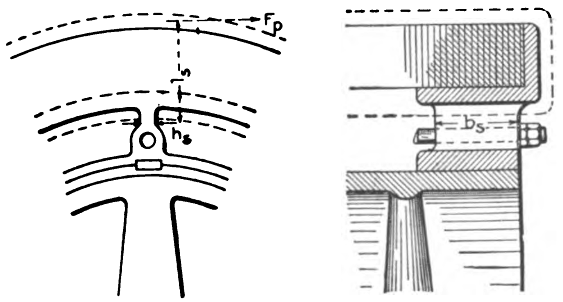


Fig. 149. Ring-Core Armature Driven by Pulley and End-Rings.

To estimate the proper size and number of binding wires required, we have that if d be the diameter (in inches) of the circular path described by a mass of weight w_1 pounds, the centrifugal force will be $= 0.0000143 \times d \times w_1 \times \overline{\text{r. p. m.}}^2$ pounds weight. So that if we assume a value of 100,000 pounds per square inch as the maximum allowable tensile stress in steel or phosphor-bronze wire, and allow a safety factor of say 10, the total section of binding wire required will be:

$$= \frac{0.0000143 \times 10 \times w_1 \times Z \times d \times \overline{\text{r. p. m.}}^2}{\pi \times 100{,}000}$$

$$= 4.55 \times 10^{-10} \times w_1 \times Z \times d \times \overline{\text{r. p. m.}}^2 \text{ square inches.}$$

From this total necessary section, and an appropriate wire table, the number of wires is then calculated, and they are then arranged in suitable belts.

Example. Let $w_1 = 0.39$ lb.; $Z = 1{,}536$; $d = 62$ in.; r. p. m. $= 150$. The total necessary section computed by the above formula is 0.379 square inch. Referring to the wire gauge tables, we find that 148 wires of No. 15 B. & S. gauge will fulfil the conditions. These may be arranged as follows: 5 belts of 16 wires each over the core body, and 4 belts of 17 wires each over the extended ends of the winding (*i.e.*, 2 belts of 17 wires each over each end).

Under each belt of binding wires, it is usual to lay a band of insulation. These bands generally consist of two layers, first a thin strip of vulcanized fibre or of hard red varnished paper slightly wider than the belt of wires, and then a strip of mica (in short pieces) of about equal width. Sometimes small straps of thin brass are laid under each belt of binding wires, having tags which can be turned over and soldered down to prevent the two ends of the binding wire from flying out.

Armature Bearings. Bearings for generators and motors should be very strong and rigid, with ample wearing surface, in order that the armature may not become materially displaced with respect to the poles as a result of magnetic attraction as well as weight, and also to prevent overheating of the journals. The following formula takes into account the increased generation of heat at higher peripheral velocities, and also provides sufficient wearing material:

$$l_b = k_3 \times d_b \sqrt{\text{r. p. m.}},$$

wherein

l_b = Length of the bearing, in inches;

d_b = Diameter of the shaft in the bearing (from page 129);

k_3 = A constant dependent upon the speed of the armature (given in Table XI).

TABLE XI

Value for Constant in Formula for Length of Armature Bearing

CAPACITY OF MACHINE (IN KILOWATTS)	HIGH-SPEED ARMATURES	LOW-SPEED ARMATURES
Up to 5 kilowatts	0.1	0.15
" 10 "	0.1	0.175
" 50 "	0.125	0.200
" 100 "	0.150	0.225
" 500 "	0.175	0.250
" 1,000 "	0.200	0.275
" 2,000 "	0.225	0.300

Losses Due to Friction in the Bearings and to Windage. These are very difficult to predetermine with even reasonable accuracy. Designers usually estimate them from previous experience. For belt-driven machines ranging in speeds from 1,800 r. p. m. to 300 r. p. m. and of capacity from 30 to 500 kw., these losses should range from 3 per cent of the output in the smaller machines to 1 per cent in the larger sizes. For direct-connected generators, this figure ranges from 1 per cent to 0.4 per cent of the output, depending upon the size and speed, being lower for machines of this type on account of the lowered r. p. m. and the better alignment.

Calculation of Efficiency. On page 63, efficiency was defined as the ratio between output and input of the machine. It may also be defined as the ratio between the output and the output *plus* the losses. These latter come under the following heads, the computation of each having been considered in the foregoing pages:

(1) *Copper Losses.* These consist of the sum of the I^2R losses in the armature field-coils, and increase as the square of the current—being, however, independent of the speed.

(2) *Iron Losses.* These are made up of the eddy-current and hysteresis losses produced in the armature core-plates owing to the changes in flux-polarity and density to which they are periodically subjected. They vary slightly with load, on account of the strained distribution produced, and are always variable with the speed, eddy currents varying as the square of the speed, and hysteresis losses as the 1.6th power of the speed.

(3) *Excitation Losses.* These consist of the watts expended as heat and utilized to drive the magnetizing current around the magnetizing coils, and are included in machine I^2R losses.

(4) *Commutator Losses.* These losses may be subdivided into:

(*a*) I^2R loss due to brush-contact resistance;

(*b*) Brush friction loss.

(*c*) Losses through sparking and through eddy currents in the commutator bars.

Of those, *a* and *b* are the only ones usually considered, the other being practically negligible except in generators furnishing very large currents at very low voltages.

(5) *Bearing Friction and Windage Losses.* The former are the losses due to the friction of the shaft in the bearings, and depends only upon the load and speed. The latter are occasioned by the armature churning the air, and are independent of the load, but vary with the speed.

(6) *Secondary Copper and Iron Losses.* These have already been considered as eddy-current loss in the armature conductors, eddy-current loss in the pole-faces, etc.

The method of calculating each of these losses has been considered in detail above, so that we have,

$$\eta = \frac{w_0}{w_0 + w_1 + w_2 + w_3 + w_4 + w_5 + w_6},$$

wherein w_0 is the output of the machine in watts, and w_1, w_2, w_3, etc., represent the losses in watts just enumerated. Representative curves of these losses are shown on pages 15 and 123; while Table XII gives the average efficiencies and apportionment of losses of direct-driven machines of various sizes.

TABLE XII

Average Efficiencies and Apportionment of Losses of Direct-Driven Machines of Various Sizes

Output of Machine (in kw.)	Commercial Efficiency (per cent)	Percentage Losses In				
		Armature Copper	Armature Iron	Field Copper	Commutator, Friction and Drop	Friction and Windage
1	80	4.3	3.7	8	0.6	3.4
2	82	4.0	3.4	7	0.57	3.03
5	84	3.7	3.1	6	0.54	2.68
10	86	3.4	2.8	5	0.50	2.30
20	88	3.1	2.5	4	0.46	1.94
30	89.5	2.8	2.2	3.5	0.42	1.58
50	91.0	2.5	1.9	3.0	0.39	1.21
100	92.0	2.2	1.6	2.75	0.37	1.08
200	93.0	1.9	1.4	2.50	0.35	0.85
300	93.5	1.7	1.35	2.35	0.33	0.77
500	94.0	1.6	1.25	2.15	0.31	0.69
1,000	95.0	1.45	1.10	1.65	0.29	0.51
2,000	96.0	1.30	1.00	1.10	0.27	0.33

In using this table, it must be borne in mind that the values may vary considerably, even in machines of the same output but of different speeds and voltages, and under different conditions of working. The figures given should be used merely as a guide in apportioning or checking the losses.

Calculation of Magnetization Curve and Voltage Drop.—*Predetermination of Magnetization Curve.* The magnetization curve of a dynamo-electric machine is the curve connecting the ampere-turns upon the magnetic circuit, and the useful flux produced by them in the armature teeth. Since the number of turns upon the field coils is usually constant, and since the no-load terminal voltage of a generator is directly proportional to the useful flux entering the teeth of the armature, it is more convenient to represent the magnetization curve by the relation between the field-exciting current in amperes, and the no-load terminal voltage. This curve is generally predetermined by calculation, and then actually tested in the finished machine for each new type, thus checking the correctness of the designer's assumptions. The experimental determination is explained later. These curves are valuable, not only to show the character of one particular machine, but are useful for comparing different ones. For this purpose a standard ratio of the scales on which the curves are based should be followed.

To illustrate the method of constructing the magnetization curve of a continuous-current generator, let us consider the case of a generator the dimensions and particulars of which are as follows:

General:	
Rated load output in kilowatts	150
Terminal voltage at rated load	250
External current, in amperes, at rated load	600
Armature speed, in r. p. m.	450
Number of poles	6
Armature Dimensions:	
External diameter of core, in inches	33
Internal " " " " "	18
Number of slots	124
Depth of each slot, in inches	1.625
Width " " " " "	0.400
Pitch of slot at armature face, in inches	0.840
Radial depth of iron in core under teeth, in inches	5.875
Total length of core, in inches	11.
Iron length of core, in inches	9.
Number of conductors	496
Style of winding	parallel
Bare dimensions of each conductor, in inches	0.7 by 0.11
Insulated dimensions of each conductor, in inches	0.73 by 0.14
Mean length of one armature turn, in inches	66

Field-Magnet Data:	
Number of poles	6
Diameter of bore, in inches	33.625
Turns per pair of poles	3,602
Shunt exciting current, in amperes	4.10
Angle covered by each pole-face, in degrees	43
Commutator Dimensions:	
Diameter, in inches	21
Number of segments	248
Active length, in inches	7.5

The magnet-coıes are of steel, circular in cross-section and bolted to the yoke, the pole-shoes being in one piece with the magnet-cores. The field frame is cast in two pieces and bolted together. All the field-exciting coils are connected in series. The armature slots are parallel-sided, of the dimensions stated above. There are two ventilating apertures in the core, each $\frac{3}{8}$ inch wide. The armature winding has six circuits in parallel, with six sets of brushes set 60° apart.

In order to construct the magnetization curve, we have:

$$E = \frac{\phi_a \times Z \times \text{r. p. m.}}{60 \times 10^8} \quad \text{(see page 62.)}$$

$$= \frac{496 \times 450}{60 \times 10^8} \times \phi_a$$

$$= 0.00000372\ \phi_a$$

As the leakage coefficient of this machine is $\nu = 1.11$ (from Table II, page 77), we may construct the following table, since $\phi_m = \nu\,\phi_a$ (from page 76):

E	ϕ_a	ϕ_m
200	5,370,000	5.960,000
230	6,170,000	6,850,000
230	6,980,000	7,750,000
280	7,510,000	8,350,000
300	8,050,000	8,940,000

From the drawings we find:

Mean length of magnetic path in magnet-yoke, in inches	26
" " " " " " two magnet-cores, in inches	28
" " " " " " armature core, in inches	15
" " " " " " two teeth, in inches	3.25
" " " " " " two air-gaps, in inches	0.625
Magnetic area of yoke, in square inches	44
" " " magnet-cores, in square inches	78.5
" " " armature body, in square inches	53

The polar angle being 43°, we have, for the number of teeth under one pole:

$$\frac{124 \times 43^\circ}{360^\circ} = 14.7.$$

Allowing for spreading of flux in the air-gap owing to high flux-density in the teeth, we may take 16 teeth as receiving flux from each pole.

As the pitch of slots at the bottom of the slots is $\frac{93.45}{124} = 0.754$ in., and as the slots are 0.4 inch wide, we have as the width of a tooth at its root, $0.754 - 0.400 = 0.354$ inch. The area of the teeth receiving flux from each pole will therefore be:

$$16 \times 0.354 \times 9 = 51 \text{ square inches,}$$

since the length of iron in the armature parallel to the shaft is 9 inches.

The air-gap area, taken as the pole-face area, is 140 sq. in.

This completes the data necessary for computation of the magnetization curve, and it is sufficient here to calculate a few points on this curve, as the method is the same for all.

Considering the machine to generate an e. m. f. of 200, 230, 260, 280, and 300 volts respectively, we obtain from the previous table, by the method explained on page 82, the accompanying tabulation (page 138).

As seen from this tabulation, we have:

$E = 200$,	Ampere-turns per pair poles	= 8,715
$E = 230$,	" " " " "	= 10,846
$E = 260$,	" " " " "	= 13,833
$E = 280$,	" " " " "	= 16,498
$E = 300$,	" " " " "	= 19,095

By plotting the curve connecting these five points, we obtain the working portion of the magnetization curve shown in Fig. 150. The complete magnetization curve may similarly be computed for the full range of the field-exciting current, taking account of the residual magnetism of the magnetic circuit; but in the design of generators, the working portion is sufficient.

It is usual to operate shunt-wound generators upon that portion of the magnetization curve just above the so-called bend, while compound-wound machines are usually designed to operate near the bend of the magnetization curve.

Computation of Voltage Drop from Magnetization Curve. At any generator load, there are four causes tending to lower the voltage at the terminals of the machine—namely, ohmic resistance of the armature and series coils (if any), drop due to brush contact, demagnetizing action of the armature, and distortion of the armature flux.

APPLICATIONS OF MAGNETIZATION CURVE CALCULATIONS

Portion of Magnetic Circuit	Material	Mean Length of Magnetic Path (Inches)	Magnetic Area (Square Inches)	$E = 200$, $\phi_a = 5,370,000$, $\phi_m = 5,960,000$			$E = 230$, $\phi_a = 6,170,000$, $\phi_m = 6,850,000$			$E = 260$, $\phi_a = 6,980,000$, $\phi_m = 7,750,000$			$E = 280$, $\phi_a = 7,510,000$, $\phi_m = 8,350,000$			$E = 300$, $\phi_a = 8,050,000$, $\phi_m = 8,940,000$		
				Flux-Density	Ampere-Turns per Inch Length	Ampere-Turns	Flux-Density	Ampere-Turns per Inch Length	Ampere-Turns	Flux-Density	Ampere-Turns per Inch Length	Ampere-Turns	Flux-Density	Ampere-Turns per Inch Length	Ampere-Turns	Flux-Density	Ampere-Turns per Inch Length	Ampere-Turns
Magnet-Yoke...	Cast Steel	26	2x44	67,800	12.5	325	77,900	18	468	88,000	25.5	663	94,900	37	962	101,500	56	1,455
2 Magnet-Cores.	do	28	78.5	76,000	16.5	462	87,200	25.0	700	98,600	47	1,315	106,200	76	2,125	113,900	107	2,995
2 Air-Gaps......	Air	0.625	140	38,100	120,100	7,503	44,100	13,800	8,630	49,900	15,600	9,750	53,700	16,800	10,500	57,500	18,000	11,250
2 Teeth..........	Sheet Steel	3.25	51	*105,000	119	387	*117,500	305	991	*130,500	625	2,030	*137,500	830	2,798	*144,000	998	3,222
Armature Core.	do	15	2x53	50,600	2.5	38	58,300	3.8	57	65,900	5	75	71,000	7.5	113	76,000	11.5	173
Ampere-turns per pair of poles.......				......	......	8,715	......	......	10,846	......	......	13,833	......	......	16,498	......	......	19,005

* Corrected as per curves on page 81.

The voltage-drop due to resistance of the armature winding, series field-coils, and brush contacts, is:

$$e = I_a r_a + I_a r_{se} + I_a r_b,$$

omitting the second term if the series winding is absent. Then, in the assumed case (Fig. 150), the no-load e. m. f. being 250, represented by P on the magnetization curve, the rated-load current being 600 amperes, and the resistance of the main circuit (including brushes, armature winding, and series field-winding) being 0.00893 ohm, we have:

$$e = 0.00893 \times 600 = 5.4 \text{ volts},$$

which, added to 250, shows that the generated e. m. f. at rated load would have to be 255.4 volts, without considering armature reaction. This is represented by the point O on the saturation curve; hence 13,500 ampere-turns are required to generate this e. m. f. In other words, at rated load and speed, assuming the terminal voltage to remain the same as at no load, we require 13,500 ampere-turns upon the field, assuming armature reaction absent.

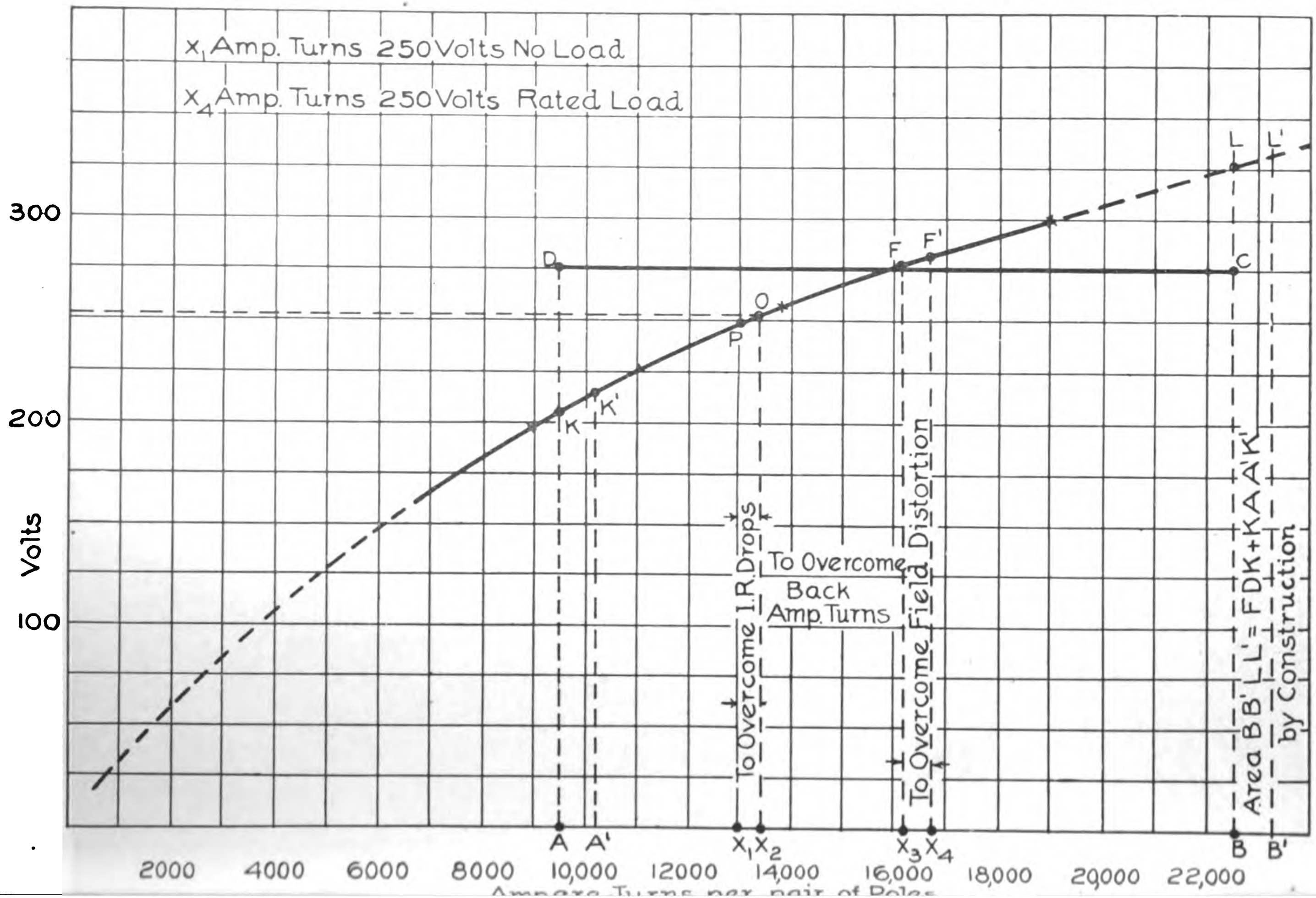
As it is often convenient to check the dimensions of an armature conductor in a preliminary design by means of this voltage-drop, Table XIII is herewith given:

TABLE XIII

Voltage-Drop as Related to Output in Shunt and Compound Machines

Output of Machine (in kilowatts)	Value of e as a Percentage of Rated-Load Terminal e. m. f.	
	Shunt Machines	Compound Machines
5	7	10
10	6	8
25	5	7
50	4	6
100	3.5	5
200	3	4
500	2.5	3
1,000	2	2.5
2,000	1.5	2

With regard to the demagnetizing ampere-turns of the armature, we know that in general these are the ampere-turns lying within twice the angle of brush lead. Assuming the brushes to be set just under the pole-tips at rated load, the demagnetizing ampere-turns will be the number of armature conductors lying between adjacent pole-corners, multiplied by the current in them.



X_1 Amp. Turns 250 Volts No Load
X_4 Amp. Turns 250 Volts Rated Load
300
200
100
Volts
D
C
L
L'
F
F'
O
P
K
K'
To Overcome I.R. Drops
To Overcome Back Amp. Turns
To Overcome Field Distortion
Area B B' L L' = F D K + K A A' K'
by Construction
A
A'
X_1
X_2
X_3
X_4
B
B'
2000
4000
6000
8000
10,000
12000
14,000
16,000
18,000
20000
22,000

These ampere-turns are multiplied by the leakage coefficient (because they have to be neutralized by the field-winding); the result is added to X_2, and set off on the diagram as X_3 (Fig. 150). By projecting this up to the curve, the point F is obtained, which corresponds to the necessary e. m. f.

Example. In the case previously considered, the number of slots lying between pole-tips is,

$$\frac{60° - 43°}{360°} \times 124 = 5.8;$$

and in each slot there are four conductors, each carrying 100 amperes at rated load. Hence the demagnetizing ampere-turns of the armature at rated load per pole (assuming that the brushes are moved right under the pole-tips, and that the leakage coefficient is 1.17), are:

$$5.8 \times 4 \times 100 \times 1.17 = 2,715.$$

Adding these ampere-turns to X_2, we get $X_3 = 16,200$ as the total ampere-turns required at rated load, assuming that there is no drop in voltage caused by diminished permeability in the teeth at the forward pole-horn due to distortion of the flux.

With a smooth-core armature, the flux distortion in the air-gap does not produce a diminution in the terminal voltage of the machine; but with toothed armatures, allowance must be made. In Fig. 151, let AB represent the width of the pole-face to scale, and EF the flux-density in the air-gap B_g. Then the area $ABCD$ is proportional to the useful flux ϕ_a, and at no-load we may regard this flux as being uniformly distributed along the air-gap as indicated by said rectangle. Assuming the permeability of the teeth to be constant, and laying off AH as the flux-density at the hindward pole-horn, and BG as the flux-density at the forward pole-horn (the flux being heaped up in the latter at rated load, and withdrawn from the former), the line HFG would represent the flux-density variation from point to point in the air-gap, and the area $AHGB$ would be equal to the area $ABCD$, since the permeability of the air-gap is constant. But the increased flux-density at the forward pole-horn causes the permeability of the teeth at this point to have a much lower value than it has with the flux-density B_g,

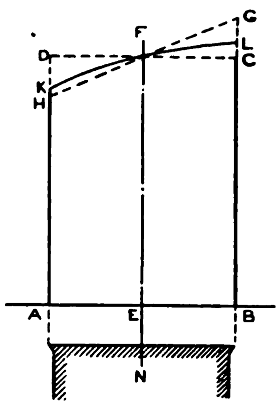


Fig. 151. Curve Showing Relation between Pressure Drop and Flux-Distortion in Air-Gap.

while, on the other hand, the permeability of the teeth under the hindward pole-horn has increased on account of the diminished flux-density in them. As a result, the line HFG takes the bent form shown by the curve KFL, and the *shape of this curve is the same as that of the magnetization curve over this range.* As can readily be seen from the figure, the area $AKLB$ is considerably less than the area $AHGB$; that is, there is a diminution of the useful flux ϕ_a, and consequently a corresponding voltage drop, which will as a rule be greater, the higher the flux-density in the teeth.

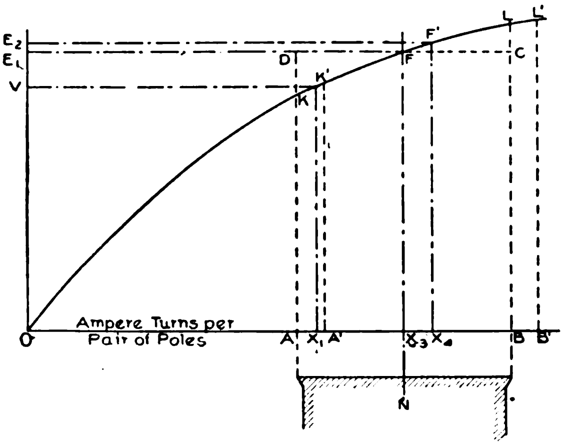


Fig. 152. Calculating Ampere-Turns Required to Compensate for Distortion of Useful Field.

One way to estimate the number of ampere-turns needed to compensate the effect produced by the distortion of the useful flux, is as follows:

In Fig. 152, let OL be the magnetization curve of the machine, the ampere-turns required for no-load, and those for rated-load induced e.m.f. at no load (and, therefore, without the extra allowance for distortion) being set off upon its scale of abscissæ OX, as X_1 and X_3, respectively, these having been estimated as shown in Fig. 150. Now, upon OX, mark off OA and OB as shown in the figure. The point A then represents the hindward pole-horn, and the point B the forward pole-horn. Had the distortion been absent, the ampere-turns required to produce E_1 volts would have produced a flux across the gap proportional to the area of the piece $ABCD$. But, as the distortion is present, the flux is proportional to the smaller area $ABLK$. Hence, we shift the point F higher up the curve to a point such as F', so that the area $A'B'L'K'$ equals the area $ABCD$. This gives a new point X_4 along OX, representing the rated-load ampere-turns required. Consequently, for a compound-wound machine, the series ampere-turns must be $X_4 - X_1$, and the shunt ampere-turns X_1, in order that the terminal volts may be OV at rated load. If the machine is shunt-wound, the resistance of the shunt rheostat must be capable of reducing X_4 ampere-turns to X_1 ampere-turns. And if there are to be neither series turns nor shunt regulator, the drop from rated load to no load would be $OE_2 - OV$ at constant speed.

Applying this reasoning to the machine under consideration, we have, for the ampere-turns under one pair of poles:

$$\frac{47^\circ}{360^\circ} \times 124 \times 4 \times 100 = 6{,}500.$$

The first factor being the slots under each pole, the second the number of inductors per slot, and the third the current per inductor, we set off, therefore, 6,500 ampere-turns on each side of the point X_3 (Fig. 150), and obtain thus the points A and B, which represent the hindward and forward pole-horns respectively. If the distortion of the main flux were absent, the area of the rectangle $ABCD$ would be proportional to it. But as this is not so, it is proportional to the smaller area $ABLK$. In order to make this latter area equal to that of the rectangle, we must shift the point F higher up on the curve to the position F', so that area $A'B'L'K'$ = area $ABCD$. In this manner we obtain the point X_4 as the necessary ampere-turns at rated load. Its value is: $X_4 = 16{,}800$.

The method just discussed for predetermining the series (compound) winding needed to give constant terminal e. m. f. at all loads between zero and rated load, may easily be extended to the case of over-compounding, by adding to the calculated voltage-drop in the machine the required increase in terminal voltage.

This method, although one of the most satisfactory, does not permit of great accuracy; but fortunately this is not important. By designing the shunt regulator liberally, and by placing a shunt across the series field-coils, the desired result may be reached by trial. This is in fact the practice of almost all dynamo builders.

The possible discrepancies between calculations thus made and results of actual test, are shown by the following values of the ampere-turns required at no-load and at rated load, as determined by the manufacturers of the machine we have been discussing:

Output	Calculated Values	Actual Values
No-load	13,400	13,000
Rated-load	16,800	15,300

The difference was caused, no doubt, by the fact that better quality of iron was used in the machine than that for which the ampere-turns were computed.

EXPERIMENTAL DETERMINATION OF CHARACTERISTIC CURVES OF CONTINUOUS-CURRENT GENERATORS

Dr. John Hopkinson, in 1879, first suggested that the behavior of a generator could best be studied from a curve representing the relation between the e. m. f. and current of the machine at different loads. In 1881, M. Marcel Deprez elaborated Hopkinson's method and gave the name of *characteristics* to these curves.

At present the characteristics most commonly developed are:

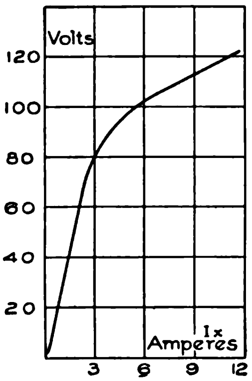


Fig. 153.

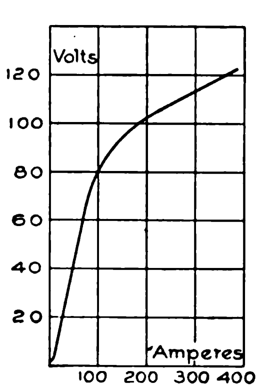


Fig. 154.

Curves Showing Effects of Residual Magnetism on the Magnetization Curve of a Dynamo.

(1) Magnetization curve.

(2) External characteristic.

(3) Curve of flux distribution (explained on page 39).

Experimental Magnetization Curve. The method of predetermining the magnetization curve of any continuous-current generator was explained on page 135.

The magnetization curve of a dynamo, however, can be determined experimentally by driving it at rated speed, and observing the voltage at the terminals for different values of the current sent through the field-winding from some outside source. Figs. 153 and 154 are typical magnetization curves of a 30-kw. generator; Fig. 153 shows the magnetization curve of the machine when its field is wound with many turns of fine wire (*i.e.*, a shunt dynamo); and Fig. 154 shows the magnetization curve of the same machine when its field is wound with a few turns of coarse wire (*i.e.*, a series dynamo).

Dependence of the Magnetization Curve upon Speed. When the magnetization curve of a dynamo has been determined for a given speed (n), the curve for any other speed (n') can be found by multiplying the ordinates of the given curve by $n' \div n$. This is evident when we consider that the flux ϕ_a has a definite value for each value of field current, so that the generated e. m. f. is proportional to the speed.

Effect of Residual Magnetism. When the field-exciting current of a generator is zero, the flux in the armature is in general *not* zero, on account of residual magnetism. This effect is indicated in Figs. 153 to 155, for it is seen here that when the field-exciting current is zero, the generated e. m. f. has a definite value.

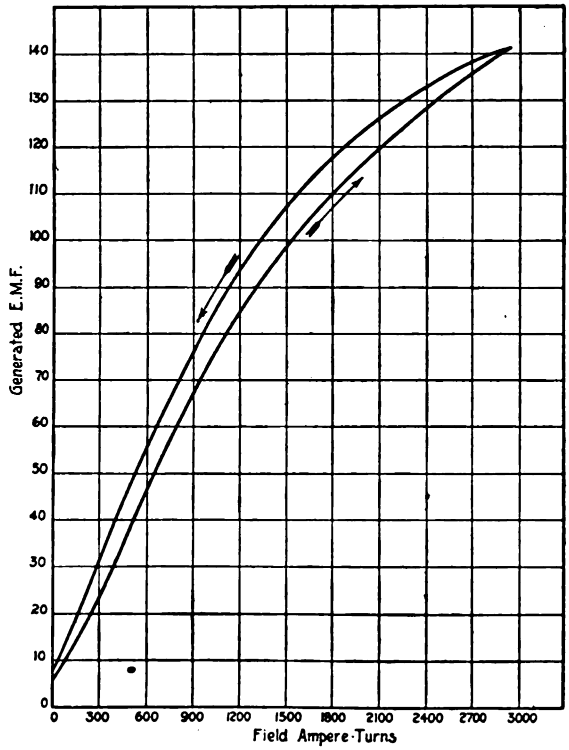


Fig. 155. Magnetization Curves of a Dynamo with Increasing and Decreasing Field-Current.

Effect of Hysteresis. On account of hysteresis in the iron portions of the magnetic circuit, the flux in the armature, and hence the no-load terminal voltage, corresponding to a given value of the field-exciting current, is smaller when the latter is increasing than when it is decreasing. Therefore the magnetization curve of a dynamo for increasing field-current, is slightly lower than that for decreasing field-current, as shown in Fig. 155. This effect of hysteresis upon the magnetization curve of a generator is usually ignored in discussing the relation to other characteristic curves. In fact, the effect of hysteresis is greatly diminished in practical operation, inasmuch as the mechanical vibrations of the machine and the slight pulsations of armature and field currents, cause the flux to settle to a normal value.

External and Other Characteristic Curves. The external characteristic curve of any dynamo-electric machine is a curve representing the relation between the terminal voltage of the machine and the external load in amperes. Besides the external characteristic curve, the *total characteristic curve*, and the *ampere-ohm characteristic curve* are sometimes considered. The former represents graphically the relation between the generated e. m. f. of the machine and the armature current, while the latter shows the relation between output of the machine in amperes and resistance of the external circuit.

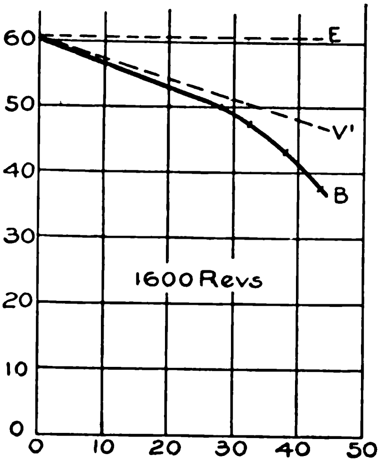


Fig. 156. Characteristic Curve of Separately-Excited Dynamo.

Inasmuch as the characteristic curves of the series, shunt, and compound generators differ markedly from one another, those pertaining to each type will be considered separately.

Characteristic Curves of Magneto and Separately-Excited Machines. In the magneto machine, the permanent magnetism of the steel may be considered approximately constant, and the same condition would obtain in a separately-excited machine if the field-current were kept constant. Owing, however, to the reactions of the armature when the current flows therein, the useful flux and terminal voltage are decreased. In Fig. 156 are given the results of tests upon a separately-excited dynamo. The line *E* represents the generated e. m. f. of the machine when operated on open circuit at rated speed and field-current. The line *V'* shows the terminal voltage which would be obtained if armature reactions were absent, and only armature and brush drop were in evidence. The curved line *B* represents the actually observed values of the terminal voltage when different currents were drawn from the machine. The pronounced droop at the lower end of the latter curve is probably due to the greater demagnetizing effect when there is a considerable load at the brushes.

The characteristic shows such a downward curvature more definitely when the field-magnets are weakly excited.

Characteristic Curves of Series-Wound Machines. The characteristic curve of a series generator may be determined experimentally by driving the machine at constant speed, and observing corresponding values of current output and terminal voltage for different resistances in the external circuit.

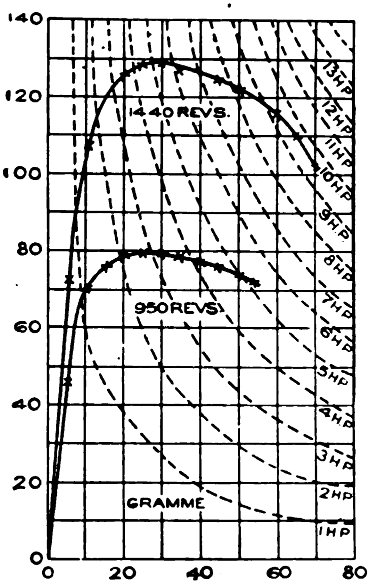


Fig. 157. Characteristic Curves of a Series-Wound Generator at Different Speeds.

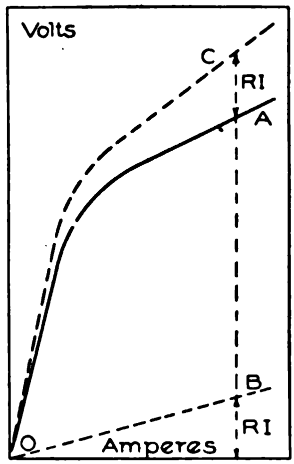


Fig. 158. Effect of Residual Magnetism on Characteristic Curve of a Series-Wound Generator.

External Characteristic Curve. Fig. 157 represents the external characteristic curves of an "A" Gramme machine, series-wound, at two different armature speeds. As is seen from the shape of the curves, the e. m. f. increases at first with the current, due to the increase in magnetization of the field-magnets. As the parts of the magnetic circuit, with increase of load, approach saturation, the reactions of the armature and I R drops become of relatively greater importance; the result is that the curve flattens out and finally bends downward.

Total Characteristic Curve. The total characteristic curve shown in Fig. 158 was plotted from the external characteristic in the following manner: Knowing that,

$$E^* = V + (r_a + r_{se} + r_b)\, I_a = V + R\, I_a\,,$$

* Page 66.

and since the armature and external currents of this type of generator are equal, we plot the values of I_aR for various values of I_a, obtaining the straight line OB in the figure. Adding to each ordinate of the external characteristic curve, the corresponding value of the I_aR drop thus found, we obtain the total or internal characteristic as shown.

The effect of residual magnetism upon the external and total characteristic curves of a series-wound generator causes the curve to intersect the axis of volts above the origin, as indicated in Fig. 158; that is, at zero external current, and hence zero field-exciting current, an e. m. f. is generated in the armature of small value, as already explained. Thus a series generator is self-starting.

Relation between Magnetization Curve and Total Characteristic Curve of a Series-Wound Generator. If it were not for the demagnetizing action of the armature current on the field, the total characteristic curve of a series-wound generator would be almost identical with the magnetization curve. The effect of the armature current is, however, either to reduce inducing flux and therefore the generated voltage which corresponds to a given field-exciting current, or to necessitate an increased field-exciting current to give the requisite terminal voltage.

Dependence of the Characteristic Curve on Speed. Since the flux has a definite value for a given value of current output of a series-wound generator, and therefore independent of the speed, the generated voltage is proportional to the speed for a given value of the output current. The external characteristic curve corresponding to the speed n' may in consequence be derived from the external characteristic curve corresponding to the speed n, as follows: Add IR to each ordinate of the given characteristic, thus finding the total characteristic for the same speed n.* Then multiply the ordinates of this characteristic curve by $n' \div n$, thus finding the total characteristic curve for the speed n'. Subtract IR from each ordinate of this curve, thus obtaining the external characteristic curve for the speed n'.

Drooping of the External Characteristic Curve. It would seem as though the useful flux entering the armature teeth of a series-wound generator should increase more and more with the current output of the machine. As a matter of fact, the effect of magnetic

* n = Initial speed; n' = Final speed.

leakage around the armature caused by the reactions of the armature current, is to cause this useful flux actually to decrease in value when the current output is excessive, especially if the iron in the field-circuit becomes saturated before that in the armature circuit. This decrease in the useful flux entering the armature means an actual decrease in the generated e. m. f.; and of course the terminal voltage falls off, though more than that generated on account of I_aR drop, as shown in Figs. 157, 158, and 159.

Fig. 159 shows the external characteristic curve (full line), and total characteristic curve (dotted line), of a Wood arc-light, series-

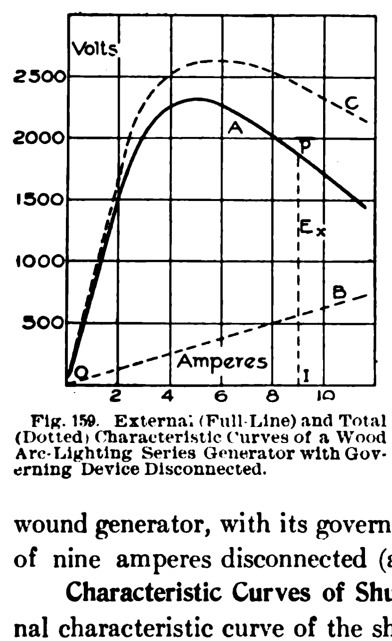


Fig. 159. External (Full-Line) and Total (Dotted) Characteristic Curves of a Wood Arc-Lighting Series Generator with Governing Device Disconnected.

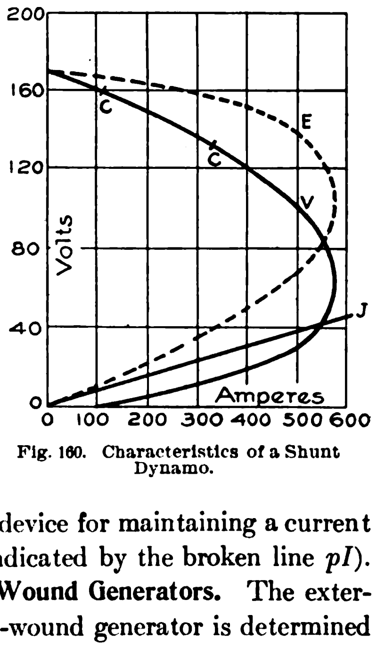


Fig. 160. Characteristics of a Shunt Dynamo.

wound generator, with its governing device for maintaining a current of nine amperes disconnected (as indicated by the broken line *pI*).

Characteristic Curves of Shunt-Wound Generators. The external characteristic curve of the shunt-wound generator is determined experimentally by running the machine at rated speed and noting the terminal voltage for various values of the external current.

External and Total Characteristic Curves. The full line in Fig. 160 represents the external characteristic curve of a typical shunt-wound generator, the portion *cc* being that part upon which machines of this type are usually operated.

The total or internal characteristic curve is shown by the broken line in the same figure, and is calculated from the external characteristic curve as follows: Consider a point upon the external characteristic curve. The corresponding point upon the total characteristic curve is found by increasing the abscissa by the value of the shunt current so as to obtain the armature current, and by adding to the ordinate the voltage-drop in the armature and brush contacts to get the generated e. m. f.

These are seen to differ radically from the corresponding curves of the series-wound machine. The figure shows that the curves begin at a point where the terminal and generated volts are maximum, and descend slightly at first and then rapidly, finally returning in the direction of the origin, but cutting the axis of abscissæ before reaching it. The straight portion of the curve, after the bend, represents the unstable state when the shunt current is less than its true critical value. The slope of the line which constitutes the latter portion of this characteristic, represents for this particular speed, that external resistance below which the magnets lose their magnetism at once.

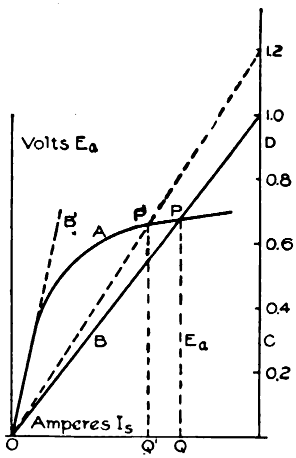


Fig. 161. Relation between Voltage and Speed in Shunt Generator.

The effect of residual magnetism upon the external characteristic curve of a shunt-wound machine is to cause it to intersect the ampere-axis to the right of the origin, as indicated in Fig. 160.

Voltage-Speed Characteristic Curve of Shunt Generator at No-Load. The relation between the speed of a shunt generator and its voltage is much more complicated than in the case of the separately excited or series-wound machines, since a higher speed increases the generated e. m. f. It thus causes a greater exciting current to flow in the field-windings, resulting in a still higher value of machine voltage until practical saturation is reached. We may construct the curve showing this relation from the magnetization curve of the machine, as follows: Let OA, Fig. 161, be the magnetization curve of a shunt-wound machine at a speed n. Draw the straight line OB, of which the abscissæ represent values of the shunt field-exciting current I_{sh}, and the ordinates represent values of the voltage $r_{sh} I_{sh}$ required to produce the corresponding values of I_{sh}. The co-ordinates of the point of intersection of OA

and OB will then represent the values of E, which is practically equal to V at no load, and to I_{sh} when the machine is driven at speed n.

Draw the line CD perpendicular to the axis of abscissæ, and draw the line OP through P until it intersects this vertical line, making $PQ = E$. The point of intersection of OP and CD then represents the value of r_{sh} at the speed n. Now lay off on CD a scale of values of r_{sh}, taking the actual value of r_{sh} at speed n as unity.

Now suppose it is required to find the value of E for a speed $n' = n \div 1.2$. As a first step, imagine that the value of r_{sh} is increased from unity to 1.2, the speed meanwhile remaining constant. Under these conditions, we have $E' = Q'P'$. Now imagine this increased value of r_{sh}, and the original speed n, to be both decreased in the ratio 1.2:1. This would bring r_{sh} back to its original value, and would reduce the value of E' (*i.e.* $Q'P'$) in the ratio 1.2:1. Therefore the required value of the generated e. m. f. at speed n' is $(1 \div 1.2)\,Q'P'$.

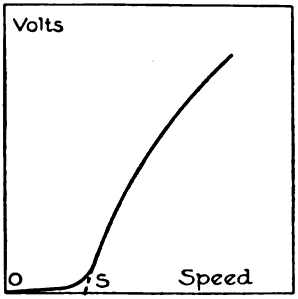


Fig. 162. Typical Voltage-Speed Characteristic of a Shunt Generator at Zero Current Output.

Fig. 162 shows a typical voltage-speed characteristic curve of a shunt generator at zero load. If it were not for the effect of residual magnetism, this curve would cut the speed axis at S. The speed corresponding to S is called the *critical speed* of the given shunt-wound generator; and when the speed is less than this value, it cannot build up at all.

The critical speed may be obtained from Fig. 161 by extending the line tangent to OA at O (*i.e.*, OB'), until it intersects CD produced, at a point which is equal to $n \div n''$; whence n'' is the critical speed.

Relation between Magnetization Curve and Total Characteristic Curve of a Shunt-Wound Generator. Let us assume OA as the magnetization curve of the machine in Fig. 163, the ordinates of the straight line OB representing the values of $V = r_{sh}\, I_{sh}$. Consider any given point P on OB. The abscissa OS is the shunt field-exciting current I_{sh}, and the ordinate SP is V. It remains to find the point P' on the total characteristic curve corresponding to P.

Let n be the number of turns of wire in the shunt field-winding, and let d be the number of demagnetizing turns on the armature, through each of which the entire armature current may be considered as flowing. Then the resultant field-excitation is $(nI_{sh} - dI_a)$* ampere-turns, which may be written $n(I_{sh} - I_a d \div n)$. It follows, then, that the actual resultant field-excitation and the actual value of E are such as would be produced by a field-exciting current equal to $I_{sh} - I_a d \div n$ acting alone; that is, the distance QP'' is equal to $I_a d \div n$, P'' being the unknown point on the magnetization curve corresponding to P Furthermore, the ordinate of P'' is, of course, E, so that the distance QP is equal to $E - V = r_a I_a$.

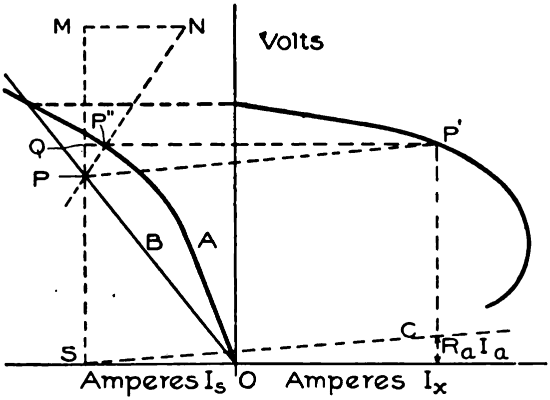


Fig. 163. Relation between Magnetization Curve of a Shunt Dynamo and Its Total Characteristic as a Generator.

Now, as I_a is as yet unknown, but since we have $PQ = r_a I_a$, and $QP'' = I_a d \div n$, it is evident that the direction of PP'' is independent of I_a. In fact, the direction of PP'' may be once for all determined by laying off $PM = r_a I_a$ and $MN = I_a d \div n$ for any arbitrary value of I_a. The line PN then fixes the direction of PP'', and the point P'' is found at the intersection of PN and OA, as indicated.

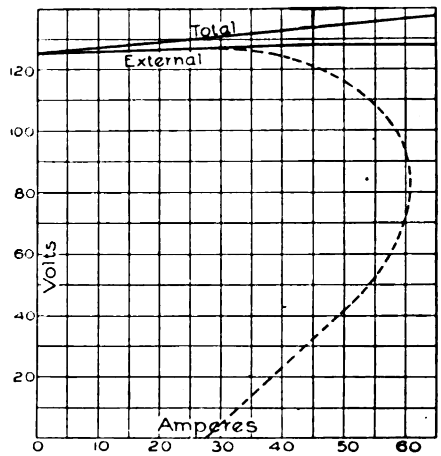


Fig. 164. Total and External Characteristic Curves of Compound-Wound Generator.

Having thus determined the point P'', the point P' on the total characteristic curve which corresponds to the chosen point P, lies

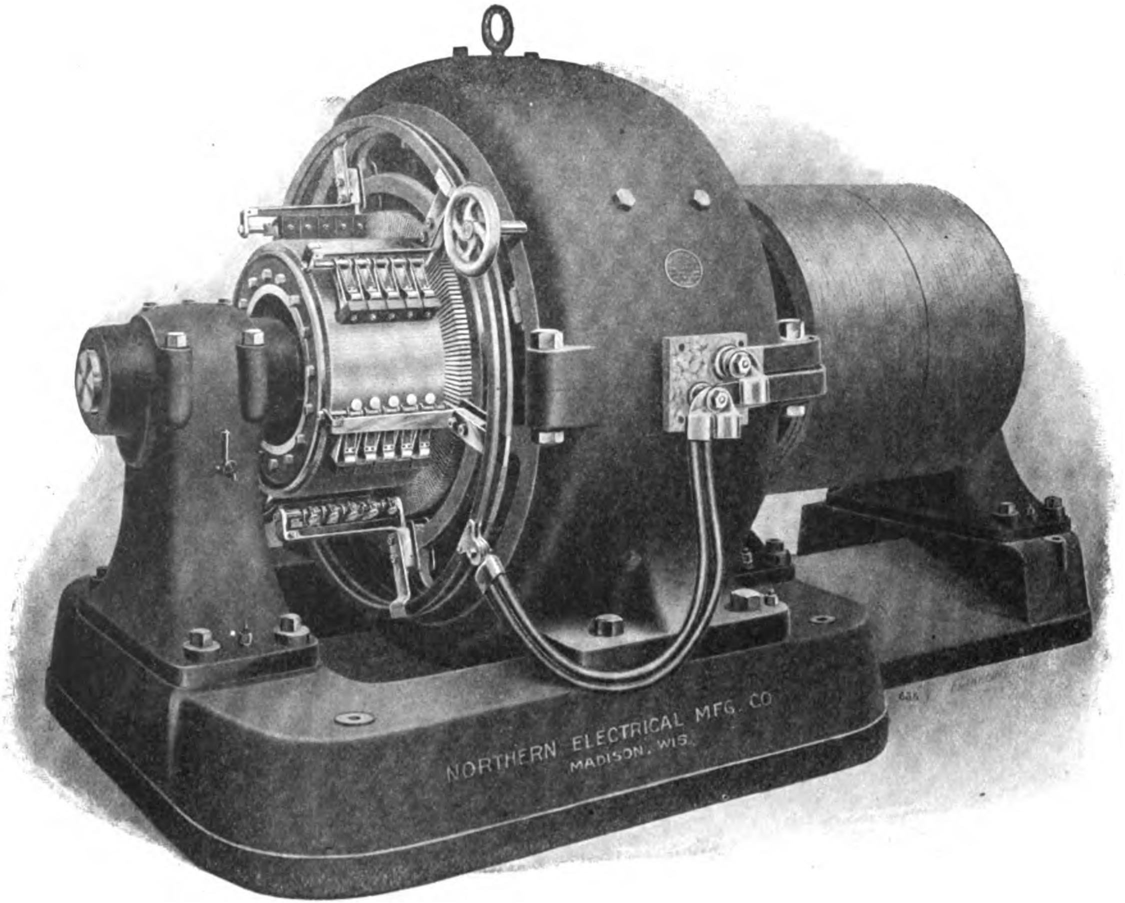
* The value of d is equal to $\frac{2\alpha}{360°} \times \frac{Z}{c}$, where α is the angle of brush lead.

on a horizontal line drawn through P'', and the abscissa of P' is determined by the condition that the corresponding ordinate of SC shall be equal to PQ ($= r_a I_a$). The point P' thus determined is most easily located by drawing a line through P parallel to SC. Such a line will intersect the horizontal line through P'' at the desired point P'.

Characteristic Curves of Compound-Wound Generators. The compound-wound generator has heretofore been treated as a shunt dynamo to which series turns have been added to compensate for the internal drop, and to raise the terminal voltage with load if desired. Consequently there is no need now to discuss this type of generator minutely.

Fig. 164 shows the external and total characteristic curves of a typical over-compound-wound generator, the terminal voltage of which rises with increase of current up to and beyond rated load. The dotted portion of the curve shows the rapid fall of terminal voltage as the load is still further increased, resulting from the great demagnetizing action of the current in the armature and from the decrease of that part of the field-excitation which is due to the shunt field-exciting current.

The computation of the number of series turns has been previously given, so that nothing further remains to be considered.



BELTED GENERATOR.

Ring Type. Three Bearing. Six Pole.

DYNAMO-ELECTRIC MACHINERY

PART III

CONSTRUCTION OF CONTINUOUS-CURRENT GENERATORS

In considering the various parts of continuous-current generators from a constructive point of view, we shall group the details under the following heads:

(1) Construction of the Frame.
(2) Construction of the Armature.
(3) Commutator and Brush Construction.
(4) Construction of the Mechanical Parts.

CONSTRUCTION OF THE FRAME

The frame of continuous-current machines is usually composed of the *magnet-yoke* or *ring*, the *field-poles* and their projections, and the *field-winding*.

Magnet-Yoke. We have seen that the ring type of magnet-frame is now generally used. It is made either of cast iron or cast steel in continuous-current machines, and in section takes one of the shapes of Fig. 165, the poles projecting inwardly. *A*, *B*, and *C* are suited to cast-iron; while *D*, *E*, and *F* are of cast-steel construction. The first two are simple types which need no explanation. *C* is employed by the Crocker-Wheeler Company, the flange on either side serving to stiffen the ring and to protect the field coils. *D* is used by the Oerlikon Company, and *E* by the General Electric Company, both designed to secure stiffness.

The choice between cast steel and cast iron for the yoke, depends upon the purpose for which the machine is intended and the ideas of the designer. The advocates of cast iron claim that by its use the machine is made heavier in the stationary part, and thus better enabled to withstand any tendency to vibrate. The other side claim that great weight is unnecessary.

The magnet-ring in all but the smallest machines is split in two along its horizontal diameter, or sometimes along its vertical diameter, to facilitate erection, inspection, and repair with respect to the armature. The two parts are usually held together by bolts at the side,

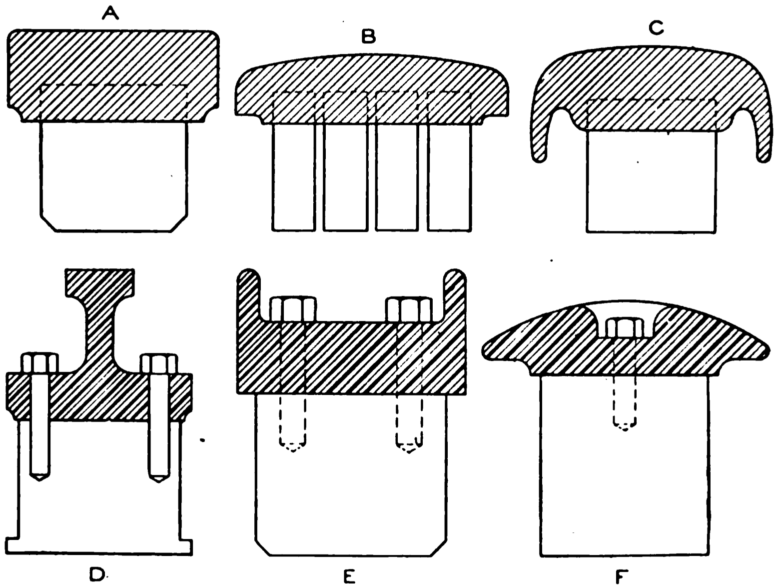


Fig. 165. Various Sections of Magnet-Yokes.

back, or interior of the ring, as indicated in Fig. 166 (*a*, *b*, *c*). One or more ring-bolts are also placed at the top or on each side of the upper half in order to make handling easy.

Field-Poles and Projections. The field-poles are generally made of wrought iron, sheet steel, or cast steel. The magnetic properties of these materials are given in Fig. 112. Wrought iron and cast steel have approximately equal permeabilities at about 95,000 lines per square inch, below which the former is a little superior. The objection to the use of wrought iron, however, is the difficulty of making it in the forms required. This may be partly avoided by using simple forms such as a plain cylinder, which can easily be made by forging or by cutting off lengths from round bars.

The cheapening and developing of the process of casting "mild" steel (soft steel), with a very small amount of carbon, has resulted in the general adoption of this material for field-magnets. It combines high permeability, cheapness, strength, and the ability to be cast in

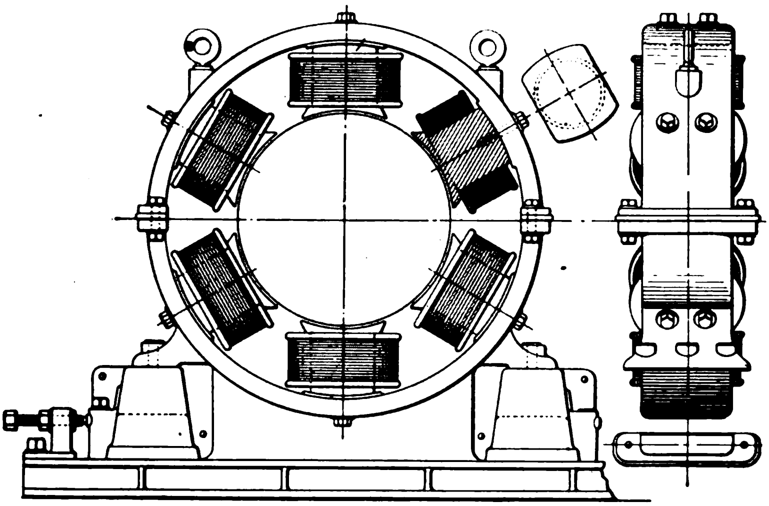


Fig. 166a. Magnet-Yoke with Parts Bolted Together at Back and Front of Ring.

any reasonable form. It is certainly not economical to use cast iron for the cores of the field-magnets, since it requires from 2 to 2.5 times

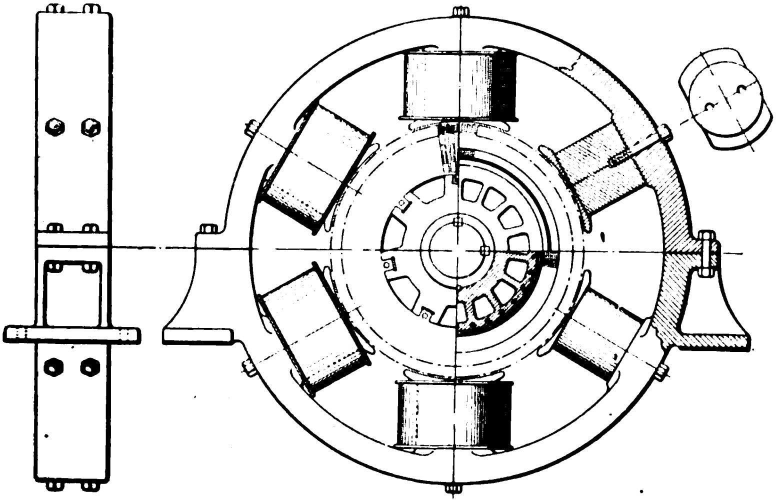


Fig. 166b. Magnet-Yoke with Parts Bolted Together at Sides of Ring.

the cross-section of wrought iron or steel for the same reluctance. With a circular cross-section, this demands about 1.5 times the length of wire for a given number of ampere-turns; and the necessary weight of cast iron being 2 or 2.5 times greater, makes it not only clumsy but more expensive. For pole-pieces, yokes, field-rings, bases, or other parts not wound with wire, the extra circumference is not so objectionable. Often the increased weight is positively advantageous in giving greater stability, so that cast iron is still used to some extent in these parts.

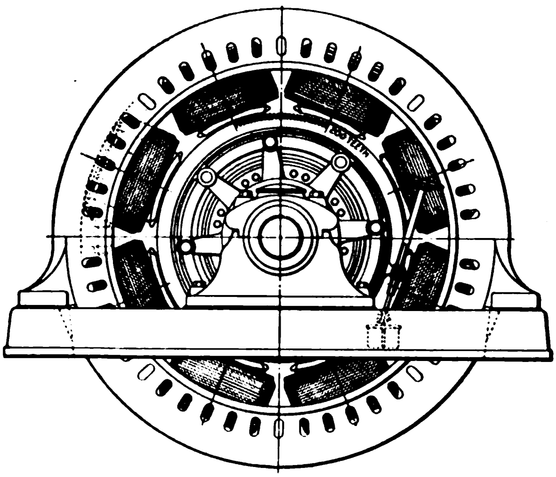


Fig. 166c. Magnet-Yoke with Parts Bolted Together on Inside of Ring.

In joining cast iron to wrought iron or steel, it is hardly sufficient to butt the two together, as indicated in Fig. 103, because the permeability of a given area of cast iron is only about one-half as great as that of an equal area of either of these other materials. Hence, in order to secure the proper surface of contact, the pieces of steel or wrought iron should be imbedded in the cast iron by placing the former in the mould when the casting is made, or the cast iron may be bored out to receive the ends of the cores. Joints in the magnetic circuit are not desirable, because they involve work in fitting, and may cause looseness or weakness—usually avoidable, however, with good workmanship. On the other hand, the common idea that they introduce great reluctance is not true, for we have seen on page 12, that an ordinary joint is equivalent to an air-gap of about 0.002 inch, which is practically insignificant, and does not warrant the making of complicated castings or forgings to avoid one or two joints in the magnetic circuit, except to simplify mechanical construction.

The length of the cores required for a given field-magnet depends simply upon the amount of field-winding. The turns needed are computed as described on pages 77-86, and the size of wire from pages 86-7. It is sufficient to make the core long enough to receive these turns properly, and expose sufficient surface to dissipate the heat generated by the field-current, to prevent excessive temperature-rise, as indicated on page 91.

The area of cross-section of the field-cores is determined by the total flux to be carried. A density of 13,000 to 16,000 lines per square centimeter (80,000 to 100,000 lines per square inch) is about the value for cast steel or wrought iron. The section is either rectangular or circular, the latter being preferable on account of ease of winding coils for this shape, and because a circle has the least circumference for a given area, thus requiring less wire. The rec-

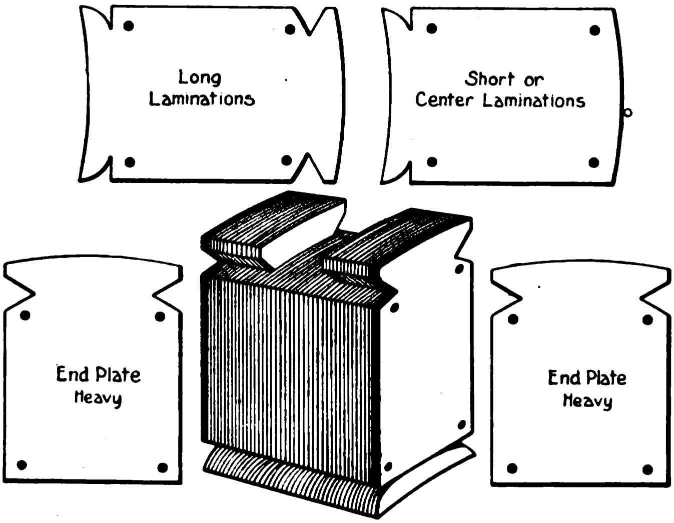


Fig. 167. Pole-Core Stampings and Assembled Pole-Piece.

tangular shape is used where the pole-core is laminated; and with the same area as one of circular cross-section, it has more radiating surface, although more wire is required for each turn.

The field-cores are attached to the yoke in several ways. The simplest method is to cast them as one piece or to bolt them together as indicated in D, E and F of Fig. 165. Another method is to place the cores of cast steel in the mould when casting the ring of cast iron. Sometimes, for large machines, only a portion of the cores is cast with the yoke, the rest being attached to the pole-pieces or shoes after mounting the field-coils. The two portions are then held together by bolts passing through the pole-shoe.

Most continuous-current machines are designed with an extended pole-piece or shoe which covers a greater surface than would the mere end of the field-core. Great attention has been paid to the special shaping of these polar extensions, as noted on page 54, and in most cases they are constructed separately and attached to the cores while assembling the machine. If the core is laminated, the pole-piece forms a part of the laminæ, as shown in Fig. 167; while, if the core is partly cast with the ring, and the remainder bolted to it, as stated above, the shoe forms a portion of this addition.

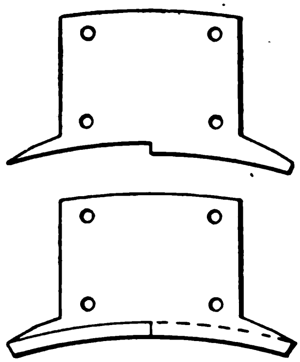


Fig. 168. Shaped Pole-Stampings.

An extended pole-piece reduces the reluctance of the air-gap, and the ampere-turns needed in the field-winding. On the other hand it is well to have the pole-shoe itself well saturated. Hence, to fulfil both conditions, either it ought to be made of a less permeable material than the pole-core (if the latter is cast steel or wrought iron, the pole-shoe may be of cast iron), or, if made of stampings of wrought iron or mild steel, it should be so designed that its edges at least will be well saturated. This can be accomplished as indicated in Fig. 168—that is, by omitting every other lamina in the pole-piece.

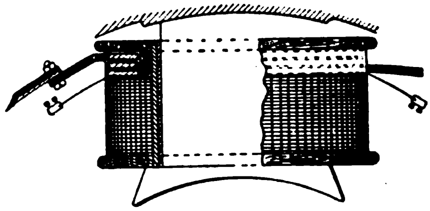


Fig. 169. Field-Magnet of Scott & Mountain's Six-Pole Generator.

Field-Winding. Coils for field-magnets may be classified as (*a*) *bobbin-wound*, and (*b*) *form-wound*. With respect to those wound on bobbins, no special instructions need be given, except for fixing and bringing out the ends, the insulation, etc. Rectangular conductors, while preferable where the cross-section of the wire is large and the radial depth of winding is considerable, cannot always be used, because special facilities are involved. Where edge-strip winding is possible, its use is generally advisable.

Field-Magnet Bobbins. These are made variously of brass with brass flanges, of sheet iron with brass flanges, of very thin cast iron, or sometimes of vulcanized fiber. Some makers use sheet metal with a flange of some hardwood, such as teak, examples of which, as well as of other common designs, are shown in Figs. 169, 170, 171, and 172. Care must be taken to line the bobbins with adequate insulating materials, such as layers of oiled silk or muslin, vulcanized fibre, or varnished mill-board. Great attention must also be paid to the manner of bringing out and securing the inner end of the coil. If a bobbin is simply put upon a lathe to be wound, the inner end of the wire, which must be properly secured, requires to be brought out in such a way that it cannot possibly make a short-circuit with any of the upper layers, as it crosses them. A method of winding which obviates this difficulty is to wind the coil in two separate halves, the inner ends of which are united, so that both ter-

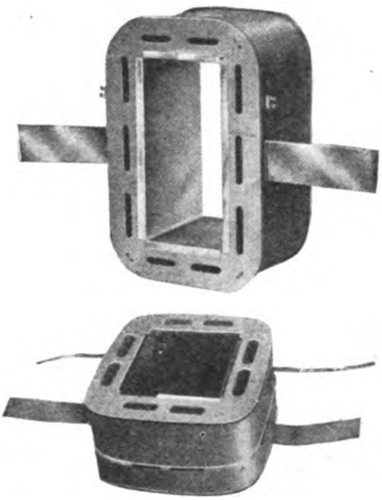


Fig. 170. Rectangular Types of Ventilated Field-Coils.

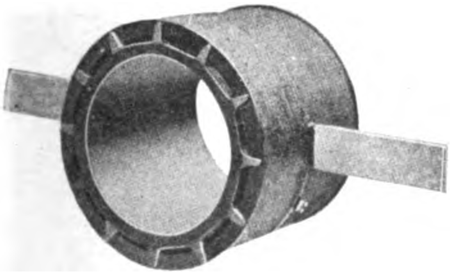


Fig. 171.

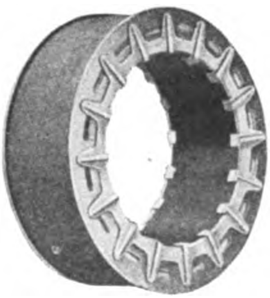


Fig. 172.

Circular Types of Ventilated Field-Coils.

minals of the coil come to the outside. Fig. 173 shows such a bobbin, this method having also been used in the manufacture of induction-coil secondaries, for which it is desirable to keep the ends away from the iron core and from the primary coil.

Again, the winding may be piled up conically, as in Fig. 174, without any end-flanges, thus avoiding some of the risks of breakdown, and bringing both free ends to the outside. In winding copper strip for some continuous-current machines, a similar plan has been adopted, the union of the two strips being effected at the interior of the coil, as indicated in Fig. 175. In still another type of continuous-current generator, the field-cores, which are removable, are themselves shaped to serve as bobbins, and, after being covered with a protecting layer of insulating material, are wound in a lathe, as illustrated in Fig. 176.

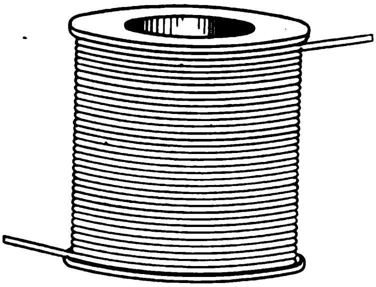


Fig. 173. Bobbin with Both Ends at Outside.

Form-wound coils are made upon a block of wood or a brass frame, to which temporary flanges are secured to hold the wires together during winding. Such coils have pieces of strong tape wound in between the layers and lapped at intervals so as to bind them together. The completed coil is then served with two or more layers of tape, each separately soaked in insulating varnish. The whole coil is soaked in an insulating varnish and then baked in an oven, current being simultaneously sent through the wire to insure interior drying. Figs. 177, 178, and 179 illustrate form-wound coils; while Figs. 171, 172, and 180 represent bobbin-wound types.

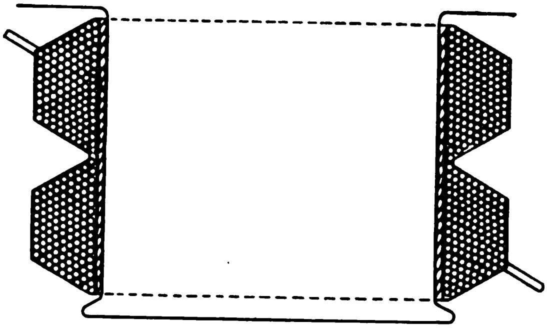


Fig. 174. Brown's Piled High-Voltage Coil.

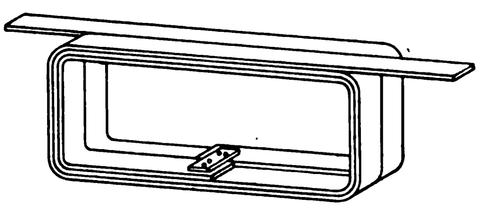


Fig. 175. Strip-Wound Coil.

Bringing Out and Fixing Ends. Figs. 181 and 182 illustrate common means for bringing out the ends of coils. In Fig. 181, copper strip, laid behind an end-sheet of insulating material, makes connection to the inner end, as shown in the upper part of the figure; while another strip, shown similarly inlaid in the under part, serves as a mechanical as well as electrical attachment for the outer end of the winding. Another method, shown in Fig. 182, also greatly reduces the danger of breaking the connection to the interior of the coil. Fig. 183 illustrates a simple device for securing the outer end by means of a terminal piece laid upon the coil, the last three or four turns of which are bared and wound over it, a permanent joint being obtained by soldering.

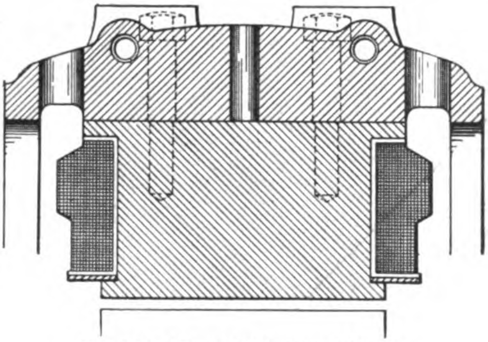


Fig. 176. Wound Pole-Core (Alioth).

Fig. 177.

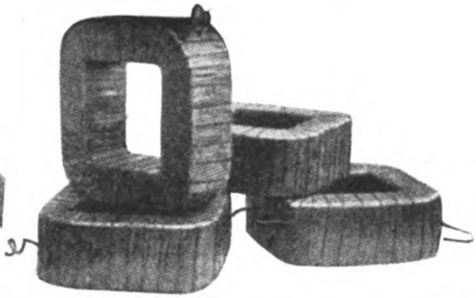


Fig. 178.

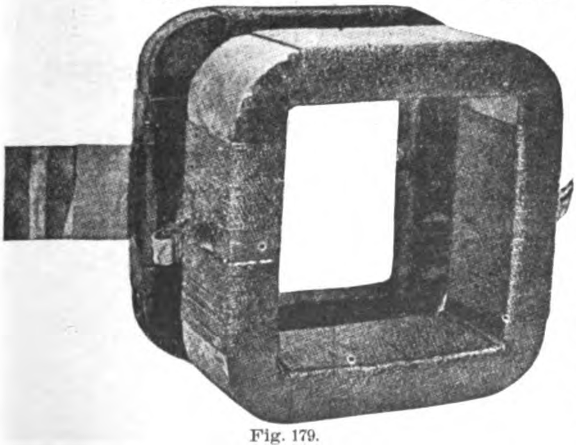


Fig. 179.

Types of Form-Wound Coils.

Insulation of Field-Magnet Coils. It is not necessary to use any mica for the insulation of field-magnet bobbins, several thicknesses of paper preparations being more often used. One-tenth inch or more thickness, if composed of several superposed layers, is generally adequate. Varnished canvas is useful as an underlay, and press-spahn or vulcanized fibre for lining the flanges. It is also important to protect the joint between the cylindrical part of the bobbin and the end flanges.

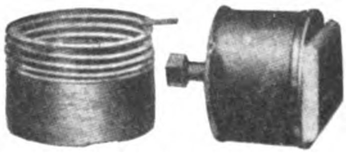


Fig. 180. Bobbin-Wound Coil.

The lagging of varnished cord with which the completed coil is usually covered, acts as a mechanical protection; but this is not altogether a benefit, since it retards the dissipation of heat.

Attachment of Magnet-Coils. The ordinary mode of supporting the field-coils is by means of the pole-shoe, which is usually removable from the core. If not so arranged, the core and shoe together are made removable. Some machines are not provided with pole-shoes, in which cases other means must be supplied to support the magnet-coils. One method consists in screwing side brackets to the end of the core. Another way, illustrated in Fig. 184, is to provide triangular blocks of hardwood, which lie in the space between the tips of two adjacent poles and are secured to the ring by bolts. Fig. 185 shows still another scheme for anchoring the field-coils.

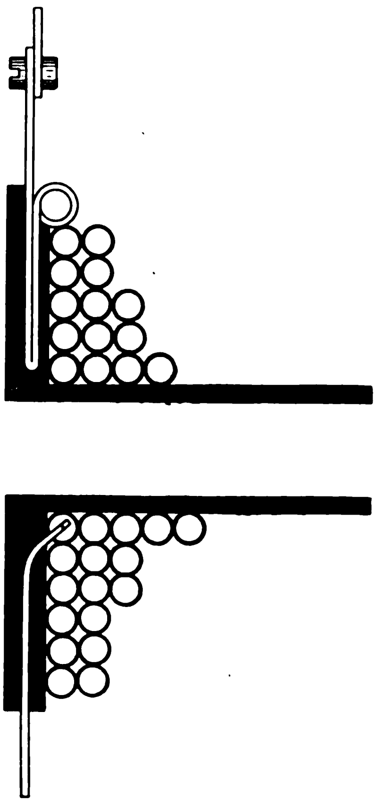


Fig. 181. Mode of Bringing Out Ends of Coils.

CONSTRUCTION OF THE ARMATURE

Core-Bodies. The cores of armatures are universally made of laminæ—thin discs—of wrought iron or mild steel. These discs are stamped out of sheet metal, and range from 0.014 inch to 0.025 inch in thickness, the former thickness being that often used at the present time. Core-discs up to about 30 inches in diameter are punched in one piece; while larger diameters are stamped out in sections (Fig. 186), and the core built up as indicated in Fig. 187, alternating the joints. These stampings are now so accurately made, that, after assembling the discs into a core, the slots need not be milled out as was formerly necessary. Milling is most objectionable, because it burrs over the edges of the discs and defeats the purpose of lamination by connecting adjacent discs and facilitating the flow of eddy currents. For the same reason, turning, after assembling, also tends to increase the iron losses. Hence, if it is found that the periphery of the core-body is irregular, it should be *ground* true.

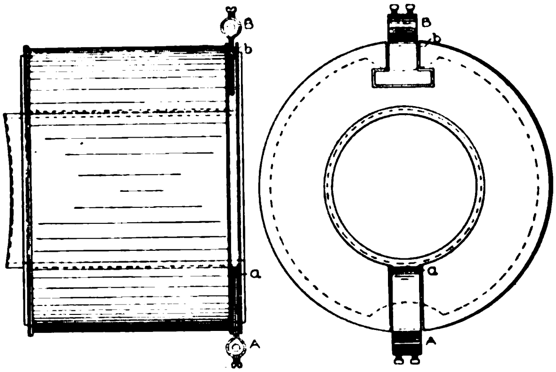


Fig. 182 Ganz's Method of Bringing Out Ends of Coils.

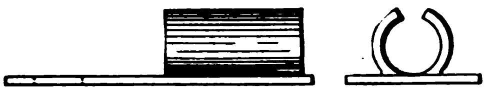


Fig. 183. Coil Terminal Piece.

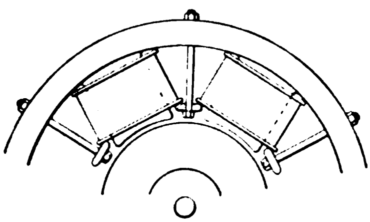


Fig. 184. Method of Anchoring Coils.

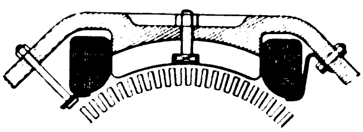


Fig. 185. Another Method of Supporting Coils.

The core-discs are insulated from each other either by a thin coating of iron oxide on the discs, a thin coating of water-glass enamel applied to the sides of the discs by a machine, or a thin coating of japan varnish similarly applied. Sometimes shellac or paper is used for insulating these laminæ; but on account of the greater expense and the fact that the efficiency is only slightly bettered, the latter are applied only in special cases.

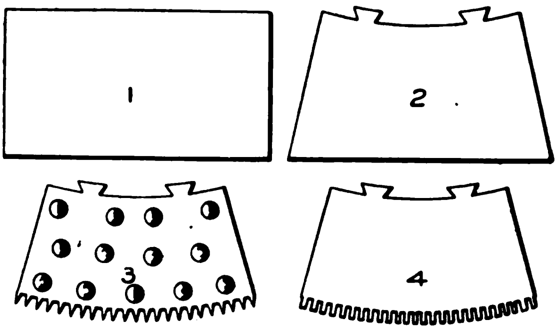


Fig. 186. Core-Segments and Ventilating Segments, Stamped.

Shapes of Armature Teeth. A common form of armature tooth is that depicted in Fig. 188, being slightly narrower at the root than at the top, the resulting slot having parallel sides. Fig. 189 illustrates a form in which the tops are slightly extended to give a larger magnetic area at the top, thus decreasing the reluctance of the air-gap, and helping to retain the conductors in the slots by the insertion of a wedge of wood. The latter object is attained by notching the teeth as in

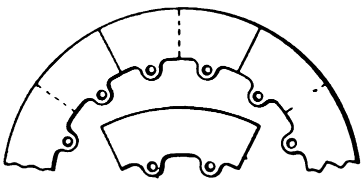


Fig. 187. Core Built of Segments.

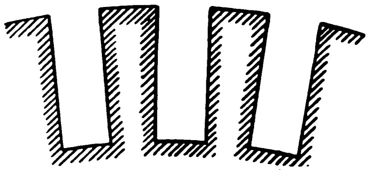


Fig. 188. Teeth with Parallel Slots.

Fig. 190, in case it is not desirable to increase the area of the top of the tooth.

End Core-Plates. It is usual to place at the ends of the core, plates of sheet iron of a greater thickness than the laminæ, so as to support and protect the latter. They are usually 0.125 inch thick, and sometimes ribbed to give added stiffness.

Binding-Wire Channels. In machines using binding wires to hold the armature conductors in the slots, it is usual to stamp some of the core-discs of slightly reduced diameter so that the binding wires may be flush with the surface of the armature. The reduction is seldom more than $\frac{1}{4}$ inch on the diameter, giving a channel not over $\frac{1}{8}$ inch deep. The width is determined by the number and size of the binding wires (see page 131).

Mounting of Core-Discs. Some mechanical means must be provided to hold the core-discs together, and to connect them rigidly

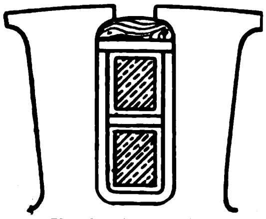


Fig. 189. Teeth with Projecting Tops.

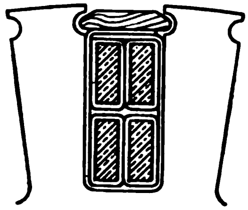


Fig. 190. Notched Teeth, to Hold a Wedge.

to the shaft. The methods may be broadly divided into two classes, depending on whether the discs are keyed directly to the shaft, or to some auxiliary support attached to the shaft.

In the case of small cores not exceeding 15 inches in diameter, the core-discs take either of the forms shown in Figs. 191 and 192, the latter being preferable on account of increased ventilation. These laminæ are simply keyed to the shaft, being held together under

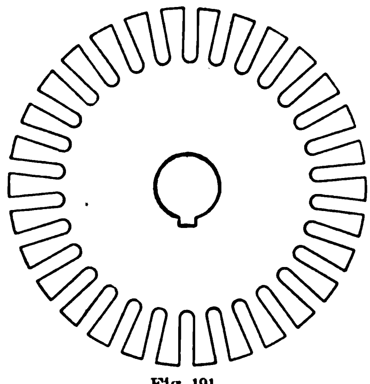


Fig. 191.

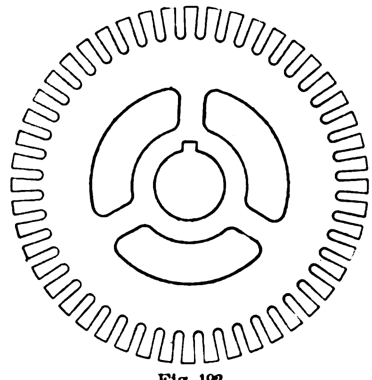


Fig. 192.

Forms of Armature Core-Discs.

heavy pressure by end-plates of cast steel or cast iron, which are in turn pressed inward either by nuts fitting in threads upon the shaft, or by bolts passing through but insulated from the armature discs and end-plates.

Large cores in which the discs are made in sections, or for which the material of the core near the shaft is not required, are built upon an auxiliary support called a *spider*, which has different forms, depending on the mode of attachment between it and the core-discs. Fig. 193 shows the discs held together and to a skeleton pulley, or spider,

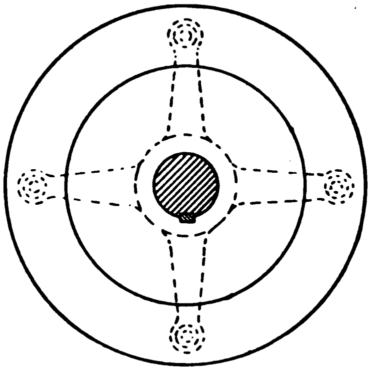


Fig. 193. Core-Discs Bolted to Spider.

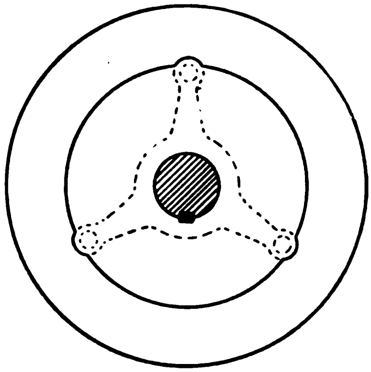


Fig. 194. Bolts Placed Internal to Core.

by bolts passing through them, the spider being keyed to the shaft. The objection to this construction is the fact that the bolt-holes reduce the effective area of the core, thus strangling the magnetic

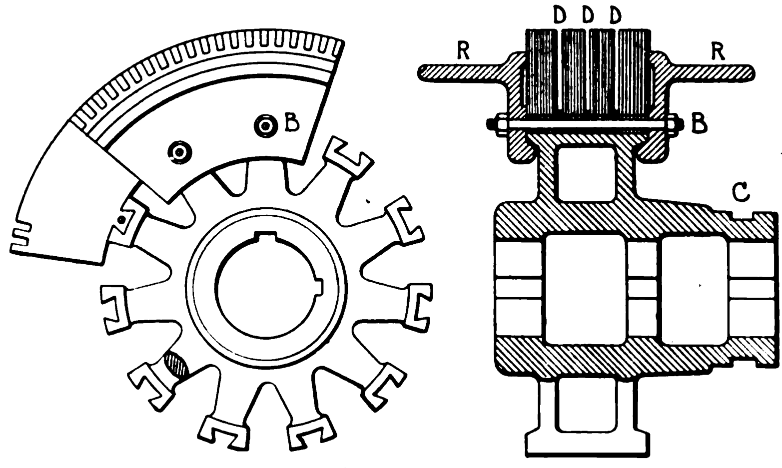


Fig. 195. Mounting of Large Armature Core.

flux. This may be overcome by placing the bolts internal to the core, as in Fig. 194, in which case they need not be so well insulated. Another arrangement which is more modern, is to provide the discs with dovetail notches or extensions, fitting into extensions or notches on the spider arms, as in Fig. 195. The sectional view shows the method of holding the laminæ together by means of bolts and end-plates, also the extension (*R R*) for supporting the end-connections of a barrel-winding.

The hubs of armature spiders, in order to facilitate fitting the shaft, are usually cleared out between their front and back bearing surfaces; and in larger sizes, the seating on the shaft is often turned to two different sizes to admit of easier erecting, as in Fig. 196.

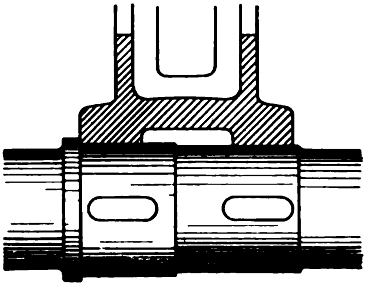


Fig. 196. Construction of Armature Hub.

Figs. 197 and 198 show a spider and other features of construction of a large machine. The rim is cut into six pieces, each of which

Fig. 197. Spider for Bullock Armature.

has four dovetail notches. If cast in one piece, trouble might arise from unequal strains in the metal, due to contraction. Ventilating apertures are provided, and on the side of each arm (Fig. 197) are seen the seatings and bolt-holes for attaching the commutator-hub and the rim which supports the winding. In Fig. 198, which depicts the completed core, are visible the supporting rim and narrow ventilating ducts.

Ventilating Ducts. Armature cores, as already explained, heat from three causes—namely, hysteresis and eddy currents in the iron, and I^2R losses in the copper conductors. In order that the tempera-

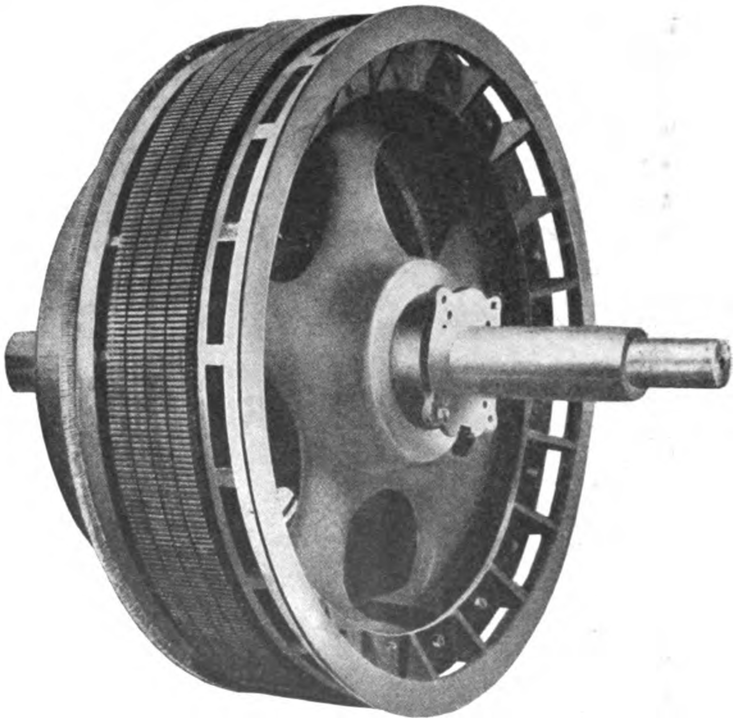


Fig. 198. Armature Core and Commutator with Temporary Shaft.

ture-rise of the armature shall not exceed a safe figure, 50°C., it has been found necessary, in the large and heavy-duty types of to-day, to resort to positive means of ventilation, usually consisting of ducts which lead the air between the core-discs. To keep the core-discs apart at these ducts, it is necessary to introduce distance pieces, or *ventilators*, Fig. 199 illustrating some of these devices.

In *a*, simple pieces of brass are riveted radially at intervals to a special core-disc 0.04 to 0.05 inch thick. This form fails to provide adequate support for the teeth, which is obviated in *c*, where behind each tooth there is a strip of brass about 0.4 inch wide set edgewise, being cast with or brazed to a special casting of brass riveted to a stout core-disc. In a recent construction shown in Fig. 200, the core-plate next to the duct is ribbed, affording good support for both the core and teeth of the next plate. Fig. 186, on page 166, illustrates a somewhat similar device.

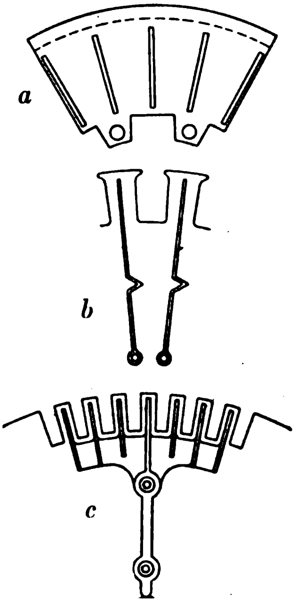


Fig. 199. Ventilating Devices.

Binding Wires. With toothed-core armatures the conductors may be held in the slots by wedges of wood, as already mentioned, or by bands of wire wound around the armature. These binding wires must be strong enough to resist the centrifugal force tending to throw the armature conductors out of the slots, and yet must occupy as little radial space as possible, in order not to interfere with the clearance between the armature and the pole-pieces. The common practice is to employ a tinned wire of hard-drawn brass, phosphor bronze, or steel, which, after winding, can be sweated together by solder into one continuous band.

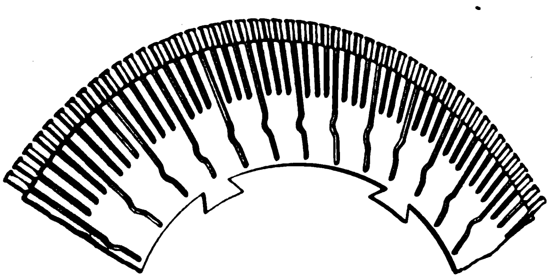


Fig. 200. Ribbed Core-Plate.

Under each belt of binding wire a band of insulation is laid, usually consisting of two layers —first a thin strip of vulcanized fibre or of hard red varnished paper, slightly wider than the belt of wire, and then a strip of mica, in short pieces, of about equal width. Sometimes a small strap of thin brass is laid under each belt of binding wire, having tags which can be turned over and soldered down to prevent the ends of the binding wires from flying out.

Wedges. In the cases where wedges are driven into grooves in the teeth, to close up the slot, the usual material employed is a well-baked hardwood, such as hornbeam or hard white vulcanized fibre. A modern method consists in using a springy strip of German silver, or a strip of *magnalium* metal.

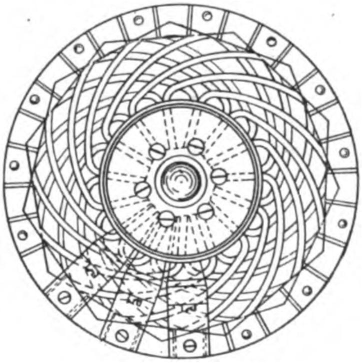


Fig. 201. Siemens Bar Armature.

Conductors. Copper is always used for the armature conductors of continuous-current machinery, either as wire strip or stranded. Wire is usually employed for machines of small or moderate current output; but rectangular conductors are preferable, especially for heavier currents, on account of better space-factor. Large, solid conductors, whether round or rectangular, are objectionable, not only on account of stiffness, but also because eddy currents may be generated in them. This is avoided by subdividing the former into several round wires or by laminating the latter.

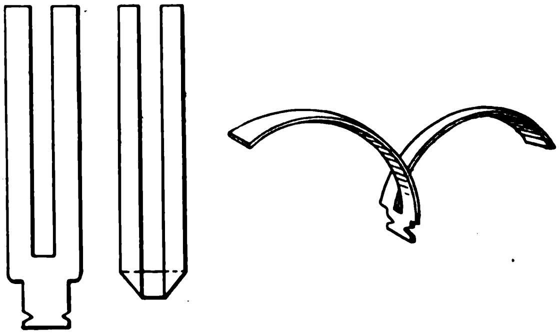


Fig. 202. Spiral End-Connectors for Evolute Windings.

Armature Windings. The different methods of armature windings have been treated at length on pages 93–120. It remains to consider the mechanical arrangements or means employed to carry out the scheme of winding adopted.

Drum Windings. Drum windings may be subdivided into (1) *hand windings;* (2) *evolute windings;* (3) *barrel windings;* (4) *bastard drum windings;* and (5) *form windings*, according to the manner in which the end-connections are made. It is essential that these latter be good conductors, sufficiently well insulated from one another, allowing of repairs and ventilation, and mechanically sound.

Hand windings, historically the first, are now seldom used, except for special machines. They involve a clumsy overlapping of wires at the ends of the armature, which stops ventilation and hinders repairs; while the outer layers, overlying those first wound, bring into close proximity conductors of widely different voltage.

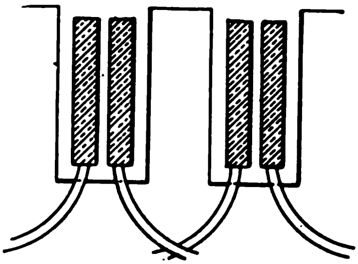


Fig. 203. Evolute Conductors in Slots.

Evolute windings, so named from the method of uniting the conductors by means of spiral end-connectors, were quite early devised to overcome the objections to the hand windings. In Fig. 201, which illustrates this construction, each inductor in the form of a bar is connected to the next by means of two evolute spiral copper strips, one bending inwardly, the other outwardly, their junction being

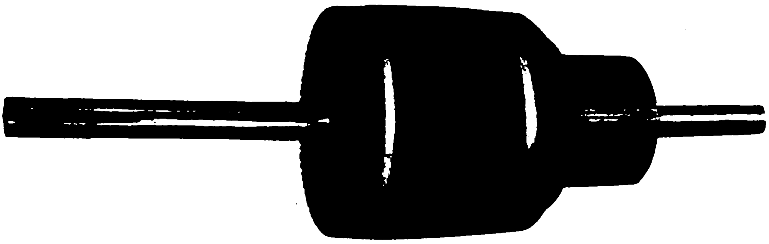


Fig. 204. Bar-Wound Armature.

in some cases secured to a block of wood upon the shaft. Their outer ends are attached to the bars by rivets or silver solder.

A common form of such end-connector is indicated in Fig. 202, another form being made of copper strip, folded. In place of the wooden block referred to above, the middle part of the evolute connector may be anchored to an insulated clamping device built up like a commutator and called from this resemblance a *false commutator.*

In evolute windings the spiral connectors lie in two planes, back of one another; hence it is necessary that the armature bars should project to different distances beyond the core-body, the shorter ones being joined to the inner layer of evolutes, the longer ones to the outer layer. For this purpose it is convenient to arrange one short and one long bar in a slot, side by side, as in Fig. 203 or in the finished armature of Fig. 204.

Barrel windings were devised by Mr. C. E. L. Brown in 1892,

Fig. 205. Armature Body before Coils are Placed in Position.

as an improvement upon the evolute windings just described, and are most extensively used to-day. The method consists in arranging the conductors in two layers, so that their ends, instead of being carried down as evolutes, are continued out upon an extension of the cylindrical surface of the armature and are bent to meet obliquely in two overlapping layers. This scheme, like the evolute winding, is

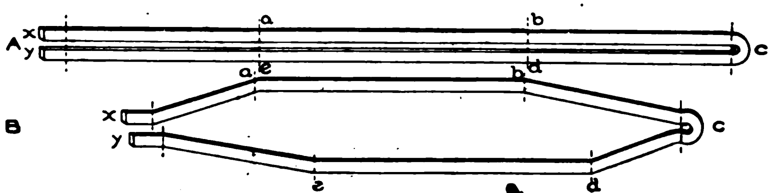


Fig. 206. Element of Lap Winding Formed from Strip.

adapted to wave as well as lap windings. Its only disadvantage lies in the fact that it requires the length of the armature parallel to the shaft to be greater than in the previous case. Its great advantage lies in the excellent ventilation made possible by the larger cooling surface, and by permitting air to enter the interior of the armature at the ends.

A usual method of supporting the extended end-connections is to attach to the end of the armature body ventilated brackets, as indicated in Fig. 205. A simple way to construct such a winding is to take a long bar of copper, and bend it as shown at *A*, Fig. 206. Then, if *ab* and *ed* are the lengths of the conductor in the slot, the bar may be opened out as in *B*, Fig. 206, if the winding is to be lap-wound, or as in Fig. 207, if the winding is to be wave-wound. Methods of computing the necessary length of the end-connections have been referred to on page 116, so that the required length of bar may be predetermined.

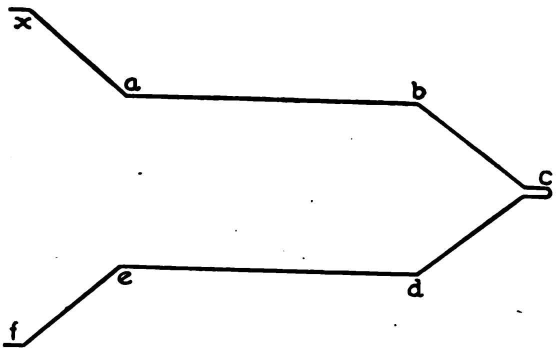


Fig. 207. Element of Wave Winding Formed from Strip.


Fig. 208. Armature of Triumph Generator.

In Figs. 208 and 209, finished armatures of this type are represented, while Fig. 210 illustrates these diagrammatically.

Thus far the windings have been described as formed of copper bars; but it is also possible to wind either of these types with wire, shaping the coils either before or after placing the wire in the slots.

Cases also occur where more than two layers of wire are necessary, either on account of the high voltage required, or to avoid harmful induction.

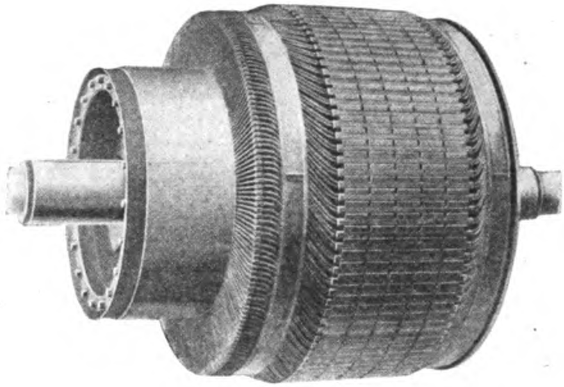


Fig. 209. Complete Armature of Crocker-Wheeler Company Engine-Type Generator.

Bastard windings is the name given to that class of armature windings whose end-connections, instead of being carried in toward the shaft in evolutes or elongated cylindrically, are partly inward and partly cylindrical. This has the effect of making the length of the armature parallel to the shaft shorter than with the pure barrel winding. It requires, however, special formers, and is applicable only to bar-wound armatures. On account of better ventilation, it is usual to combine a bastard winding at one end of the armature, with a barrel winding at the commutator end, as in Fig. 211; while Figs. 212, 213, 214 show the relation of this scheme to the two previously mentioned.

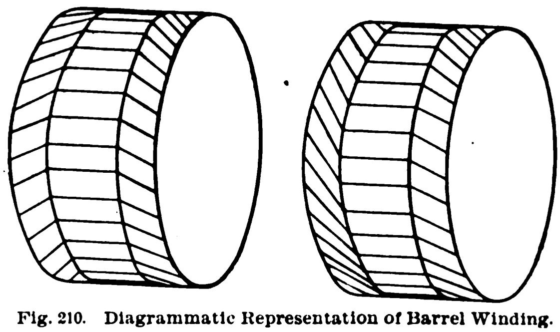


Fig. 210. Diagrammatic Representation of Barrel Winding.

Form-Wound Drum Windings. It was early found that hand-wound drums were both expensive in labor and unsymmetrical electrically. This resulted in the development of schemes for arranging the winding in coils on *formers*, and then laying these *formed coils* in their respective places upon the core-body. The individual sections of the winding are first wound and shaped upon a frame or former, the wire being plain cotton-covered; and each such section is again separately insulated by winding with tape, usually half-lapped; then baked, varnished, and baked again.

Alioth, according to the patent records, was the first to devise

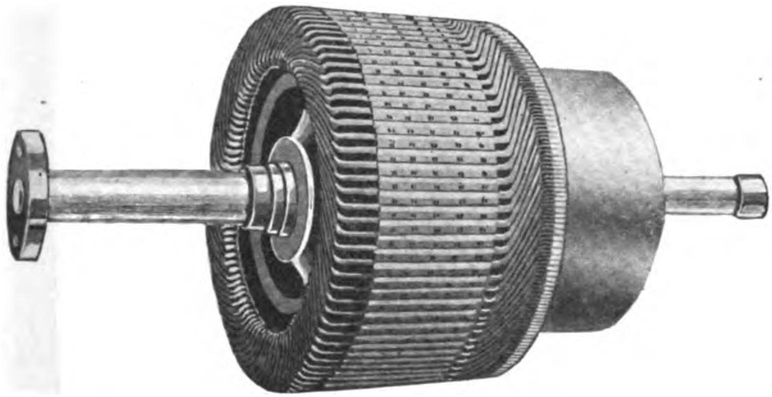


Fig. 211. Armature of Westinghouse Generator—Bastard Winding.

this plan. He was followed by Eickemeyer, who in 1888 patented a method of winding formed coils for evolute windings. This method attained almost universal use during the vogue of the evolute winding; and the first three stages in the construction of such a section are illustrated in Fig. 215; while Fig. 216 illustrates a later type of the

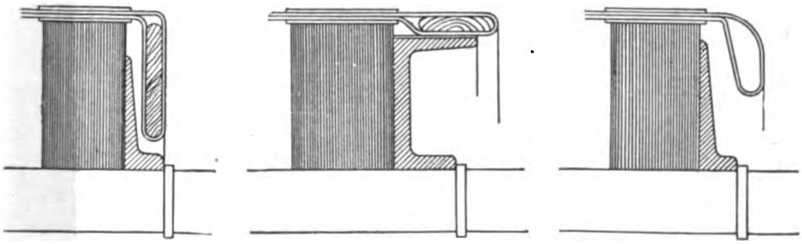


Fig. 212. Evolute-Wound Armature. Fig. 213. Barrel-Wound Armature. Fig. 214. Bastard-Wound Armature.

former, and Fig. 217 a completed armature winding built up of such coils.

What the Eickemeyer coil accomplishes for the evolute winding, may be accomplished for the barrel winding by use of "straight-out" formers. Fig. 218 illustrates a simple former of this type, upon which a coil for a wave winding has been wound and then opened out. Figs. 212, 213, and 214 illustrate the three principal types of formed windings; while Figs. 205, 219, and 220 illustrate successive stages

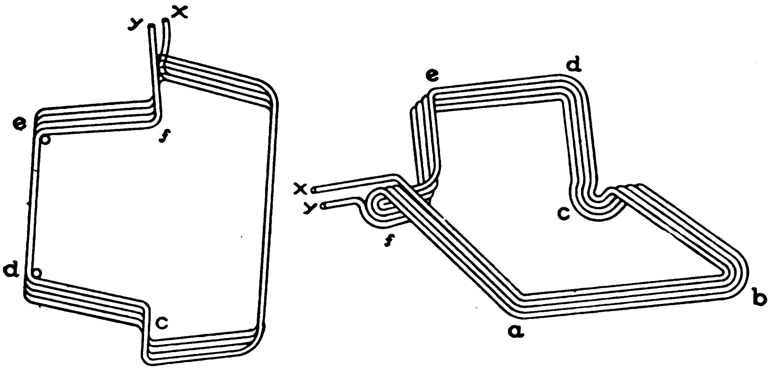


Fig. 215. Eickemeyer Former-Wound Coil, and Same Bent Up.

in the construction of a barrel-wound armature using formed coils.

Ring Windings. These windings are almost always hand-

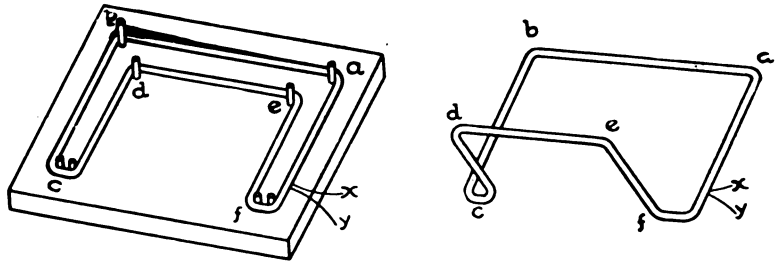


Fig. 216. Eickemeyer Coil on Former and Opened Out.

wound, because the connections at the ends are not nearly so complicated as those of a drum-winding, and the winding is in general

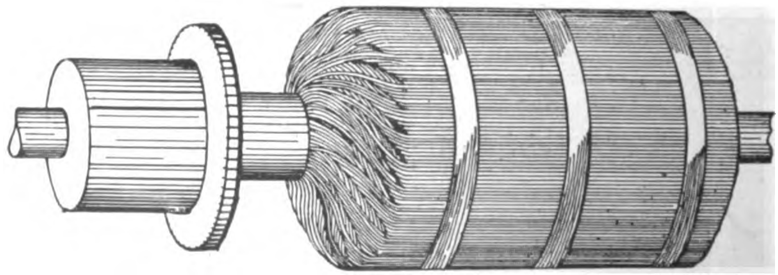


Fig. 217. Eickemeyer Armature, Complete.

easily applied. Nevertheless care must be exercised, since the various sections are usually wound upon the core separately, the ends being left projecting. A careless workman may connect them so that some may generate in opposition, thus reducing the terminal voltage of the machine; hence it is usual to tag the ends of the coils, indicating the beginning and end of each section. Fig. 221 illustrates a partially completed ring-wound armature, the core being made in two parts to facilitate winding.

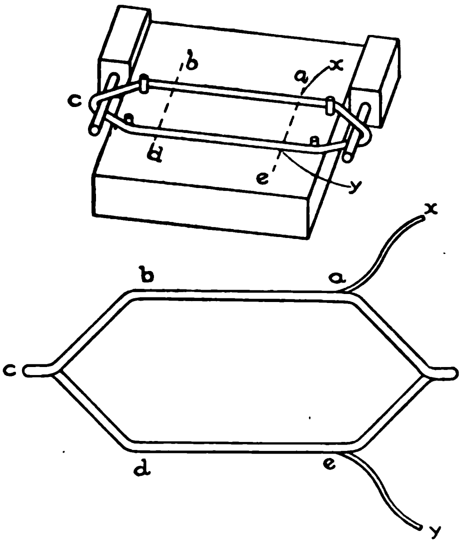


Fig. 218. "Straight-Out" Former-Wound Coil, and Coil Opened Out.

Arrangement of Conductors in Slots. Various methods of arranging the conductors in the slots have been mentioned. The most frequent plan in large continuous-current generators is that of putting them in two layers, either two or more in a slot. Form-wound coils lend themselves to the two-layer arrangement, which, however,

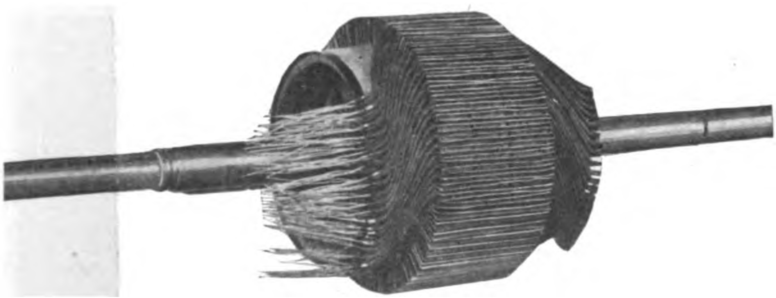


Fig. 219. Armature Body Showing Coils as Placed in Position.

is adapted to be used only with parallel-sided slots. Yet, by grouping the conductors three or four in a slot, as indicated in Fig. 222, or six in a slot, as in Fig. 223, T-shaped teeth can be employed. It must be remembered that, owing to the magnetic shielding of the teeth, the conductors are subjected practically to centrifugal force only. Unless the pole-faces are laminated, the top breadth of the slots

Fig. 220. Generator Armature, Complete.

must be kept very narrow (*i. e.*, not wider than 2½ times the length of the air-gap, because of eddy currents being otherwise generated in the pole-faces); also, if straight teeth are employed, they must be kept very narrow, otherwise the high flux-density required in the teeth for sparkless collection of current will not be attained.

All electric and magnetic considerations point to having

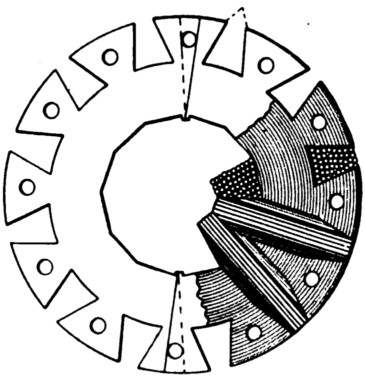


Fig. 221. Partially Completed Ring-Wound Armature.

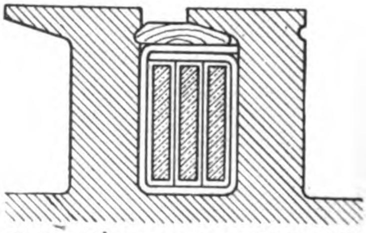


Fig. 222. Three Conductors Grouped in Slot.

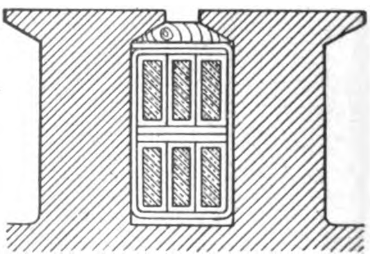


Fig. 223. Six Conductors Grouped in Slot.

the slots and teeth narrow and numerous; while mechanical considerations impose a limit upon the minimum width of teeth. Standard practice for parallel-wound armatures has had to choose a mean, and it is usual to put four conductors in a slot.

CONSTRUCTION OF COMMUTATOR AND BRUSH-RIGGING

Commutator Bars. These are always made of copper; other metals, such as brass, iron, or steel, are not satisfactory, on account of pitting and burning. Rolled copper is preferable, because of its toughness and uniform texture; but in some cases, on account of the shapes necessitated by different methods of connection to the armature conductors and various clamping devices, the segments are either cast or drop-forged, the latter being at present the commercial type.

In order to secure a good fit, the cross-section of the bars should be properly tapered according to the number that go to make up the whole circumference. It is obvious that if the number of segments = 360, each segment plus its insulation (on one side) should have a taper of 1 degree; while if $K = 36$, the taper would be 10 degrees. It is not practicable, however, to use mica insulation that has not parallel faces; hence the segment is tapered, and any defect in the taper of the latter cannot be made good with insulation. It is found, however, that when the segments exceed 150, bars of the same taper can be used in constructing a commutator having either two more or two less than the designed number.

Insulation. It is needful to have good insulation between each bar and its neighbor, and especially good insulation between the bars and the sleeve or hub around which they are mounted, as well as between the bars and the clamping devices that hold them in place, since the voltage between bars is not so great as that between the bars and the metal-work of the machine. It is essential that the insulating material be such that it will not absorb oil or moisture; hence asbestos, plaster, and vulcanized fibre are inadmissible. The end insulation rings may be of micanite, or, if for low voltage, of that preparation of paper pulp known as *press-board* or *press-spahn*. The conical rings are usually built of micanite moulded under pressure while hot. Fig. 224 illustrates such an end-ring, cut away to show its section.

Commutators using air-gaps between the segments as insulation have been tried; but, excepting in the case of arc-lighting machines where the segments are few in number and the air-gap large, they have not proven successful, owing to trouble in keeping the gaps free from metallic dust.

It is of importance that the mica selected for insulating the bars from one another should be soft enough to wear away at the same rate as the copper bars, and not project above the segments. Amber mica, soft and of rather cloudy color, is preferred to the harder clear white or red Indian variety. The usual thicknesses are as given in Table XIII.

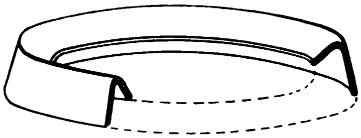


Fig. 224. End Insulation Ring of Commutator.

Commutator Construction. For small machines a common construction is that shown in Fig. 225. The commutator segments

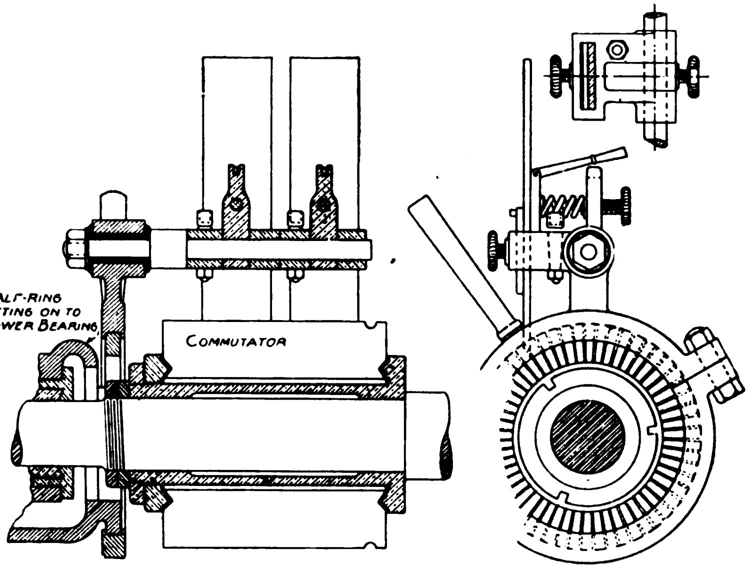


Fig. 225. Common Method of Commutator Construction for Small Machines.

TABLE XIII

Thickness of Commutator Insulation

Voltage of Machine	Thickness of Mica	
	Between neighboring segments	Between segments and shell, and between segments and clamping device
Less than 150	0.020 to 0.03 in.	0.06 to 0.10 in.
Less than 300	0.025 to 0.04 in.	0.08 to 0.13 in.
Less than 1,000	0.04 to 0.06 in.	0.10 to 0.16 in.

are secured between a bushing or hub and a clamping ring, the latter being mounted on the hub, and forced to grip the bars by means of a nut on the hub or by bolts passing through the ring and hub, as in Fig. 226. The ends of the bars are beveled so that the ring and bushing draw the segments closer together on tightening.

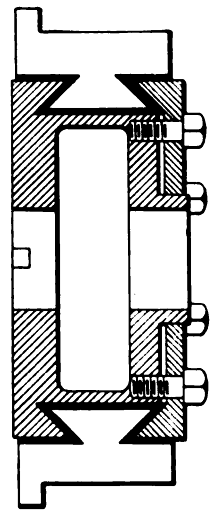


Fig. 226. Construction of Commutator of Medium Size.

The hub, in small machines, is usually of cast iron keyed to the shaft; but in large machines, the commutator is built upon a strong flange-like support or shell, bolted to the armature spider, as indicated in Fig. 208 and Fig. 227, or mounted on a separate spider secured to the shaft, as in Fig. 228.

When drawn copper strip is used, the design should be such that the available surface for the brushes takes up nearly the whole length of the bar, and the beveled ends should be as simple as possible. With drop-forged segments, this is not so important.

In building commutators it is usual to assemble the bars to the proper number, with the interposed pieces of mica, clamping them temporarily around the outside with a strong iron clamp, or forcing them into an external steel ring under hydraulic pressure. They are then put into a lathe, and the interior surface is bored out, after which the ends are turned up, with the angular hollows to receive the clamping pieces. The whole is then mounted with proper insulation, upon the sleeve, and the clamping end-pieces are screwed up. It is then heated, and the clamps still further tightened up, after which the temporary clamp or ring is removed and the external surface turned up.

Commutator Risers. Connection is made with the armature conductors by means of radial strips or wires sometimes called *risers*, which are inserted into a cut at the corner of each bar and firmly held there by a screw clamp and solder. Figs. 229, 230, and 231 illustrate various modes of making connection to the commutator bar.

These risers are connected to the armature winding in several different ways, as indicated in Fig. 232.

In some evolute windings no risers are needed, the ends of the evolute being fastened to the commutator as indicated in Fig. 204. Similarly, in the case of barrel-wound armatures, no risers are needed if the commutator diameter is very nearly that of the armature.

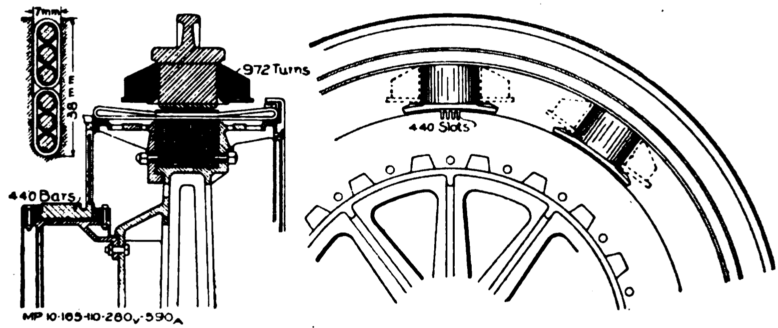


Fig. 227. Ten-Pole Lighting Generator of the Oerlikon Company. Commutator support bolted to armature spider.

Brushes and Brush-Rigging. As we have seen on page 42, carbon brushes are almost the only type that are now considered. Their shape depends upon the type of brush-holder selected, and upon whether the brushes are applied to the commutator semi-tangentially or radially. Fig. 233 illustrates various shapes.

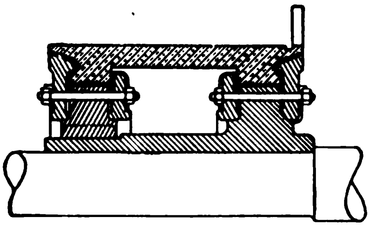


Fig. 228. Commutator for Large Currents.

The mechanism for holding the brushes must fulfil the following requirements:

1. The brushes must be held firmly against the commutator, while allowing them to follow any irregularity in the contour of the latter without jumping away.

2. The mechanism must permit of the brushes being withdrawn while the commutator is rotating, and must feed them forward as required.

3. Spring pressure must be adjustable, *and the spring must not carry current.*

4. The springs must not have too great inertia, in order that they may readily fulfil condition 1, in regard to following the commutator.

5. Insulation must be very thorough.

6. The mechanism must be so arranged as to permit of the position of the brushes being shifted.

7. All parts must be firm and strong, so as not to permit of the brushes chattering as the result of vibration while running.

The commercial forms of holders for carbon brushes may be classified under three types:

1. Hinged structures.
2. Parallel spring holders.
3. Reaction holders.

Fig. 234 illustrates a hinged brush-holder, and an arm holding several. The carbon moves in a light frame, being held against the commutator by a spring whose tension may be adjusted. Connection between the brush and the holder is made by means of a flexible lead, tinned and laid in a slot in the upper part of the carbon. A metal cap placed over the top and sweated in place makes a permanent contact. This is shown by the two illustrations of the brush.

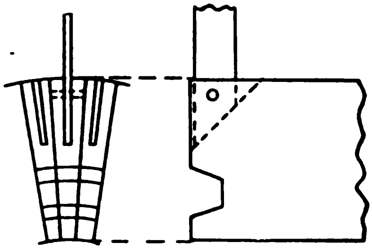


Fig. 229.

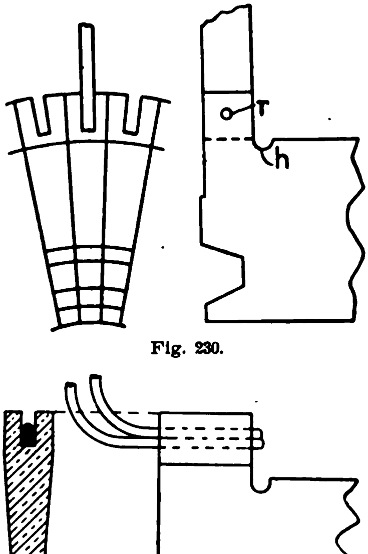


Fig. 230.

Fig. 231.

Methods of Connecting Commutator Risers to Commutator Bars.

Fig. 235 illustrates a parallel-movement type, also depicted in Fig. 144, on page 126. The brush is held firmly in the holder by a clamping screw, the whole arrangement then being pressed against the commutator by the spring, whose tension may be varied by means of the adjusting screw. Connection is made between the brush and the stationary part of the holder, by means of two sets of rolled-copper leaves which at the same time act as flexible joints.

In Fig. 236 is illustrated a reaction type of brush-holder. The brush C is pressed against the commutator by the adjustable spring L, the holder B being secured firmly to the rocker-arm P by means of the set-screw *g*. The brush is furnished with a dovetail-shaped projection along its entire inner edge, this projection fitting into a groove in the face of the holder *B*.

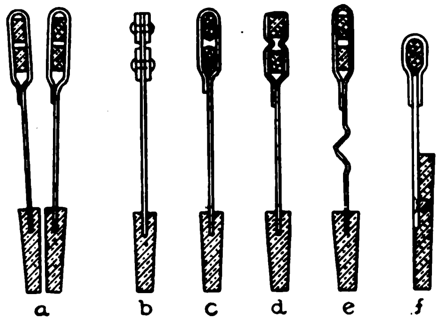


Fig. 232 Methods of Connecting Commutator Risers to Armature Winding.

Rockers and Rocker-Arms. For small machines, the rocker is usually clamped upon a shoulder turned upon the bearing pedestal as indicated in Fig. 225. For large multipolar generators, the rocker arms—that is, the rods on which the brush-holders are held—are fixed at equidistant points around a cast-iron rocker-ring, which is itself supported on brackets projecting from the magnet-yoke. This construction is indicated in Fig. 237.

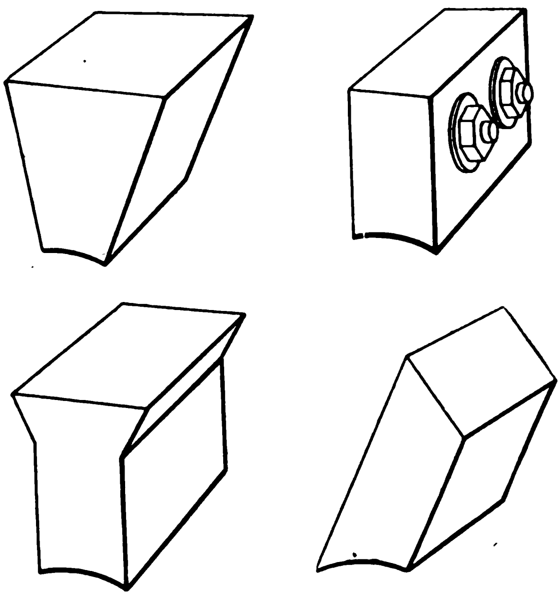


Fig. 233. Various Forms of Carbon Brushes.

Sweating Lugs and Terminal Thimbles. Among the details of brush-gear are the contrivances for bringing the current to and from the brush-pillars or rocker-rings. This is usually accomplished by the use of large, flexible connections made of stranded copper wire well insulated. It is necessary that all such flexible leads should make good contact at their ends to solid metallic pieces. On the rocker are usually provided sweating lugs (Fig. 238) of copper or brass, into which the ends of the flexible cable are sweated. Their other ends are then sweated

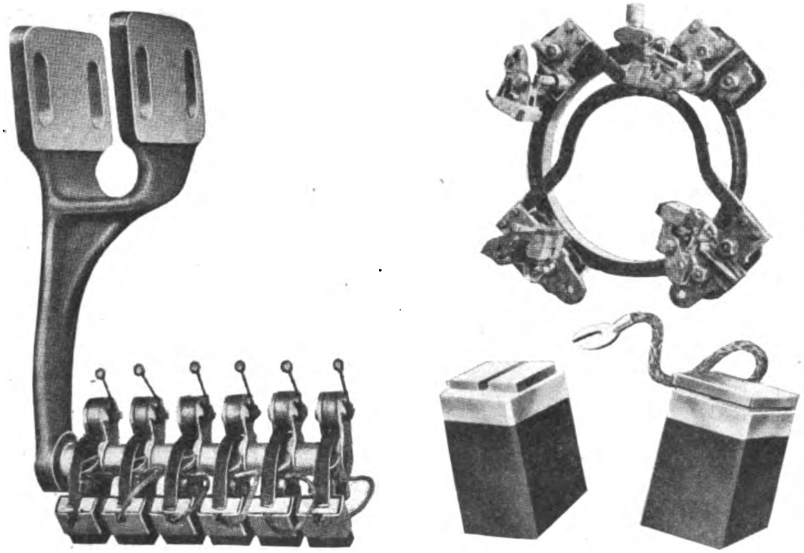


Fig. 234. Brush-Rigging and Brushes.

into suitable thimbles or sockets on a terminal board (Fig. 239) which is attached to some convenient point on the magnet-frame.

CONSTRUCTION OF MECHANICAL PARTS

Bearings and Pedestals. Bearings for generators are always made divided, so that the armature can be lifted into and out of its bed, and usually with steps of brass or gun-metal seated in an appropriate pedestal. Often the pedestal is made in two parts bolted together, the joint occurring at the level of the under side of the armature to admit of the latter being withdrawn, and

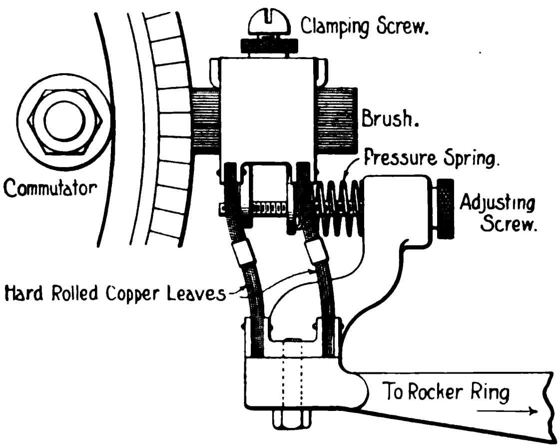


Fig. 235. Parallel-Movement Type of Brush-Holder.

affording a resting point during removal. Where long bearings are used, they are sometimes made of cast iron with a lining of Bab-

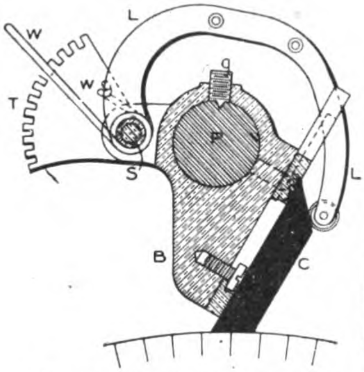


Fig. 236. Reaction Type of Brush-Holder.

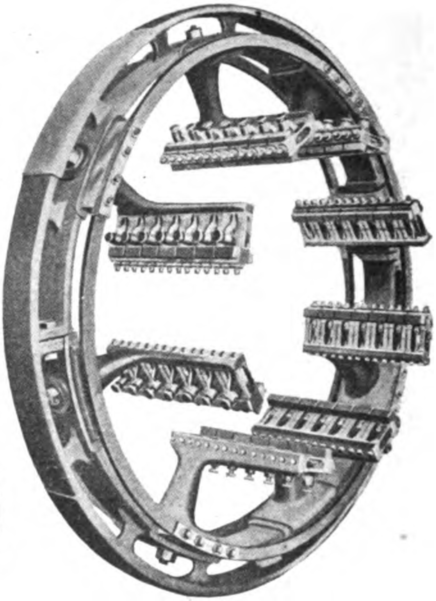


Fig. 237. Rocker-Ring and Brush-Gear. Crocker-Wheeler Company.

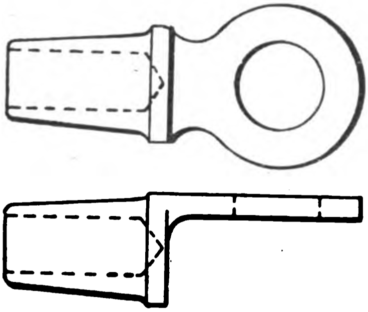


Fig. 238. Sweating Lug.

bitt or similar soft metal, such anti-friction metal being cast in hollows in the cast-iron step prepared for that purpose. In the case of generators whose armatures are mounted on the end of the engine shaft for direct driving, only the outboard bearing (if any) is provided by the generator manufacturer, the other being part of the engine; while in some cases the armature is overhung and requires no outer bearing, as in Fig. 240.

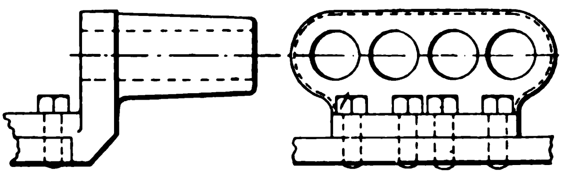


Fig. 239. Sweating Thimbles on Terminal Board.

In cases where the bearing is very long, it is necessary that the bearing be made self-aligning, by providing it with an enlarged central portion of spherical shape (Fig. 241), held in a spherical seat formed in the pedestal by turning, milling, or by casting Babbitt or other fusible metal around it, thus allowing the bearing to adjust itself to the exact direction of the shaft. The upper half of the box can be taken off to facilitate renewal, etc. Fig. 242 also illustrates a bearing of this type; while Fig. 243 illustrates a simple bearing showing the division of the pedestal.

Ball-bearings have recently been applied to generators and motors—particularly the latter, on account of their low static friction. Where space and low friction losses are essential, and where there is little lateral dragging due to belts, these bearings have given excellent results.

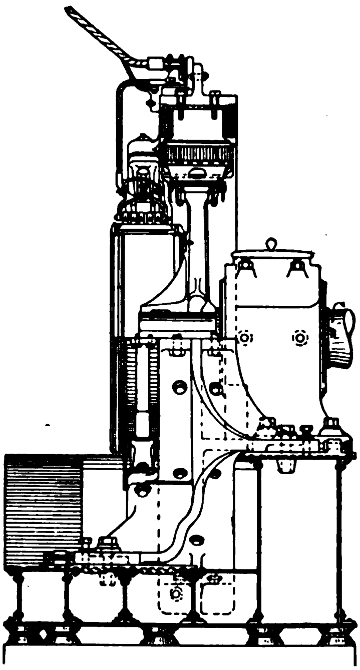


Fig. 240. Direct-Connected Generator with Overhung Armature.

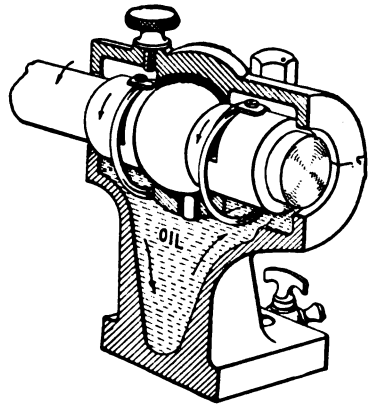
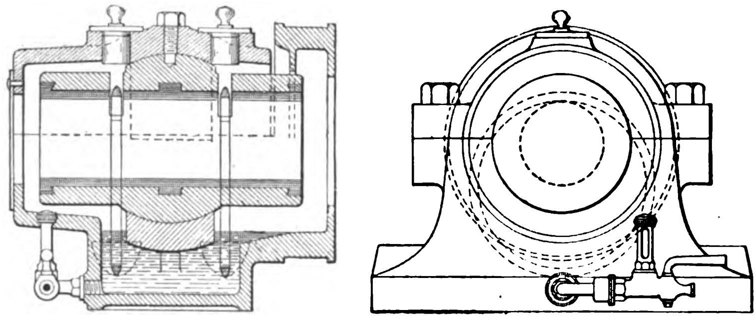


Fig. 241. Self-Oiling Bearing.

Figs. 244 and 245 show ball-bearing mountings for horizontal and vertical motors, respectively. The section at the left of Fig. 244 is for the pulley end, while that at the right is for the commutator end. Fig. 245 shows a form of mounting for vertical motors. It is differentiated from the horizontal type, simply by the introduction of devices for keeping sufficient lubricant in the bearing to permit the balls always to drop through it. Fig. 246 illustrates a side view of a portion of one of these bearings, showing the steel balls with elastic separators between them. The separators contain felt plugs which incidentally store up lubricant to guard the bearings for a time against neglect.



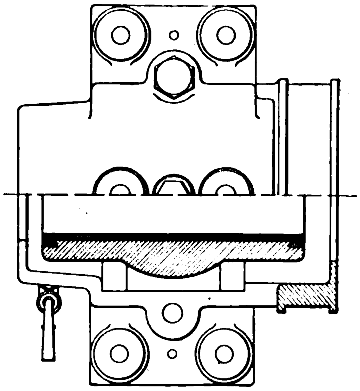


Fig. 242. Self-Aligning Spherical Bearing.

An advantage that attends the use of these bearings is that the feature of non-wear permits making them oil-proof and dust-proof without the usual added complications.

Lubricators. Provision must be made for supplying the bearings with oil or grease; and for this purpose it is usual to provide an oil-well in the hollow casting of the pedestals, into which the oil drains from the brasses. Self-lubricating bearings are now almost uni-

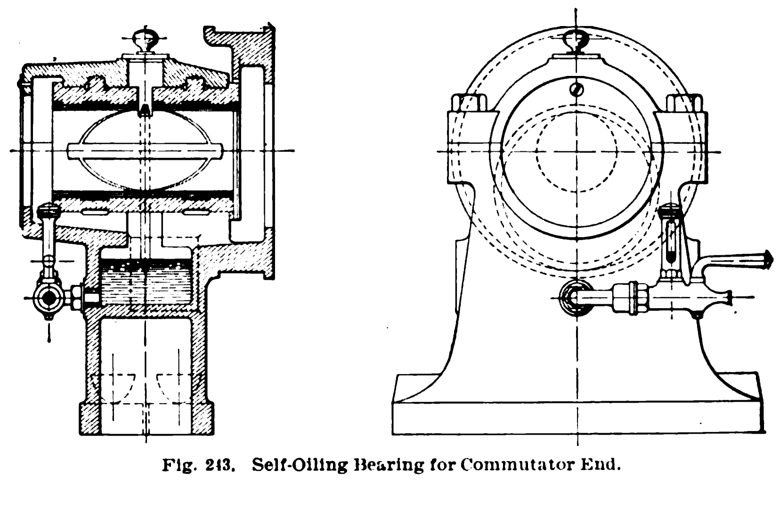


Fig. 243. Self-Oiling Bearing for Commutator End.

versal in the ordinary types of generators. Fig. 241 illustrates one of this type. The rings here shown revolve with the shaft, and feed the latter with oil, which they continuously bring up from the reservoir below. The dirt settles to the bottom and the upper portion of the oil remains clean for a long period, after which it is drawn off through the spigot, and a fresh supply poured in through openings provided in the top. The latter are often located directly over the slots in which the rings are placed, so that the bearings can be lubri-

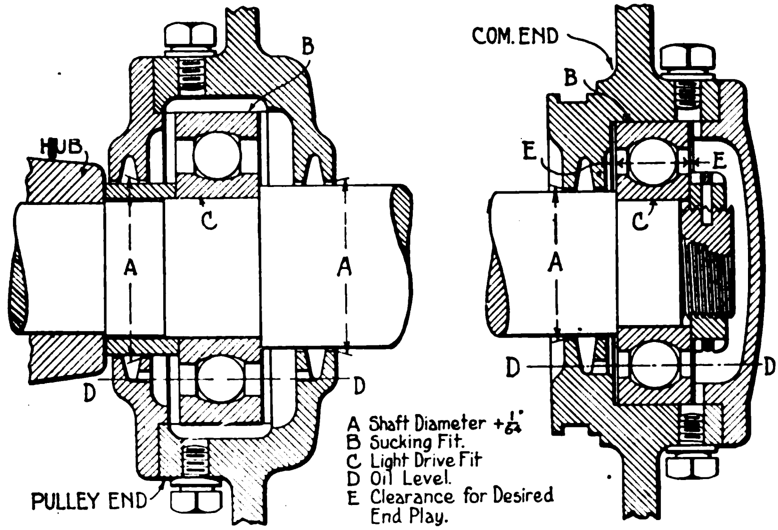
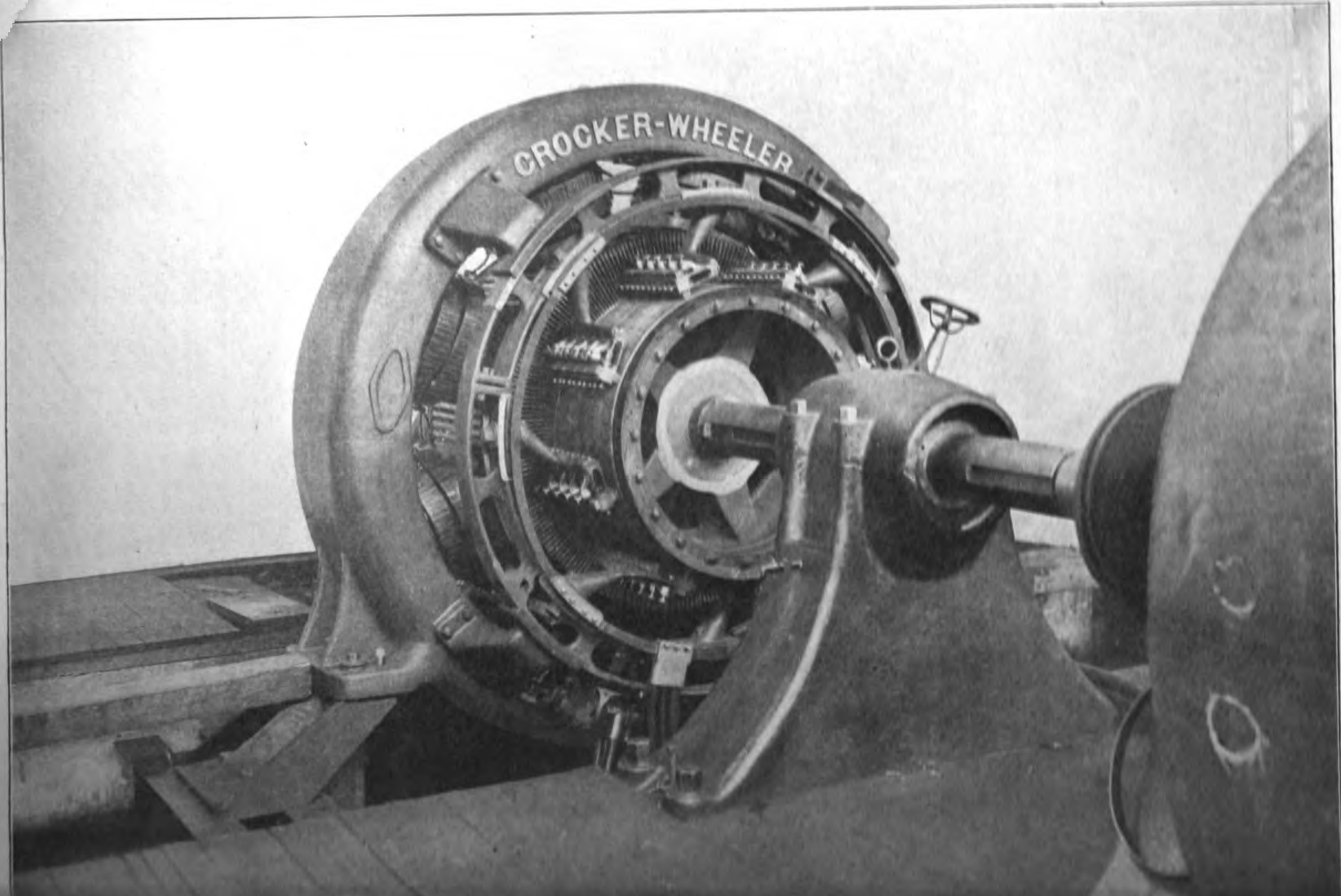


Fig. 244. Ball-Bearing Mounting for Horizontal Motor-Shaft.

cated directly by means of an oil-cup, if the rings fail to act or the reservoir becomes exhausted.

Bed-Plates. In most cases a generator is supplied with a cast-iron base or bed-plate which supports the bearings and magnet-yoke. It consists of a simple box, open at the bottom in order to give stiffness without great weight. It must be sufficiently rigid to withstand any reasonable strain without bending.

In belt-connected machines the iron base usually rests upon rails bolted to the foundations, the base being arranged to slide back and forth upon the same in order to regulate the tension of the belt, by means of set-screws. A direct-connected generator of small or medium size is usually bolted to an extension cast-iron base or sub-base of the engine. In some cases a generator and engine are coupled


CROCKER-WHEELER

together, each being complete in itself and having its own base. Very large direct-connected generators and engines are set on separate foundations.

DESIGN OF CONTINUOUS-CURRENT GENERATORS

The design of a generator may be considered in the light of a problem in which it is required to produce a machine which shall operate satisfactorily at all loads from no load to 50 per cent overload, which shall be efficient, and conform to the conditions of prescribed speed, voltage, and current output. This involves the theoretical and practical features already considered. In order to guide the student, it has been thought advisable to follow through the complete design of a particular modern generator. No hard-and-fast rules can be given covering all cases which come up, so that the tables given below should be used only as guides, each machine requiring a separate solution of the general problem.

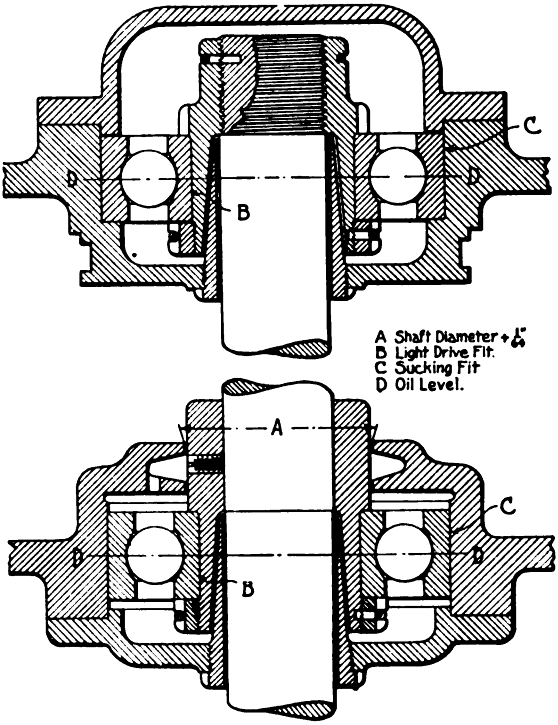


Fig. 245. Ball-Bearing Mounting for Vertical Motor-Shaft.

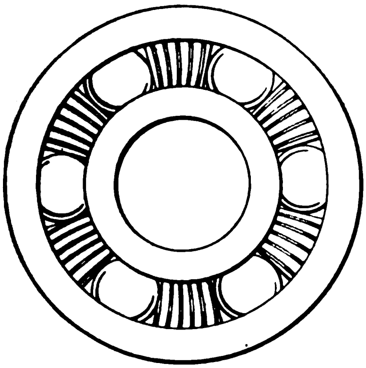


Fig. 246. Side View of Ball-Bearing Mounting, Showing Steel Balls with Elastic Separators between them.

Specifications. To design a continuous-current generator, it is

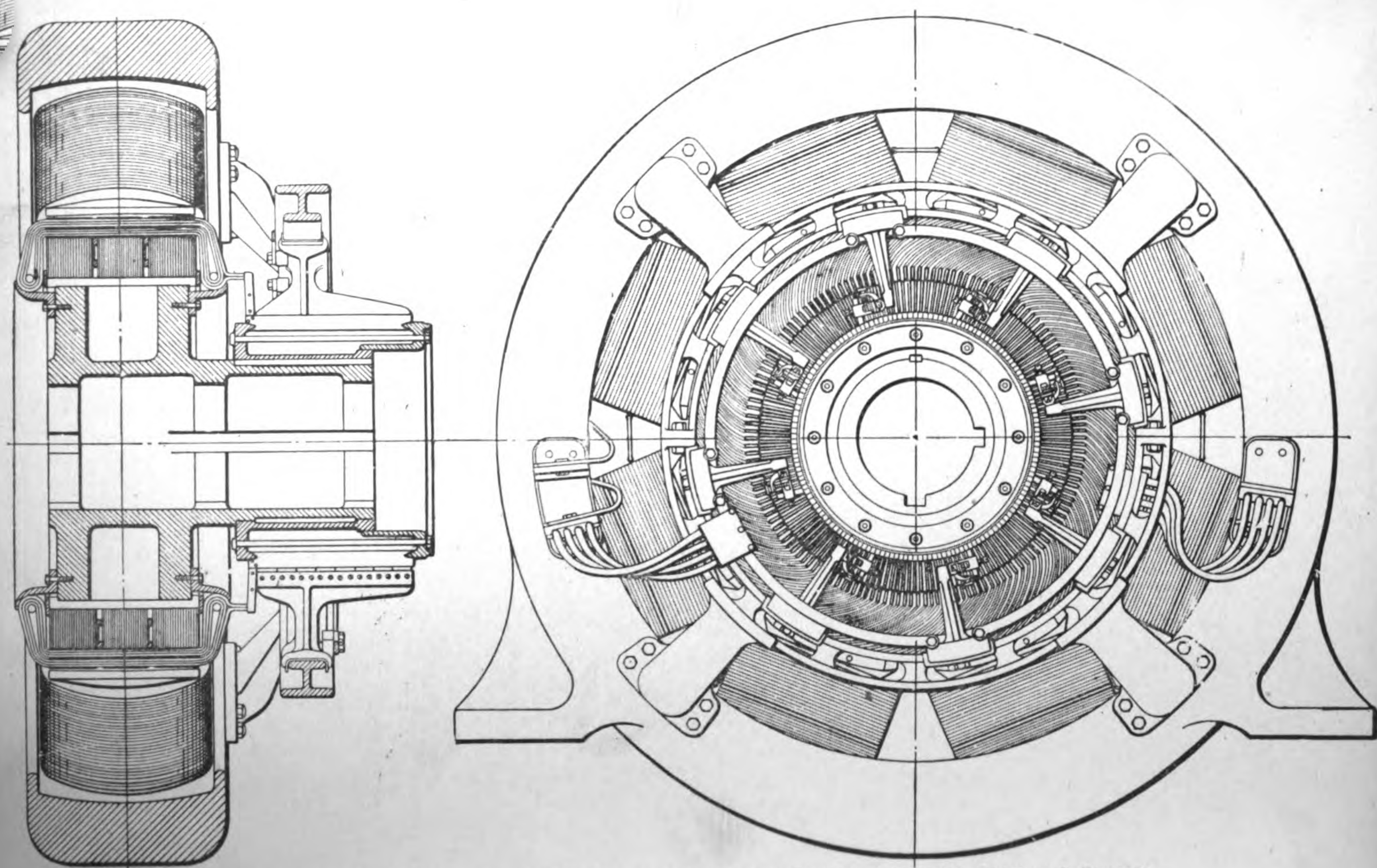


Fig. 248. Front and Side Elevation of Columbia University Dynamo, Size 280. Crocker-Wheeler Electric Company.

sufficient to be given the capacity of the machine in kilowatts, the terminal voltage at rated load (also at no load, if compound-wound), and the speed of rotation of the armature, although Table XIV will supply the latter quantity, if absent. Let us assume for the purposes of this design:

Kw. output	150
Terminal volts, rated load	250
Terminal volts, no load	240
Armature r. p. m	225

The generator is direct-connected to the engine driving it, and it must be compound-wound in order that its terminal voltage at rated load shall be 10 volts higher than at no-load.

TABLE XIV

Relation of Output to Speed of Direct-Current Generators

Capacity (in kw.)	Direct-Connected Generators r. p. m.	Low-Speed Belted Generators r. p. m.	High-Speed Belted Generators r. p. m.
1	....	700 to 1,400	1,400 to 2,800
2	....	670 to 1,250	1,250 to 2,450
5	400 to 800	640 to 1,170	1,170 to 2,200
10	340 to 480	610 to 1,050	1,050 to 1,950
15	305 to 415	580 to 960	960 to 1,770
20	270 to 385	550 to 900	900 to 1,650
30	230 to 355	510 to 800	800 to 1,450
40	200 to 340	480 to 740	740 to 1,320
60	175 to 325	460 to 660	660 to 1,110
80	140 to 310	450 to 620	620 to 975
100	120 to 290	440 to 590	590 to 850
150	110 to 250	420 to 540	540 to 700
200	100 to 230	395 to 495	495 to 625
250	92 to 205	380 to 460	460 to 570
300	86 to 180	360 to 435	435 to 520
350	80 to 160	345 to 410	410 to 475
400	76 to 140	325 to 380	380 to 440
500	70 to 124	295 to 335	335 to 380
600	66 to 112	275 to 300	300 to 325
700	62 to 105	....	....
800	60 to 100	....	....
1,000	59 to 92	....	....
1,200	58 to 88	....	....
1,400	56 to 86	....	....
1,600	55 to 84	....	....

Since the generator is rated at 150 kw. at 250 volts, the rated load current will be:

$$\frac{150 \times 1{,}000}{250} = 600 \text{ amperes.}$$

Number of Poles. We must next decide upon the number of poles. This may be fixed either with a view to keeping down the iron losses in the armature, or to keeping the current collected per brush set low. In the former case, the frequency of magnetic reversal should not exceed 20 per second in shunt-wound machines, and 25 per second in compound-wound machines. In the second case, in order that the current may be commutated sparklessly, not more than 200 amperes ought be collected by each brush set; that is, the current output of the machine, divided by the number of poles, should not exceed 100.

From the first criterion, we find (since the magnetism of any part of the armature core undergoes a reversal as it passes each pole), for the number of poles:

$$p \geqq \frac{25 \times 60}{\text{r.p.m.}} = \frac{25 \times 60}{225} = 7$$
$$\geqq 7.$$

And from the second criterion:

$$p \geqq \frac{600}{100} \geqq 6.$$

To be quite sure of avoiding trouble as to sparking, and since an odd number of poles cannot be employed, let us take 8 poles, which, as we see from Table XV, is good practice for this size and type of machine.

TABLE XV

Relation of Capacity and Type to Number of Poles

Type	Output in Kilowatts	Number of Poles
Direct-Connected	0 to 2,030	4
	15 to 400	6
	90 to 400	8
	200 to 900	10
	300 to 1,800	12
	600 to 2,200	14
	800 to 2,500	16
Low-Speed, Belted	0 to 600	4
	15 to 600	6
High-Speed, Belted	0 to 20	2
	0 to 200	4
	60 to 800	6

Diameter and Length of Armature. The diameter of armature is limited by the peripheral speed allowable (Table XVI). It is also

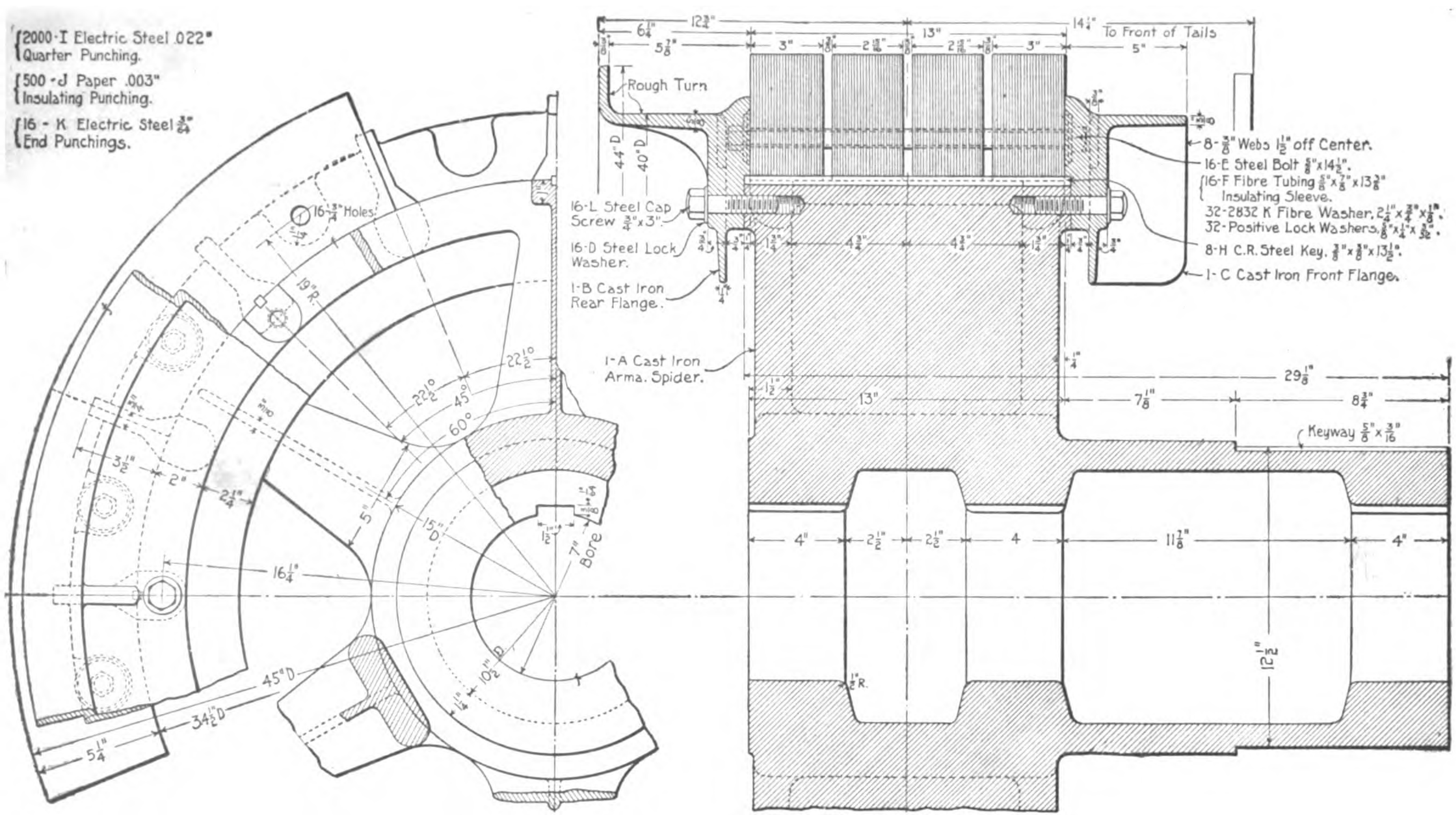


Fig. 249. Details of Armature and Spider of Generator whose Construction is Described in Text.

dependent upon the size of the magnet-poles and their number, the size, number, and arrangement of the armature conductors, and the output of the machine, the length being also a function of these quantities. Various empirical formulæ have been proposed for computing the length and diameter of armatures, but they all contain constants whose values must be learned by experience.

TABLE XVI

Peripheral Velocities of Direct-Current Armatures

Type of Generators	Peripheral Speeds in Feet per Minute		
	Minimum	Mean	Maximum
Bipolar high-speed, belted	2,000	3,000	3,500
Multipolar high-speed, belted	3,500	4,000	5,500
Multipolar slow-speed, belted	2,000	2,800	3,500
Direct-connected	1,800	2,400	3,300

For this reason it has been thought more advisable to append tables giving current practice in regard to the diameters and lengths of armatures, trial values being selected from these.

TABLE XVII

Diameters of Belted Multipolar Armatures *

Capacity (kilowatts)	Outside Diameter (in inches)			Ratio of Length to Diameter		
	Minimum	Mean	Maximum	Minimum	Mean	Maximum
1	4	7	10	0.36	0.65	0.80
2	5	8	11	0.36	0.64	0.80
5	6	9	12	0.36	0.63	0.80
10	8	11	15	0.35	0.62	0.80
20	11	14	19	0.34	0.59	0.80
30	14	17	23	0.33	0.56	0.75
50	17	21	29	0.31	0.52	0.71
75	20	25	35	0.28	0.48	0.67
100	22	29	40	0.26	0.44	0.63
150	26	34	46	0.23	0.40	0.58
200	30	38	51	0.22	0.38	0.55
300	34	44	60	0.21	0.36	0.52
400	38	49	65	0.20	0.34	0.50
500	40	54	66	0.20	0.32	0.49
600	43	57	68	0.19	0.30	0.48

* It is to be noted that for any given output and speed, the product of the diameter by the length of the armature is practically a constant.

In the design which we are considering, let us assume a peripheral velocity of say 2,650 feet per minute. At the required armature rotative speed of 225 r. p. m., this will give us a diameter of

$$\frac{2,650 \times 12}{225 \times \pi} = 45 \text{ in.},$$

which we see by Table XVIII to be about right. Assuming a length 29 per cent of the diameter, we get 45 in. × 0.29 = 13 in.

TABLE XVIII

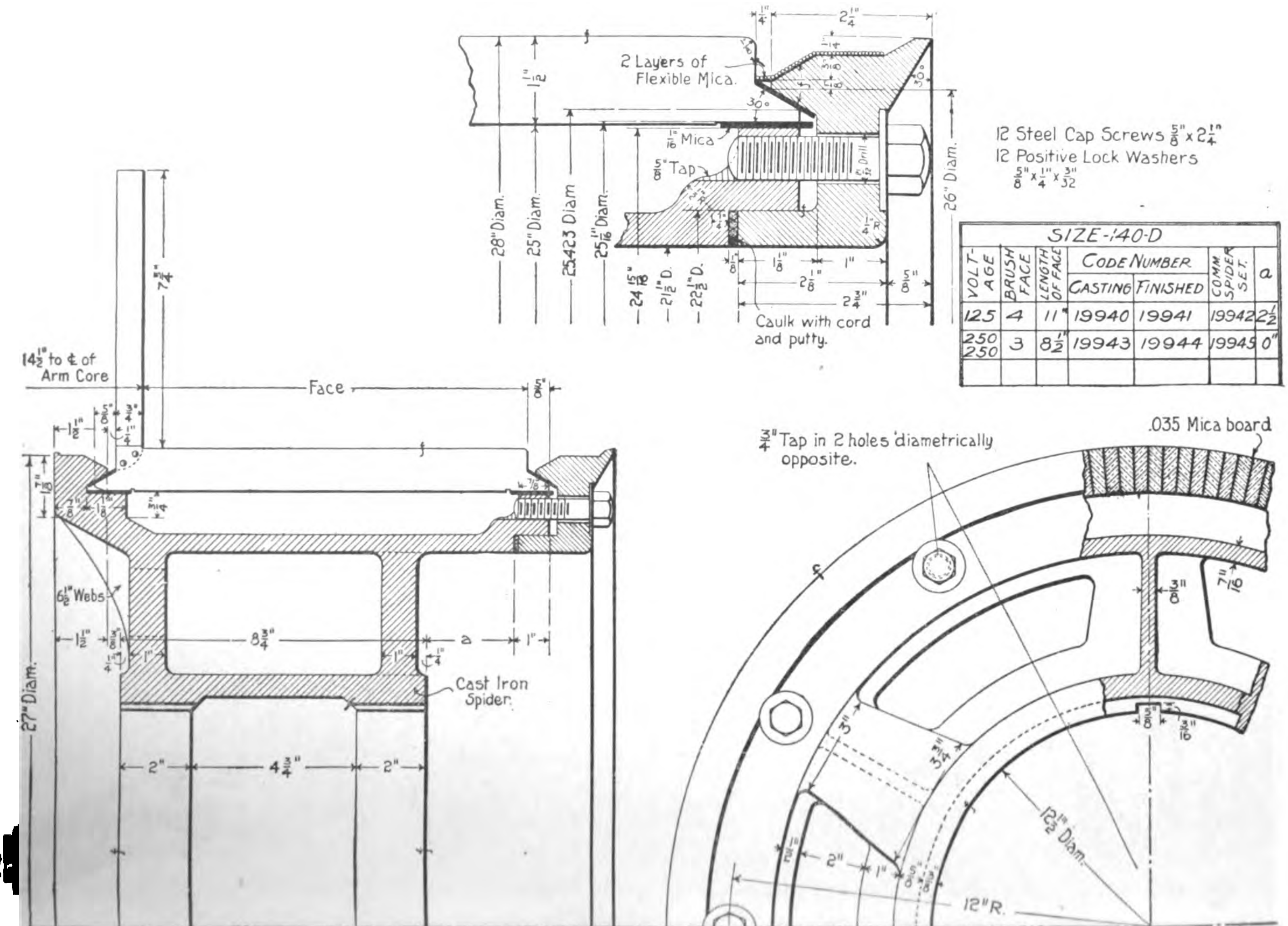
Diameters of Direct-Connected Armatures *

Capacity (kilo-watts)	Outside Diameter (in inches)			Ratio of Length to Diameter		
	Minimum	Mean	Maximum	Minimum	Mean	Maximum
5	15	20	25	0.15	0.25	0.50
15	17	22	27	0.15	0.25	0.48
25	18	24	29	0.15	0.25	0.46
50	21	27	34	0.15	0.25	0.44
75	24	30	39	0.15	0.25	0.42
100	26	34	44	0.15	0.25	0.40
150	31	41	52	0.14	0.24	0.38
200	35	47	61	0.14	0.23	0.36
300	44	58	77	0.14	0.22	0.34
400	52	69	89	0.14	0.21	0.32
500	60	80	100	0.13	0.20	0.30
600	67	87	108	0.13	0.19	0.28
700	74	95	115	0.13	0.18	0.26
800	80	100	121	0.13	0.17	0.24
900	87	107	127	0.12	0.16	0.23
1,000	92	112	131	0.12	0.16	0.22
1,200	100	120	140	0.12	0.15	0.21
1,400	116	130	148	0.11	0.15	0.20
1,600	122	133	152	0.11	0.14	0.19

Magnetic Flux per Pole. After deciding upon the number of poles (p), the diameter (d), and the length (l) of the armature, we may obtain a trial value for ϕ, the magnetic flux per pole entering or leaving the armature, by assuming proper values for the magnetic flux-density in the air-gap and the surface of the armature covered by the poles. The flux-density in the air-gap varies from 40,000 lines to 55,000 lines per square inch (Table IV), while a usual value for the fraction of the armature covered by the poles is $\Psi = 0.75$. We may then write:

$$\phi = B_g \times d \times \pi \times l \times \Psi \div p.$$

*It is to be noted that for any given output and speed, the product of the diameter by the length of the armature is practically a constant.



SIZE-140-D						
VOLT-AGE	BRUSH FACE	LENGTH OF FACE	CODE NUMBER CASTING	CODE NUMBER FINISHED	COMM SPIDER SET	a
125	4	11"	19940	19941	19942	2 1/2
250 250	3	8 1/2"	19943	19944	19945	0"

Fig. 260. Commutator Design of Generator whose Construction is Described in Text.

Assuming, in our case, $\Psi = 0.72$, and $B_g = 46{,}000$, we have:

$$\phi = 46{,}000 \times 45 \times 13 \times 3.1416 \times 0.72 \div 8 = 7{,}600{,}000$$

as the assumed flux entering the armature. The value thus found will require adjustment after Z has been determined, the fundamental equation of dynamo-electric machines being used for this purpose. From page 62, this is:

$$(\text{Average})\ E = \frac{Z \times \text{r.p.m.} \times \phi \times p}{60 \times 10^8 \times c}.$$

That is,

$$\phi = \frac{E \times c \times 60 \times 10^8}{Z \times p \times \text{r.p.m.}}.$$

Number of Armature Conductors. Having obtained a trial value for the magnetic flux per pole, we can compute the corresponding Z from the preceding formula, adjusting ϕ and Z until the latter comes out properly for the winding selected (see Table VI, page 112). In our case,

$$Z = \frac{263.5^* \times 8 \times 10^8 \times 60}{225 \times 7{,}600{,}000 \times 8} = 924 \text{ (say 928 as a trial number).}$$

Number of Commutator Segments. This is of course equal to the number of conductors divided by 2, 4, 6, etc., although in all but the smallest modern machines, $K = Z \div 2$. The considerations which fix the number have been discussed on page 122. Hence we have:

$$K = 928 \div 2 = 464 \text{ commutator segments.}$$

Size of Commutator. As a rule it is well to make the diameter of the commutator at least $\frac{3}{4}$ of that of the armature. For large machines, it should be from 12 inches to 18 inches smaller than the armature. Using this as a trial value, divide the periphery by K, to see whether the width allowed per segment is suitable. This should be about 0.2 to 0.8 inch, inclusive of insulation between segments. The necessary provisional length may be found by assuming that the (carbon) brushes will cover from 3 to $3\frac{1}{2}$ segments, and that about 40 amperes may be collected by each square inch of brush-contact area. A margin should be added to this, the working face (see also page 123). The result so obtained should be checked later when the watts lost in commutator heating have been estimated, by seeing whether the surface of the commutator is sufficiently large to dissipate the heat generated, without undue temperature-rise (see page 126). A commutator ought to have

*Note.—Corrected to provide for lost volts (see pages 72 and 214 and Table XIII, page 189).

about 0.6 square inch of peripheral surface per watt to be dissipated.

Having decided in our case that the commutator shall have about 464 segments, and as each segment plus the necessary insulation cannot be less than about 0.2 inch wide at the face of the armature, the periphery of the commutator must be at least $464 \times 0.2 = 92.8$ inches long. That is, the diameter should be about $92.8 \div \pi = 29.5$ inches.

Allowing 40 amperes per square inch of brush contact, and assuming that a brush covers 3 segments, we have for the net length of the commutator (parallel to the shaft):

$$l_{com} = \frac{150}{3 \times 0.2 \times 40} = 6.25 \text{ in.},$$

each brush set collecting 150 amperes, as there are 4 pairs of brush sets and the total current output of the machine at rated load is 600 amperes. Adding to the length thus obtained $\frac{1}{3}$ as a margin, we have as the length of the commutator:

$$6.25\ (1 + 0.33) = 8.3 \text{ inches (say } 8\tfrac{1}{4} \text{ inches).}$$

Commutator Brushes. Allowing 40 amperes per square inch of brush contact, the area of all the positive (or negative) brushes = 15 sq. in.—*i.e.*, $3\frac{3}{4}$ sq. in. per set. Let us have 3 brushes 3 inches long, $2\frac{1}{4}$ inches wide, and $\frac{1}{2}$ inch thick per set. From the curve of Fig. 141, page 124, brush-contact drop = 1.5 volts.

Style of Armature Winding. We must now settle upon the type of armature winding to be employed. Modern practice tends toward preserving the utmost simplicity, that is to say, it favors the lap-wound drum executed as a barrel winding so as to have ample cooling surface, the conductors being in two layers so as to take advantage of form winding, and placing two, four, six, or eight conductors in each slot.

Choosing in our case a simplex, singly re-entrant, lap-wound drum winding, the maximum winding pitch will be $y_f = 115$; $y_b = -113$, since we must span about $\frac{1}{8}$ of the periphery, there being eight poles (compare page 112, Table VI). As we have assumed a pole span of about 0.75, the minimum values would be about $y_f = 87$; $y_b = -85$. Assuming that the conductors are placed 8 in each slot, there will be about 14 slots to the pole-pitch, requiring the coils to span 14 teeth if we select the largest possible value of the winding-pitch, and 10 teeth if we select the smallest value. Suppose, therefore, that we span over 13 teeth, in which case we shall have $y_f = 107$; $y_b = -105$.

Apportionment of Losses and Checking Size of Armature. We must apportion the losses in order to check up our previous computations in regard to permissible heating limits. Assuming an efficiency of 92 per cent (Table XII), we may allow 2.2 per cent for armature copper loss, 1.6 per cent for armature iron loss, 2.75 per cent for excitation loss, 1.05 per cent for commutator loss, and 0.4 per cent for friction loss, as suggested by the above-mentioned table. The periphery of the armature being $45 \times \pi = 141.4$ inches, and the length over conductors being 27 inches,* the total cylindrical radiating surface will be $141.4 \times 27 = 3{,}820$ square inches; and as the total armature losses are assumed to be 1.6 per cent + 2.2 per cent = 3.8 per cent, or $0.038 \times \frac{150{,}000}{0.92} = 6{,}200$ watts, the peripheral surface will have to dissipate $6{,}200 \div 3{,}820 = 1.63$ watts per square inch. As the peripheral speed is assumed to be 2,650 feet per minute, we see from curve *cc*, Fig. 139 (page 121), that the probable temperature-rise will be $26° \times 1.63 = 42.5°$ C., which will not be too high, since 50° C. rise is permitted by the Standardization Rules of the American Institute of Electrical Engineers. A useful and fairly accurate empirical rule states that the exposed surface of the armature should not be less than 24 square inches for each kilowatt of output. Hence we should need $24 \times 150 = 3{,}600$ square inches. As the armature has 3,820 square inches, there should be ample surface.

Number and Dimensions of the Slots. We may now settle upon the number and dimensions of the slots. The former depends upon the type of winding used, and upon the number of commutator segments. It is almost universal practice to wind all but small armatures with copper strip, the current-density varying from 2,000 to 3,000 amperes per square inch. Assuming, in our case 2,700 amperes per square inch, we require a conductor $\frac{600}{8} \div 2{,}700 =$ 0.0278 square inch in cross-section (say 0.028 square inch). As we have decided to place the conductors 8 in a slot (page 202), the total

* Assuming length over conductor of barrel-wound armatures to equal twice length over core.

TABLE XIX

Number and Sizes of Armature Slots and Teeth

DIAMETER OF ARMATURE (in inches)	NUMBER OF SLOTS OR TEETH	DEPTH OF SLOTS OR TEETH (in inches)
10	25 to 75	0.40 to 1.70
20	50 to 135	0.60 to 1.80
30	75 to 190	0.80 to 1.90
40	95 to 240	1.00 to 2.00
50	110 to 280	1.10 to 2.05
60	125 to 320	1.20 to 2.10
80	150 to 400	1.30 to 2.20
100	175 to 450	1.35 to 2.25
120	190 to 500	1.40 to 2.30
140	200 to 540	1.45 to 2.35
160	210 to 580	1.50 to 2.40

Ratio $\frac{\text{Depth of slots}}{\text{Width of slots}}$, from 1:5 to 4

Ratio $\frac{\text{Width of slot}}{\text{Width of tooth}}$, from 0.75 to 1.5

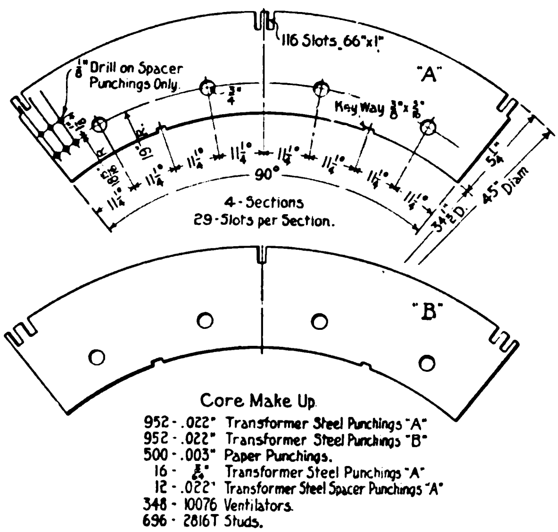


Fig. 251. Lamination Stamping of Armature whose Construction is Described in Text.

copper section per slot will be $8 \times 0.028 = 0.224$ square inch. Assuming a space-factor (page 88) of, say, 0.34, we have as the area of the solt, $0.224 \div 0.34 = 0.66$ square inch, nearly. As there will be $928 \div 8 = 116$ slots (which is within the limits set by Table XIX), and an equal number of teeth in a total perimeter of 141.4 inches, the width of a slot and a tooth at the face of the armature cannot exceed $141.4 \div 116 = 1.22$ inches. Making the ratio $\frac{\text{Width of slot}}{\text{Width of tooth}} = 1.18$, we have the width of a tooth =

$\frac{1.22^*}{1 + 1.18,} = 0.56$ inch, so that the width of a slot is $1.22 - 0.56 =$ 0.66 inch. Hence the depth of the slot will be 0.66 sq. in. ÷ 0.66 in. = 1 inch. These values for the sizes of slots and teeth are seen to lie within the limits suggested by Table XIX.

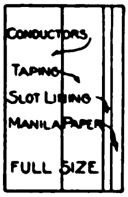


Fig. 252. Section of Part of an Armature Slot.

An enlarged drawing of the slot, showing to scale the arrangements of conductors, is now made (Fig. 252). Each conductor is wrapped with tape to a thickness of 30 mils on each side, and allowing a slot insulation at each side of, say, 24 mils of press-board (two thicknesses, and a wrapping for four conductors of manila 25 mils thick), each conductor must be 80 mils wide, which leaves a clearance of 2 mils. The depth of conductor will be 0.028 ÷ 0.080 = 0.35 inch, or 350 mils. Allow, say, 12 mils of press-board between the upper and lower layers, and 60 mils between the lower layer and the bottom of the slot. We may then account for the contents of a slot as follows:

WIDTH

4 Conductors side by side, bare	4 x 0.080 =	0.320 inch
8 Thicknesses of taping	8 x 0.030 =	0.240 "
2 Thicknesses of slot lining	2 x 0.024 =	0.048 "
2 Thicknesses of manila	2 x 0.025 =	0.050 "
Total		0.558 inch

DEPTH

2 Conductors deep	2 x 0.350 =	0.700 inch
4 Thicknesses of tape	4 x 0.030 =	0.120 "
4 Thicknesses of manila paper	4 x 0.025 =	0.100 "
6 Thicknesses of lining	6 x 0.012 =	0.072 "
Total		0.992 inch

Now, the length of one armature turn (found by drawing the winding to scale and then measuring it), is 87.5 inches; and as the resistance of a copper conductor whose area of cross-section is one square inch, and whose length is 1 foot, at 50° C., is 0.000009088 ohm, we have as the total resistance of the armature winding at 50°C.:

$$r_a = \frac{0.000009088 \times 87.5 \times 464}{64 \times 0.028 \times 12} = 0.0172 \text{ ohm.}$$

Internal Diameter of Core. The internal diameter of the core

*Or let x = Width of slot; y = Width of tooth. Then $x + y = 1.22$, and $\frac{x}{y} = 1.18$ Hence $x = 1.18\,y$; and we have $y + 1.18\,y = 1.22$, or $y = \frac{1.12}{1 + 1.18}$.

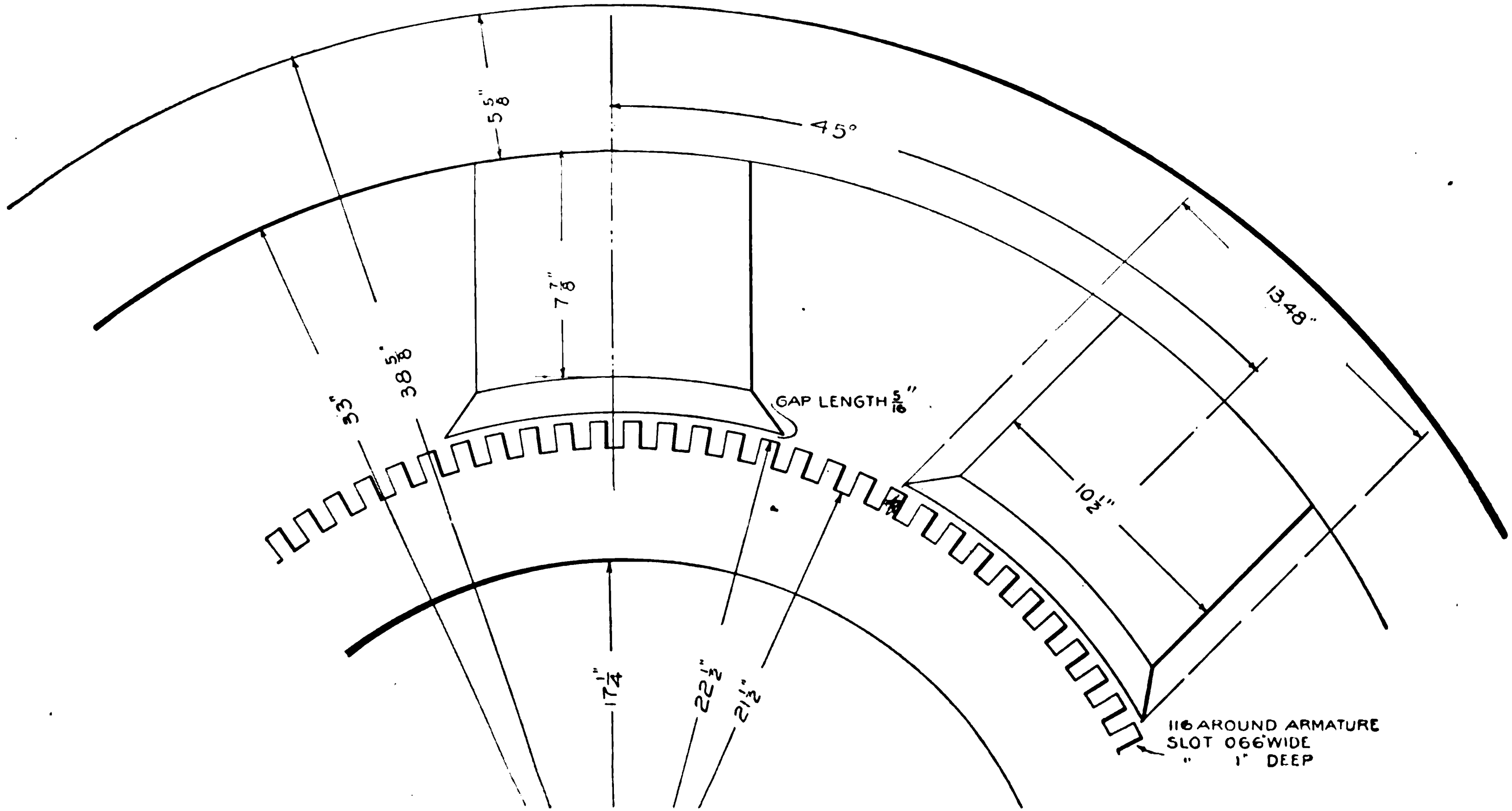


Fig. 253. Dimensioned Diagram of Magnetic Circuit of Generator whose Construction is Described in Text.

TABLE XX

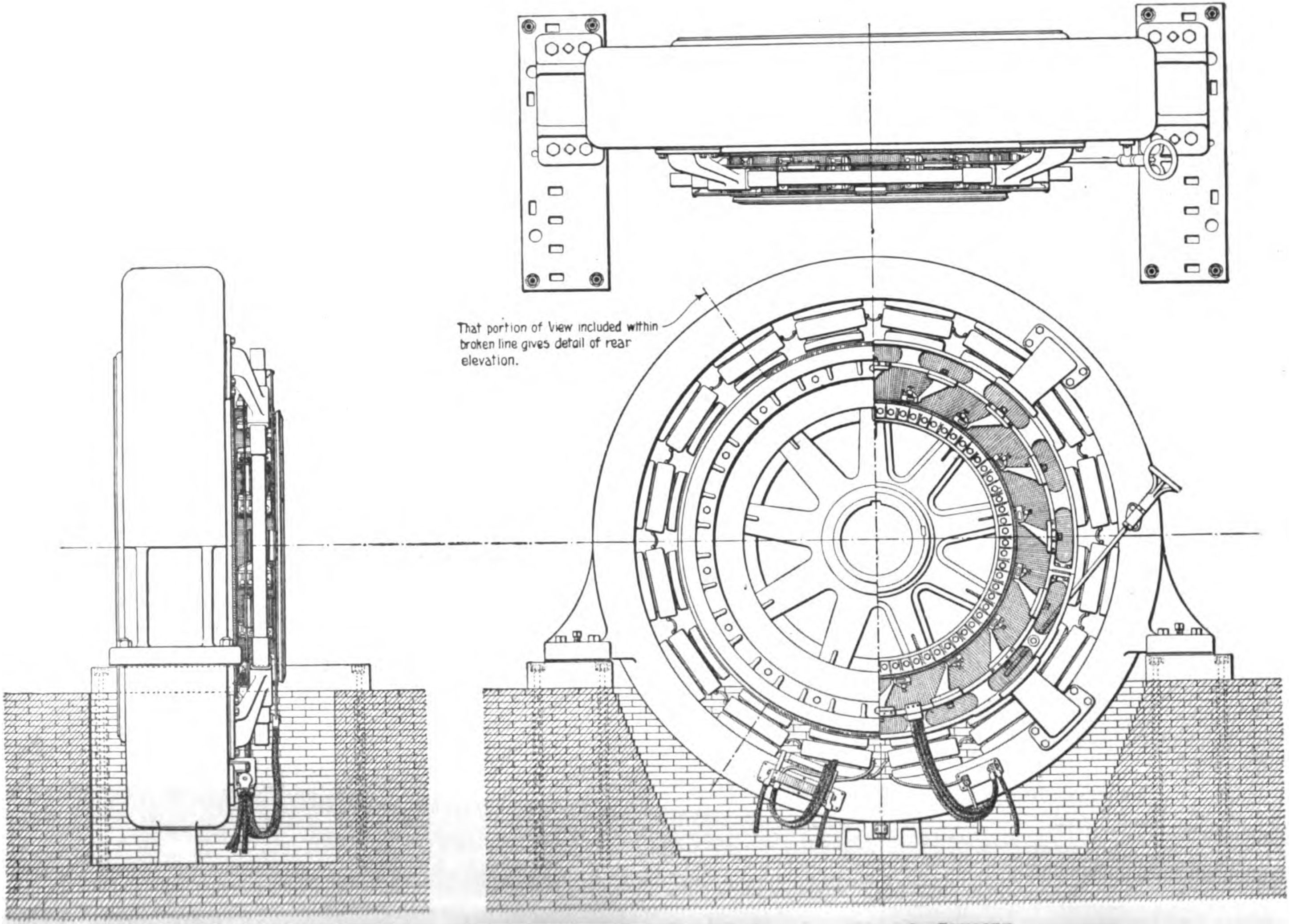
Flux-Densities in Armature Cores

Type	Flux-Density (in lines per sq. in.)
Bipolar drum-core	50,000 to 90,000
Bipolar ring-core	65,000 to 95,000
High-speed multipolar ring-core	45,000 to 85,000
Slow-speed multipolar ring-core	65,000 to 97,000

may now be fixed by ascertaining the requisite radial depth of the core to give an adequate cross-section of iron below the teeth. The final value of this depends upon the permissible iron-loss, which limits the flux-density possible. Table XX gives values for average flux-densities in armature cores; and as our design contemplates a slow-speed multipolar ring-core armature, we may select a flux-density of, say, 83,000 lines per square inch.

Now, the flux through the armature core at rated load is $\frac{1}{2}\ \phi = \frac{7,600,000}{2} = 3,800,000$, so that the area of cross-section of the armature core will be $3,000,000 \div 83,000 = 45.8$ square inches. The total length of the armature core over laminations being 13 inches, we have the net length $13 \times 0.814 = 10.575$ inches, allowing 10 per cent of the gross length for insulation between the sheets (page 79), and 1.125 inches for 3 ventilating slots, each $\frac{3}{8}$ inch wide. Hence the radial depth of the armature will be $45.8 \div 10.575 = 4.35$ inches—say $4\frac{1}{4}$ inches. The internal diameter of the armature is therefore $45 - (2 \times 4.25 + 2 \times 1) = 34.5$ inches.

Dimensions of Air-Gap. In assigning a length to the air-gap, it should be borne in mind that this portion of the magnetic circuit of continuous-current machines is not a mere clearance, as in some alternating-current motors. It plays a definite part in the process of commutation. It has been found by experience that a long air-gap, though it necessitates more ampere-turns upon the field-magnets, is of advantage in commutation, as it offers an obstacle to the distortion of the useful flux by the reacting ampere-turns of the armature. Similar results ensue by making the flux-density in the armature teeth high; and it is found that the sum of the ampere-turns required for the air-gap and armature teeth per pole must bear a certain proportion to the number of ampere-turns of the armature under one pole-face at rated load.


That portion of View included within broken line gives detail of rear elevation.

Now, since the ampere-turns needful for the air-gap are proportional to the length of the gap l_g and the flux-density in the gap B_g, the following simple approximate rule for the requisite gap-length can be given, assuming that the ampere-turns needful for the teeth bear some definite proportion to those needful for the gap—for instance, that they are equal to 25 per cent of the latter at rated load:

$$l_g = k_4 \times \frac{q\ d}{p\ B_g},$$

where k_4, the stiffness coefficient, varies from about 4 to 8.5 (the lower value applying to cases where the saturation of the teeth exceeds 130,000 lines per square inch); d = diameter of armature; q = number of ampere-conductors per inch of periphery of armature; and p = number of poles. Making $k_4 = 5$, in our design, we have:

$$l_g = 5 \times \frac{\frac{928 \times 75}{141.8} \times 45}{8 \times 46,000} = 0.302 \text{ inch (say } \tfrac{5}{16} \text{ inch).}$$

The flux-density in the air-gap, we obtain from Table XXI.

TABLE XXI

Approximate Values of Density in Air-Gap with Multipolar Machines Having Slotted Armatures

Output of Machine (in kilowatts)	Density in Air-Gap (in lines per sq. in.)
1	30,000
5	35,000
10	37,500
25	40,000
50	42,500
100	45,000
200	47,500
300	50,000
500	53,000
1,000	56,000
2,000	59,000

Dimensions of Magnet-Pole Cores. These must have sufficient cross-section to carry the flux required at rated load, including that which forms by leakage—the stray flux. The densities in this portion vary from 75,000 to 100,000 lines per square inch (Table IV, page 90), and the usual leakage coefficients are given in Table II, (page 77). The length of the core must be sufficient to carry the field-exciting winding; and, as a trial value, we may take this equal

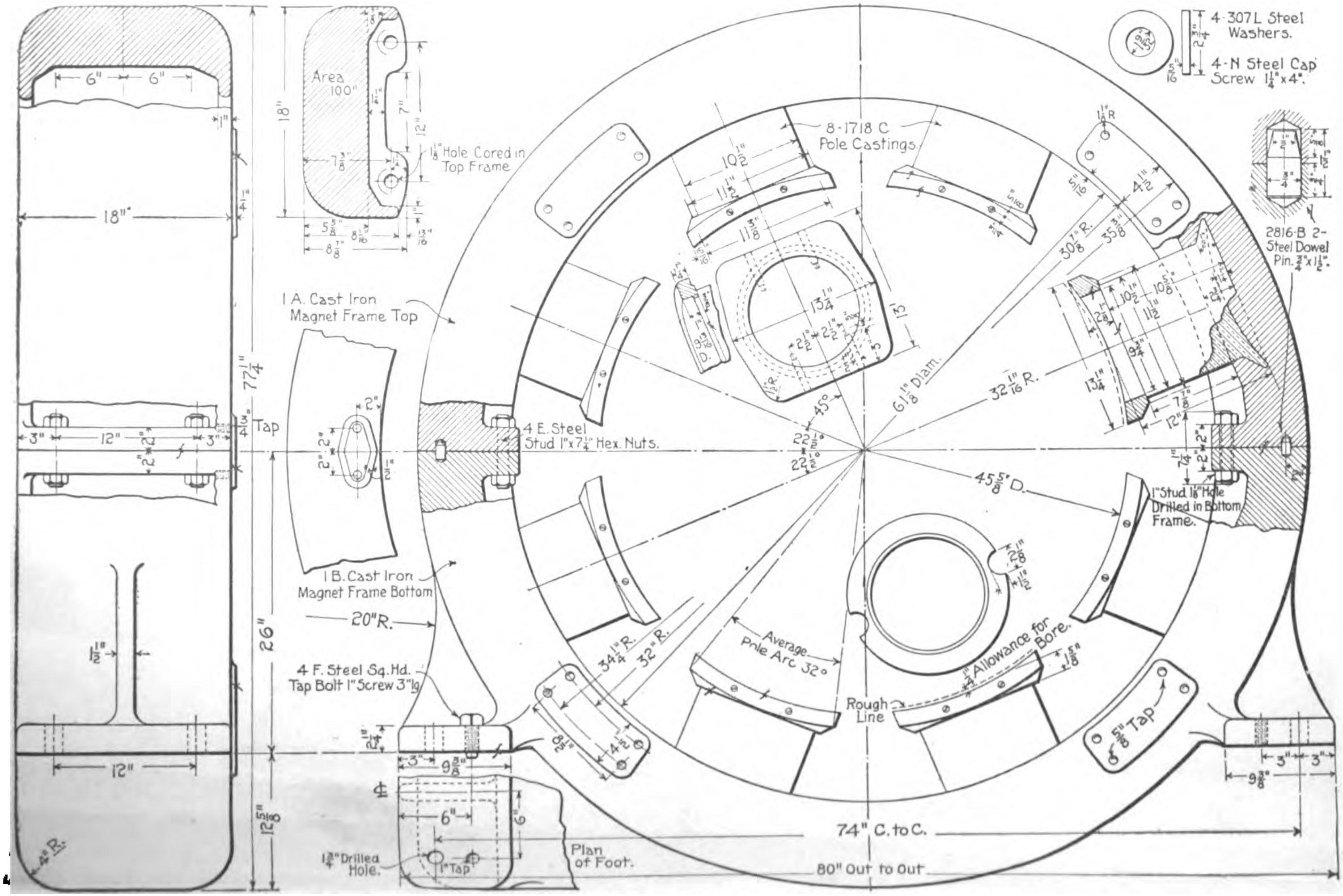


Fig. 234. Details of Magnet-Frame and Poles of Generator whose Construction is Described in Text.

to from $\frac{3}{4}$ to 1 time the diameter (if the core is cylindrical), reducing the value so assumed, if necessary, later on. In case the core is not cylindrical, we may take the length of the pole-core as 20 times the length of the air-gap, if the machine is shunt-wound, and 40 times the length should it be compound-wound.

In our case, the total flux entering the armature at rated load was assumed to be 7,600,000 lines; and if we assume a leakage coefficient of 1.09, the total flux in the pole-cores will be 7,600,000 × 1.09 = 8,300,000 lines at rated load. Assuming a flux-density in the pole-cores of 96,000 lines per square inch, we have 8,300,000 ÷ 96,000 = 86.5 squae rinches as the area of cross-section of a pole-core. Making them circular in cross-section, we have $2\sqrt{86.5 \div \pi} = 10.5$ inches, as the diameter of the pole-cores. Making the radial length of the cores $\frac{3}{4}$ the diameter, we get $\frac{3}{4} \times 10.5 = 7\frac{7}{8}$ inches, as a trial value.

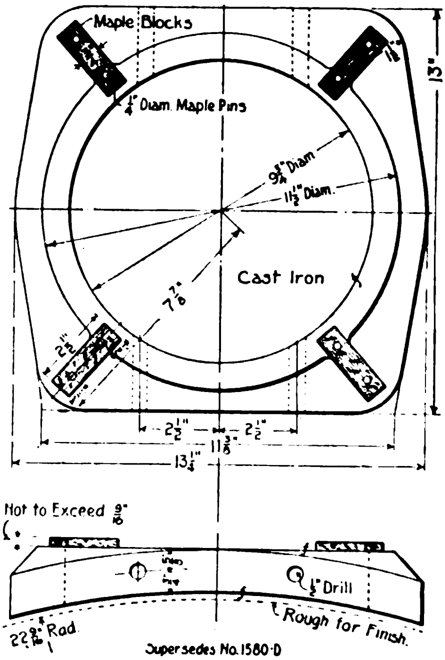


Fig. 255. Make-Up of Pole-Shoe of Generator whose Construction is Described in Text.

Cross-Section of the Yoke. We may now decide upon the requisite area of cross-section of the yoke, this being fixed when we know the flux-density and the total flux. The latter is 8,300,000 ÷ 2 = 4,150,000 (see page 79); while, if we make the yoke of cast iron, the flux-density should be about 41,000 (Table III); 4,150,000 ÷ 41,000 = 101 sq. in. (say 100 square inches), making a flux-density of 41,500 lines per square inch.

Preliminary Summary. We may now collect and tabulate the values thus far obtained, as follows:

General Specifications:

Rated load, kilowatts	150
Rated load, terminal volts	250
Rated load, amperes	600
Armature, r. p. m	225
Peripheral speed of armature, in ft. per minute	2,650
Number of poles	8

Armature:

Core-discs, external diameter, in inches	45
" " internal " " "	34.5
Length of core over laminations, in inches	13
Number of slots	116
Depth of slots, in inches	1
Width of slots, in inches	0.66
Pitch of slots at armature face, in inches	1.22
Depth of iron in core under teeth, in inches	4.25
Number of conductors	928
Arrangement	8 per slot
Style of winding	Simplex parallel
Dimensions of each conductor, in inches	0.08 by 0.35
" " " " insulated	0.14 by 0.41
Section of each conductor in square inches	0.016
Winding pitch in number of teeth	13
Length of armature over all, in inches	27

Commutator:

Diameter, in inches	29.5
Number of segments	464
Length, in inches	8.25
Width of segment at face, in inches	0.16
Thickness of mica insulation	0.04

Field-Magnet:

Outer diameter of yoke, in inches	77.25
Inside diameter of yoke, in inches	66.0
Breadth of yoke, in inches	18.0

All the preliminary computations have now been made, and it now remains to proceed with the final calculations. A scale drawing (similar to Fig. 254) should now be made of the machine, using the trial values thus far found. From this, the designer will be able to judge of the ultimate dimensions of the machine, and, with its aid, he will be able to make a complete set of calculations in accordance with the principles of the preceding pages, for excitation, heating, sparking, and efficiency, as will presently be done. From the results of such calculations, it is then easy to see in what manner to alter the original design in order to fulfil the required conditions.

Excitation. We shall first construct the magnetization curve of the machine by the method described on page 135. We have:

$$E = \frac{Z \times p \times \text{r.p.m.} \times \phi_a}{60 \times 10^8 \times c},$$

$$= \frac{928 \times 225 \times 8}{60 \times 10^8 \times 8} \phi_a,$$

$$= 0.0000348 \; \phi_a$$

With the aid of this equation, we may compute the following table, the leakage coefficient of the machine being 1.09, by actual measurement:

Generated E. M. F.	Flux Entering Armature per Pole (ϕ_a)	Flux per Pole in Magnet Cores ($\phi_a \times 1.09$)
180	5,180,000	5,650,000
200	5,750,000	6,260,000
220	6,320,000	6,890,000
240	6,900,000	7,520,000
260	7,470,000	8,150,000
280	8,050,000	8,780,000
300	8,620,000	9,400,000
330	9,490,000	10,320,000
360	10,340,000	11,290,000

From the drawings, Figs. 253 and 254, we obtain the following dimensions:

Mean length of magnetic path in magnet-yoke, in inches.......	29
" " " " " " two magnet-cores, in inches...	15.75
" " " " " " armature core, in inches......	10
" " " " " " two teeth, in inches..........	2
" " " " " " two air-gaps, in inches	0.625
Magnetic area of magnet-yoke, in square inches	100
" " " magnet-cores, " " "	36.5
" " " armature core, " " "	45.6

The polar angle being 32°, we have the number of teeth under each pole $\frac{32°}{360°} \times 116 = 10.3$ (say 11 teeth), with the allowance for fringing.

The area of the teeth under each pole may then be taken as $11 \times 0.505 \times 10.72 = 59.5$ square inches.

The area (effective) of the air-gap, being equal to the area of the pole-face, is 163 square inches.

We now have all the data for constructing the magnetization curve of the machine; and in the accompanying table (top of pages 214

Computation of Ampere-Turns

Portion of Magnetic Circuit	Material	Mean Length of Magnetic Path (Inches)	Magnetic Area (Square Inches)	$E = 180$, $\phi_a = 5{,}180{,}000$, $\phi_m = 5{,}650{,}000$			$E = 200$, $\phi_a = 5{,}750{,}000$, $\phi_m = 6{,}260{,}000$		
				Flux-Density	Ampere-Turns per Inch Length	Ampere-Turns	Flux-Density	Ampere-Turns per Inch Length	Ampere-Turns
Magnet-Yoke.........	Cast Iron	29	2×100	28,250	24	695	31,300	28	812
Two Magnet-Cores...	Cast Steel	15.75	86.5	65,400	5	79	72,500	15	236
Two Air-Gaps........	Air	0.625	163	31,800	9,960	6,230	35,300	11,020	6,900
Two Teeth............	Sheet Steel	2	59.5	87,000	23	46	96,600	52.5	105
Armature Core.......	do	10	2×45.6	56,700	2.5	25	63,000	3.8	38
Ampere-turns per pair of poles..............				......	......	7,075	......	......	8,091

and 215), the ampere-turns required for various generated e. m. f.'s have been computed as outlined on pages 135–143.

From the computed data we locate the following points on the scale:

E	Ampere-Turns per Pair of Poles
180	7,075
200	8,091
220	9,252
240	10,694
260	12,493
280	14,412
300	16,517
330	20,219
360	24,392

Plotting a curve between these points, we have the magnetization curve of Fig. 256.

Voltage-Drop Compensation. We have seen that the necessary ampere-turns at rated load will be greater than those at no load by an amount depending upon:

1. The value of the IR drop in the armature and the series field-winding.
2. The value of the brush-contact drop.
3. Amount of armature demagnetization.
4. Amount of armature distortion.

The resistance of the armature winding at 50° C. was found to be 0.0172 ohm; and the rated-load current being 607 amperes, the IR drop will be $607 \times 0.0172 = 10.5$ volts. The current in the

for Various Generated E. M. F.'s

$E = 220$, $\phi_a = 6{,}320{,}000$, $\phi_m = 6{,}890{,}000$			$E = 240$, $\phi_a = 6{,}900{,}000$, $\phi_m = 7{,}520{,}000$			$E = 260$, $\phi_a = 7{,}470{,}000$, $\phi_m = 8{,}150{,}000$			$E = 280$, $\phi_a = 8{,}050{,}000$, $\phi_m = 8{,}780{,}000$			$E = 300$, $\phi_a = 8{,}620{,}000$, $\phi_m = 9{,}400{,}000$		
Flux-Density	Ampere-Turns per Inch Length	Ampere-Turns	Flux-Density	Ampere-Turns per Inch Length	Ampere-Turns	Flux-Density	Ampere-Turns per Inch Length	Ampere-Turns	Flux-Density	Ampere-Turns per Inch Length	Ampere-Turns	Flux-Density	Ampere-Turns per Inch Length	Ampere Turns
34,450	38	1,100	37,600	46	1,332	40,750	58.5	1,698	43,900	72.5	2,102	47,050	81.5	2,362
79,500	19	300	86,900	25.4	400	94,200	39.5	622	101,500	56	882	108,900	85	1,339
38,800	12,120	7,590	42,400	13,250	8,280	45,900	14,360	8,960	49,400	15,450	9,650	53,000	16,600	10,380
106,200	99	198	11,600	287	574	127,800	524	1,048	135,300	762	1,524	145,000	1,003	2,006
69,300	6.4	64	75,600	10.8	108	81,900	16.5	165	88,200	25.4	254	94,500	43	430
......	......	9,252	......	......	10,694	......	......	12,493	......	......	14,412	......	......	16,517

brushes being 40 amperes per square inch of contact, we have from Fig. 141 the drop due to brush contact = 1.5 volts. Allowing 1.5

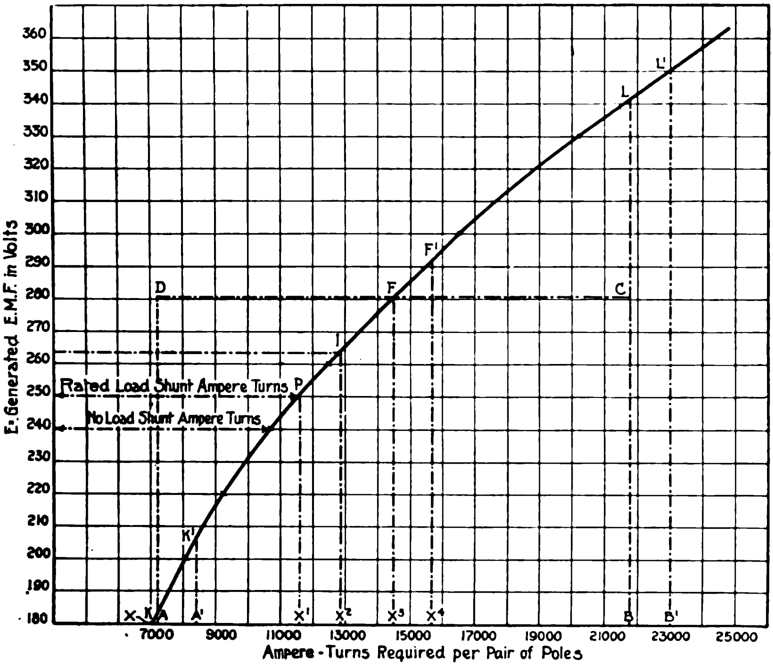


Fig. 256. Magnetization Curve of 150 K. W. 250 Volt Generator, 225 R. P. M.

volts for drop in the series field-winding, we see that the machine must generate 250 + 13.5 = 263.5 volts at rated load.

Finding this point on the scale of ordinates of the curve, Fig. 256, we find the point X_2 on the scale of abscissæ, which corresponds to the ampere-turns required per pair of poles at rated load if armature reaction were entirely absent. This makes $X_2 = 12{,}830$.

At rated load the brushes are given a lead of 5 segments—that is, a lead of 8.6 per cent. Hence the percentage of demagnetizing ampere-turns = 17.2 per cent of the total armature turns. As there are 464 turns on the armature, each carrying 75 amperes, the demagnetizing ampere-turns per pair of poles will be:

$$\frac{460 \times 76 \times .172}{4} = 1{,}510.$$

Multiplying this by the coefficient of magnetic leakage, the compensating ampere-turns per pair of poles will be $1.09 \times 1{,}510 = 1{,}645$.

Adding these to X_2, we find $X_3 = 14{,}470$, assuming, for the moment, that there is no drop in pressure due to diminished permeability of the teeth at the forward pole-horn. For this latter we must allow, as explained on pages 141–144.

We have the distorting ampere-turns per pair of poles $= \frac{464 \times 76 \times 0.828}{4} = 7{,}270$. Therefore set off 7,270 ampere-turns on each side of the point X_3 upon the scale of abscissæ, and thus obtain the points A and B, which represent the hindward and forward pole-horns respectively. If the distortion of the main flux were absent, the latter would be proportional to the area $A\,B\,C\,D$; but as it is not so, it is proportional to the smaller area $ABLK$. In order to make this area equal to that of the rectangle, we must shift the point F higher up the curve to some such position as F', so that area $A'B'L'K'$ = area $A\,B\,C\,D$. In this manner we obtain the point $X_4 = 15{,}700$ as the necessary number of ampere-turns per pair of poles at rated load.

Shunt Field-Winding. From Fig. 256 we see that 10,700 ampere-turns are needed when the terminal voltage of the generator is 240 volts—that is, when no external current is being drawn. Hence we shall require 5,350 ampere-turns per pole.

Assuming a depth of winding of about 1½ inches, we get the length of a mean turn as 3.54 feet. Then, from formula on page 87, we get No. 10 wire as the most suitable size to use. Planning to have

72.5 per cent of the available 250 volts (that is, 181.5 volts) as the terminals of the field spools when hot (the remainder being con-

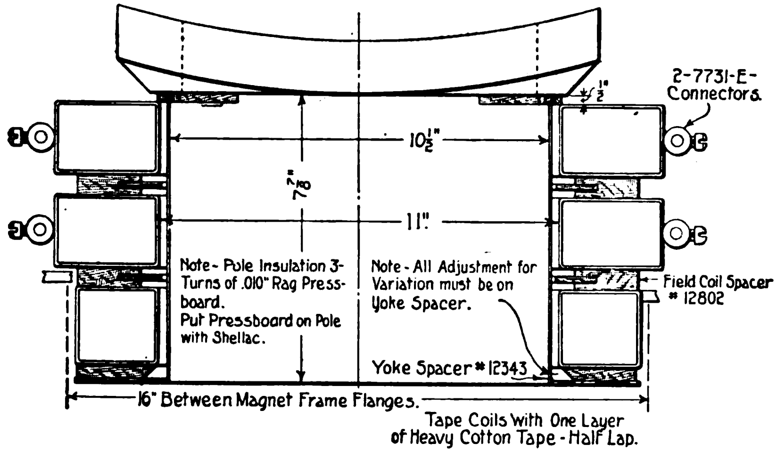


Fig. 257. Make-Up of Field-Coils of Generator whose Construction is Described in Text.

sumed in the field rheostat), we require $\frac{181.5 \div 8}{2.9} = 6.96$ amperes per spool. Hence the turns per shunt spool will be $\frac{5,570}{6.96} = 800.$ The length of 800 turns will be 2,830 feet, giving a resistance of very nearly 2.9 ohms per shunt spool. They will be arranged in 25 layers of 32 turns each (2 coils per pole).

Series Field-Winding. This winding is required to supply 2,280 ampere-turns at a rated load of 607 amperes. Planning to divert 31.6 per cent of this current through a rheostat in parallel with the winding, we find $0.684 \times 607 = 415$ amperes available for series excitation. Hence each series coil should consist of $\frac{2,280}{415} = 5.5$

Cumulative Compound Dynamo.						
Case	Dimension of Strip.		No. in ‖ in one Coil	No. of Leads.	Depth of Spacers.	Length of Shunt Coil Form.
A	$1\frac{1}{4}$ x .015		1 -	1	$\frac{3}{8}$	$2\frac{1}{8}$
B	$1\frac{1}{4}$ x $\frac{1}{16}$		1 - 3	1	"	$2\frac{1}{8}$
C	$1\frac{1}{4}$ x $\frac{1}{16}$		4 - 8	2	"	$2\frac{1}{8}$
D	$1\frac{1}{2}$ x .015		1 - 8	1	"	2
E	$1\frac{1}{2}$ x $\frac{1}{16}$		1 - 3	1	"	2
F	$1\frac{1}{2}$ x $\frac{1}{16}$		4 - 8	2	"	2.
G	$1\frac{3}{4}$ x .015		1 - 8	1	"	$1\frac{7}{8}$
H	$1\frac{3}{4}$ x $\frac{1}{16}$		1 - 3	1	"	$1\frac{7}{8}$
I	$1\frac{3}{4}$ x $\frac{1}{16}$		4 - 8	2	"	$1\frac{7}{8}$
J	1 x .015		1 - 8	1	"	$1\frac{3}{4}$
K	2 x $\frac{1}{16}$		1 - 3	1	"	$1\frac{3}{4}$
L	2 x $\frac{1}{16}$		4 - 8	2	$\frac{3}{8}$	$1\frac{3}{4}$

Length of Coil 2"

Fig. 258. Table for Make-Up of Field-Coils.

turns. The mean length of one turn is found to be 3.4 feet, so that 5.5 turns have a length of 18.7 feet.

The series winding per spool consists of 5.5 turns, made up of 5 strips of sheet copper 1.5 inches by $\frac{1}{16}$ inch section = 0.465 square inch. At 20°C. the resistance will therefore be:

$$\frac{0.00000814 \times 18.7}{0.465} = 0.000327 \text{ ohm.}$$

Losses. *Armature.* For the armature copper loss we have:

$$607^2 \times 0.0172 = 6{,}350 \text{ watts.}$$

To compute the armature iron loss, we have:

$$\text{Volume of teeth} = \frac{0.560 + 0.505}{2} \times 1 \times 10.72 \times 116 = 663 \text{ cu. in.}$$

and

$$\text{Volume of core} = \frac{\pi}{4}\left(\overline{43}^2 - \overline{34.5}^2\right) \times 10.72 = 5{,}555 \text{ cu in.}$$

Hence, from formulæ on pages 14 and 15, we have:

Hysteresis loss in core	$= 0.83 \times 0.004 \times 15 \times \overline{83{,}000}^{1.6} \times 5{,}555 \times 10^{-7}$	=	1,970 watts
" " " teeth	$= 0.83 \times 0.004 \times 15 \times \overline{126{,}000}^{1.6} \times 663 \times 10^{-7}$	=	477 "
Eddy-current loss in core	$= 40.6 \times \overline{0.022}^2 \times \overline{15}^2 \times \overline{83{,}000}^2 \times 5{,}555 \times 10^{-12}$	=	169 "
" " " " teeth	$= 40.6 \times \overline{0.022}^2 \times \overline{15}^2 \times \overline{126{,}000}^2 \times 663 \times 10^{-12}$	=	46 "
	Total iron losses at rated load	=	2,663 watts

Hence, total armature losses = 6,350 + 2,662 = 9,012 watts.

Excitation. The resistance of the shunt field-coils per pole at 50° C. = 2.9 ohms, and they are then supplied with 6.96 amperes. Hence the I^2R loss at rated load = $\overline{6.96}^2 \times 3.22 \times 8 = 1{,}240$ watts. The total loss in shunt field and rheostat at rated load = 250 × 6.96 = 1,740 watts.

The resistance of the series winding of each pole at 50° C. is 0.000365 ohm; so that at rated load, with 415 amperes in this winding, the loss = $\overline{415}^2 \times 0.000365 \times 8 = 490$ watts.

The resistance in parallel with the series winding will be $\frac{415 \times 0.000365 \times 8}{188} = 0.00644$ ohm. Hence the loss in the parallel rheostat at 50° C. and rated load = $\overline{188}^2 \times 0.00644 = 227$ watts.

The total loss in series field-winding and resistance, therefore, = 490 + 227 = 717 watts, giving a drop at rated load of 1.18 volts.

Commutator. Upon the commutator are pressed 24 brushes, each having an area of contact of 1.125 square inches. The total area of all the brushes will therefore be 27 square inches. Hence, by formula on bottom of page 125, assuming a brush tension of 1.25 pounds per square inch, the brush-friction loss = 27 × 1.25 × 0.3 × 1,650 × 746 ÷ 3,300 = 378 watts.

The total brush-contact drop is 1.6 volts. Hence the loss at

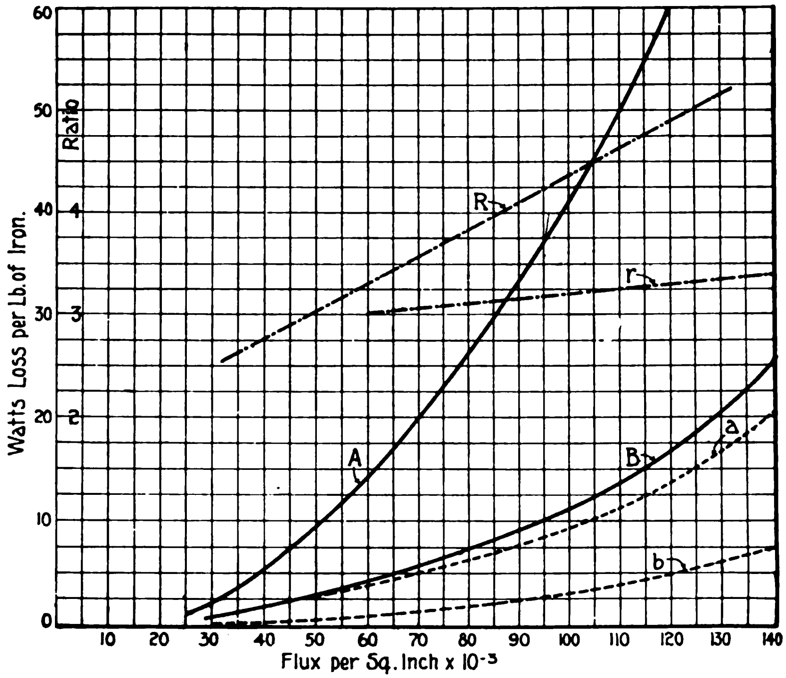


Fig. 259. Curves of Machine Losses.

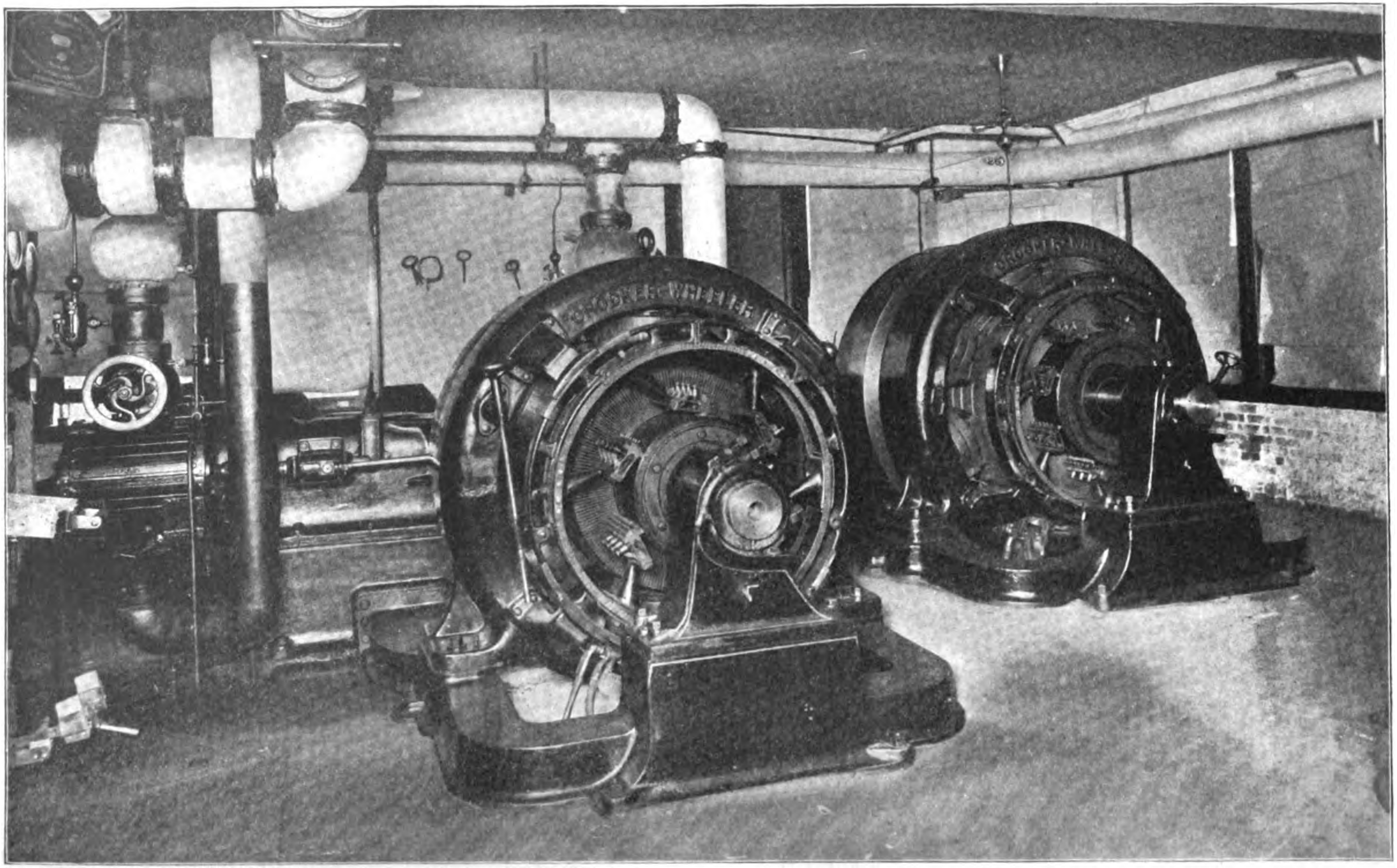
A—Machine Losses at 30 Cycles per Second; *a*—Sample Losses at 30 Cycles per Second; *R*—Ratio between *a* and *A*; *B*—Machine Losses at 15 Cycles per Second; *b*—Sample Losses at 15 Cycles per Second; *r*—Ratio between *b* and *B*.

brush contact = 607 × 1.6 = 971 watts. This makes the total commutator loss = 971 + 378 = 1,249 watts.

Bearing Friction and Windage. Owing to this being a direct-driven (slow-speed) machine, we may assume the losses due to bearing friction and windage as ⅗ of 1 per cent of the output (that is = 1,000 watts).

Efficiency. The total rated-load losses are:

Armature loss	9,012	watts	= 5.51	per cent
Excitation loss	2,457	"	= 1.50	" "
Commutator loss	1,249	"	= 0.58	" "
Bearing friction and windage	1,000	"	= 0.61	" "
Total losses	13,718	"	8.20	" "



Crocker-Wheeler Generators of Type Described in Text, Installed in Whitehall Building, New York City.

Hence the efficiency is:

$$\frac{150{,}000}{163{,}440} = 91.8 \text{ per cent.}$$

Heating. (*a*) *Armature.* From the drawings the radiating surface of the armature is found to be 4,510 square inches (counting cylindrical surface, and tails of rear flanges); the peripheral speed is 2,650 feet per minute.

The total armature loss being 9,012 watts, we must radiate $\frac{9{,}012}{4{,}510} = 2$ watts per square inch of radiating surface. Fig. 139 shows that this will give a rise of 50° C. at rated load and speed; but actual tests on the machine have shown an increase (by thermometer) of only 25° C.

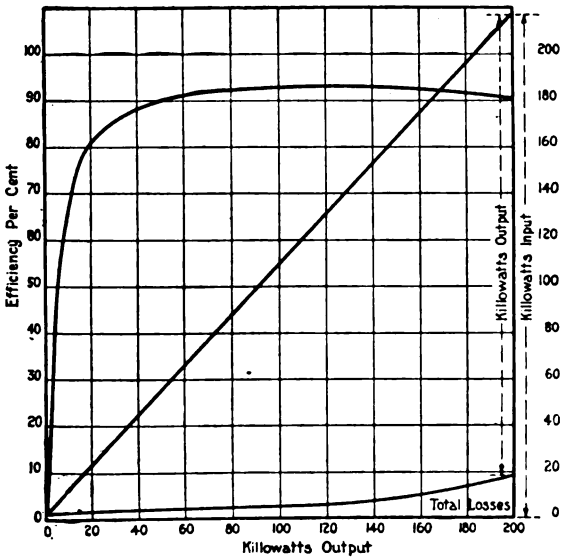


Fig. 260. Efficiency Curve of 140 D Generator, 250 V., 150 KW., 225 R. P. M.

(*b*) *Magnet System.* The total radiating surface provided for the shunt winding = 1,740 square inches, so that it is necessary to radiate 0.715 watt per square inch. Assuming $h = 35$ in formula on page 91, we have:

$$\theta_m = 35 \times 0.715 = 25° \text{ C. for the shunt winding.}$$

Actual test showed it to be 22.5° C.

The total radiating surface allotted to the series-winding = 615 square inches, and as 490 watts are consumed here, we must radiate $\frac{490}{615} = 0.796$ watt per square inch. Therefore,

$$\theta_m = 35 \times 0.796 = 27.8° \text{ C.}$$

Commutator. For the probable testing of this portion of the machine, we have, from page 126:

$$\theta_c = \frac{46.5 \times 971}{1{,}100(1 + 0.005 \times 1{,}650)} = 23° \text{ C.}$$

Sparking. The ratio of the ampere-turns required at full excitation to drive the flux through the air-gap and teeth, to the whole number of ampere conductors (at rated load) that lie under one pole-face, is 5,000 ÷ 3,635 = 1.37, providing a stiff field. The amperes collected per brush set are 150. The voltage between commutator segments is 4.32, and the *stiffness ratio* (page 208) is (46,000 ÷ 928 × 76) × 141.8 = 92*; all of which indicate sparkless commutation.

DETAIL SHEET

GENERATOR DESIGN

Name . . . . *Date submitted* . . . .

SPECIFICATION

1	Kilowatts	150
2	Terminal volts, rated load	250
3	Kilowatts no load	240
4	Amperes, rated load	600
5	Revolutions per minute	225
6	Number of poles	8
7	Frequency in cycles per second	15
8	Peripheral speed of armature, feet per minute	2,650

MATERIALS

9	Armature core	Sheet Steel
10	Armature spider	Cast Iron
11	Armature binding wire	No. 16 Phosphor Bronze
12	Conductors	Copper
13	Commutator segments	Copper
14	" leads	Copper
15	" spider	Cast Iron
16	Pole-pieces	Cast Iron
17	Magnet-cores	Cast Steel
18	Magnet-yoke	Cast Iron

*If $92 < \dfrac{\text{Stiffness coefficient} \times \text{Diameter of armature}}{p \times \text{Length of air-gap}}$, the conditions as regards air-gap length are correct.

19	Brushes	Carbon
20	Shaft	Steel (0.35%C.)
21	Bearings	

DIMENSIONS

Armature—

22	Diameter over all	45 in.
23	Diameter at bottom of slots	43 in.
24	Internal diameter of core	34.5 in.
25	Length over conductors	27 in.
26	Length of core over laminations	13 in.
27	Insulation between sheets %	9.8%
28	Number of ventilating ducts	3
29	Width of each ventilating duct	0.375 in.
30	Effective length, magnetic iron	10.72 in.
31	Effective length of core ÷ total length	82.5%
32	Thickness of sheets	0.022 in. and $\frac{3}{64}$ in. at ends
33	Number of sheets	479 of 0.022 in. and 4 of $\frac{3}{64}$ in.*
34	Number of slots	116
35	Depth of slot	1 in.
36	Width of slot at root	0.66 in.
37	" " surface	0.66 in.
38	Width of tooth at root	0.505 in.
39	Width of tooth at armature face	0.560 in.
40	Size of conductor, Diam	Depth..0.35 in. Width..0.08 in.
41	Size of conductor insulated	0.14 in. by 0.41 in.
42	Pitch of winding, No. of teeth	13
43	Total number of face wires or bars	928
44	Arrang. of wires or bars per slot	4–0.08 in. wide; 2–0.35 in. deep
45	Number in parallel per slot	0
46	" " series " "	8
47	Copper section ÷ slot section	0.34
48	Total insulation between cond. and core	0.079 in. on sides of slots 0.127 in. on bottom do.
49	Thickness insulation between conds	0.060 in. vertically. 0.110 in. between layers

Gap—

50	Length in center	$\frac{5}{16}$ in.
51	Length maximum	do.
52	Bore of field	$45\frac{5}{8}$ in.

Pole-Piece—

53	Length parallel to shaft	13 in.
54	Length of arc, max	13.48 in.
55	Length of arc, min	11.57 in
56	Thickness at edge of core	$1\frac{3}{8}$ in

*4 sections per sheet.

Magnet-Core—

57 Length of magnet-core, radial .... 7⅞ in.
58 Diameter of magnet-core .... 10½ in.
59 Length parallel to shaft .... 10½ in.
60 Distance between magnet-cores .... 9 in.

Magnet-Coils—

61 Length over all winding space .... 7⅞ in.
62 Thickness of insulation on flanges ....
63 Thickness of insulation on body .... $\frac{1}{16}$ in.
64 Length of main winding space, ex. insuln. (shunt) .... Each coil = 2 in.
65 Length of compound winding space, ex. insuln. .... 1½ in.
66 Depth of winding space, ex. insuln. ....
67 Total section of field copper .... 9.12 sq. in.
68 Size of shunt conductor .... No. 10 B. and S.G.
69 Turns in series per pole .... 2 coils, each 400 turns
70 Size of compound conductor ...... 5 strips, 1½ in. by $\frac{1}{16}$ in., in parallel
71 Turns in series per pole 5½

Yoke—

72 Outside diameter .... 77¼ in.
73 Inside diameter .... 66 in.
74 Thickness .... 5⅝ in.
75 Diameter over ribs ....
76 Thickness of ribs .... 1 in.

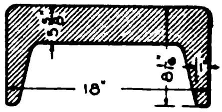


Fig. 261. Section of Yoke.

77 Length along armature .... 18 in.

Commutator and Brushes—

78 Diameter .... 28 in.
79 Number of segments 464
80 " " per slot 4
81 Width of segment at commutator face .... 0.158 in.
82 Width of segment at root .... 0.138 in.
83 Useful depth of segment .... 1.25 in.
84 Thickness of mica insulation .... 0.035 in.
85 Available length surface of segment .... 8.25 in.
86 Cross-section commutator leads .... 0.0468 sq. in.
87 Total length of commutator .... 12.5 in.
88 Peripheral speed .... 1,650 ft. per min.
89 Number of sets of brushes 8
90 Number in one set 3
91 Length .... 3 in.
92 Width .... 2.25 in.
93 Thickness .... 0.50 in.
94 Area of contact, one brush .... 1.125 sq. in.
95 Area of contact, one set .... 3.375 sq. in.
96 Type of brush .... Radial Carbon

ARMATURE

97 No-load voltage .... 240 volts
98 Type of winding .... Simplex, Singly Re-entrant, Lap-Wound Drum

99	Number of circuits	8
100	Mean length, one armature turn	87.5 in.
101	Total armature turns	464
102	Turns in series between brushes	58
103	Length between brushes	423 ft.
104	Cross-section one arm. conductor	0.028 sq. in.
105	Amperes per square inch in armature conductor	2,714
106	Resistances between brushes at 20° C.	0.123 ohm
107	Resistances between brushes at 50° C.	0.138 ohm
108	Total resistance of armature at	20° C. 0.0154 ohm 50° C. 0.0172 ohm
109	C. R. drop in armature at 50° C.	10.5 volts
110	Total internal voltage, rated load	263.5 volts
111	Amperes per square inch in commutator connections	1,210

Commutator

112	Average volts between bars	4.32
113	Amperes per square inch of brush contact	45
114	Drop in brush contacts	1 5 volts

Commutation

115	Average voltage between commutator segments	4.32
116	Armature turns per pole	58
117	Amperes per turn	76
118	Armature ampere-turns per pole	4,400
119	Allowable ampere-turns per pole	4,560*
120	Segments lead of brushes: no load	
	half load	
	rated load	5
121	Percentage lead of brushes, rated load	8.6%
122	Percentage demagnetizing ampere-turns, rated load	17.2%
123	Percentage distorting ampere-turns, rated load	82.8%
124	Demagnetizing ampere-turns per pole	755
125	Distorting ampere-turns	3,635

Shunt or Main Field

126	No. of turns in series per pole	2 × 400 = 800
127	No. of coils in series	16 (*i.e.*, 2 per pole)
128	Mean length of turn	42.6 in.
129	Resistance of mean turn 20° C.	0.00362 ohm
130	Total number of turns	6,400
131	Total resistance at 20° C.	23.2 ohms
132	Total resistance at 50° C.	26.1 ohms
133	Amperes, no load	6.675
134	Amperes, rated load	6.96
135	Volts at field terminals, no load	240
136	Volts at field terminals, rated load	250
137	Amperes per sq. in., no load	818

*Allowable ampere-turns per pole = number of ampere-turns per pole required to maintain the rated-load flux in the air-gap.

138	Amperes per sq. in., rated load	855
139	Rheostat resistance	24 ohms
140	C. R. drop rheostat 50° C.	68.5 volts

SERIES OR COMPOUND FIELD

141	No. of turns in series per coil	5½
142	No. of coils in series	8
143	Mean length of turn	40.7 in.
144	Resistance of mean turn	0.0000585 ohm
145	Total number of turns	44
146	Total resistance at 20° C	0.00257 ohm
147	Total resistance at 50° C	0.00290 ohm
148	Amperes, rated load	415
149	Amperes per sq. in., rated load	892
150	Resistance of rheostat in parallel with series field	0.00644 ohm

MAGNETIC

151	Megalines entering armature per pole, no load	6.9
152	Megalines, entering armature per pole, rated load	7.6
153	Coefficient of magnetic leakage, actual	1.09
154	Megalines in field, no load	7.5
155	Megalines in field, rated load	8.3
156	*Armature,* section	45.6 sq. in.
157	Length, magnetic	10 in.
158	Density no load	75,600
159	" rated load	83,000
160	Ampere-turns per inch length, no load	10.8
161	Ampere-turns per inch length, rated load	18.0
162	Ampere-turns, no load	108 } per pair of poles
163	Ampere-turns, rated load	180 } per pair of poles
164	*Teeth* transmitting flux from one pole-piece	$\frac{320}{3600} \times 116 = 10.3$
165	Allowances for spread of flux	.07
166	Section of roots	59.5 sq. in.
167	Length	2 × 1 = 2 in.
168	Apparent density, no load	116,000
169	" " rated load	127,800
170	Corrected " no load	114,000
171	" " rated load	123,000
172	Ampere-turns per inch length, no load	287
173	Ampere-turns per inch length, rated load	565
174	Ampere-turns, no load	574 } per pair of poles
175	Ampere-turns, rated load	1,130 } per pair of poles
176	*Gap,* section at pole-face	163 sq. in.
177	Length gap	2 × 5-16 in. = 0.625 in.
178	Density at pole-face, no load	42,400
179	" " rated load	46,000
180	Ampere-turns, no load	8,280 } per pair of poles
181	Ampere-turns, rated load	9,090 } per pair of poles
182	*Magnet-Core,* section	86.5 sq. in.
183	Length (magnetic)	2 × 7.875 = 15.75 in.

184 Density, no load........86,900
185 Density, rated load........96,000
186 Ampere-turns per inch length, no load........25.4
187 Ampere-turns per inch length, rated load........42
188 Ampere-turns, no load........400 } per pair of poles
189 Ampere-turns, rated load........661 } per pair of poles
190 *Magnetic Yoke*, section........100 sq. in.
191 Length per pole........29 in.
192 Density, no load........37,600
193 Density, rated load........41,500
194 Ampere-turns per inch length, no load........46
195 Ampere-turns per inch length, rated load........61
196 Ampere-turns, no load........1,332 } per pair of poles
197 Ampere-turns, rated load........1,769 } per pair of poles

Ampere-Turns per Pole

		No Load and 240 Volts.	Rated Load and 263.5 Internal Volts
198	Armature core	54	90
199	Armature teeth	287	565
200	Gap	4,140	4,545
201, 202	Magnet-pole, Magnet-core	200	330
203	Magnet-yoke	666	884
		5,347	6,414

204 Demagnetizing ampere-turns per pole, at rated load........755
205 Allowance for increase in density through distortion........615
206 Total ampere-turns at rated load and 250 terminal volts........7,850
207 If the rheostat in the shunt circuit is adjusted to give 5,347 ampere-turns at 240 volts, then, when the terminal voltage is 250, the shunt excitation will amount to $\frac{250}{240} \times 5{,}347 = 5{,}570$ ampere-turns. $7{,}850 - 5{,}570 = 2{,}280$ ampere-turns must be supplied by the series winding.

Calculation of Spool Winding

Shunt—

208 Mean length of one shunt turn = ...42.6 in.
209 Ampere-turns per shunt spool at rated load........5,570
210 Ampere feet........19,800
211 Total radiating surface of two shunt field-spools + series field-spool........294 sq. in.
212 Proportion available for shunt = ——— × = ...217 sq. in.
213 Permit .40 watt per square in, at 20° C........
214 ∴ 217 × .40 = 87 watts per shunt spool at 20° C........
215 And 98 watts per shunt spool at 50° C........
216 Plan to have 72.5 per cent of the available 250 volts (*i.e.*, 181.5) volts at the terminals of the field-spools when hot, the remainder being consumed in the field rheostat. This is 161.5 volts at 20° C., or

20.2 volts per spool. Hence require $\frac{20.2}{2.9}$ = 6.96 amperes per spool.

217 Turns per shunt spool = $\frac{5.570}{6.96}$ = ...800

218 Length of 800 turns....................................2,830 ft.

219 Pounds per 1,000 ft..................................40 "calculated"

220 No. 10 B. and S. has 31.5 lbs. per 1,000 ft., 2.83 × 31.5 = 89 lbs. "used" per pole.

221 Bare diameter....................................0.102 in.

222 S. C. C. diameter....................................0.108 in.

223 Cross-section of copper....................................0.00815 sq. in.

224 Amperes per square inch....................................855

225 Length of the portion of winding space available for shunt winding. 4 in.

226 Winding consists of 25 layers of 32 turns each, of No. 10 B. and S.

Series Winding

227 The series winding is required to supply 2,280 ampere-turns at rated load of 600 amperes.

228 Planning to divert 31.6 per cent through a rheostat in parallel with the series winding, we find we have 607 × 0.684 = 415 amperes available for the series excitation; hence each series coil should consist of $\frac{2,280}{415}$ = 5.5 turns.

229 Mean length of series turn....................................40.8 in.

230 Total length of 5.5 turns....................................18.7 ft.

231 Radiating surface available for series coil....................................77 sq. in.

232 Permit .40 watt per square inch in series winding at 20° C.

233 Watts lost per series spool at 20° C. = .40 × 77 = ...31

234 Hence resistance per spool at 20° C. = $\frac{31}{(415)^2}$ = 0.00018 ohm.

235 Copper cross-section = 0.465 square inch, "calculated."

236 Series winding per spool consists of 5.5 turns made up of 5 strips of sheet copper 1.5 in × $\frac{1}{16}$ in.

Thermal Calculations and Losses

Armature—

237 I^2R loss, rated load, at 50°C ....6,350 watts

238 Hysteresis loss, rated load { core....................................1,970 " ; teeth....................................477 "

239 Eddy-current loss, rated load { core....................................169 " ; teeth....................................46 "

240 Total hys. and eddy-cur. losses, rated load.................... 2,662 "

241 Total hys. and eddy-cur. losses, no load....................2,300 "

242 Total armature loss, rated load....................................9,012 "

243 Radiating surface of armature....................................4,510 sq. in.

244 Watts per square inch radiating surface....................................2

245 Assumed increase of temperature per watt per square inch of radiating surface as measured by increased resistance.................... = 25°C.

246 Hence, estimated total increase temperature of armature at rated load.................................... = 50°C.

SHUNT OR MAIN FIELD—

247 I^2R total, no load 50° C. . . . . 939 watts
248 I^2R total, rated load 50° C. . . . . 1,240 "
249 Radiating surface . . . . 1,740 sq. in.
250 Watts per sq. in., rated load 0.715
251 Total increase in temperature, rated load . . . . 25° C.
252 I. E. rated load, field and rheostat . . . . 1,740 watts

SERIES OR COMPOUND FIELD—

253 I^2R total, rated load . . . . 490 watts
254 Radiating surface . . . . 615 sq. in.
255 Watts per sq. in.., rated load 0.796
256 Total increase in temperature, rated load . . . . 27.8° C.
257 I. E. rated load, field and resistance . . . . 717 watts

COMMUTATOR—

258 Area of all positive brushes . . . . 13.5 sq. in.
259 Brush-contact loss . . . . 971 watts
260 Brush pressure assumed, 1.25 lbs. per square inch . . . . 33.8 lbs.
261 Coefficient friction 0.3
262 Peripheral speed of commutator, feet per minute 1,650
263 Brush friction . . . . 10.1 lbs.
264 Stray power lost in commutator . . . . 378 watts
265 Total commutator loss . . . . 1,249 watts
266 Radiating surface in sq. in. 1,100
267 Watts per square inch radiating surface of commutator, rated load 1.14
268 Increase of temperature per watt per sq. in. radiating surface = 20° C.
269 Total estimated increase of tem. of commutator, rated load . . . 22.8° C.

BRUSHES—

270 Total estimated increase of temperature . . . . 30° C.
271 Total losses, rated load . . . . 13,440 watts
272 Total losses, no load . . . . 4,690 watts

EFFICIENCY CALCULATION

273 Output, rated load . . . . 150,000 watts
274 Core loss . . . . 2,662 "
275 Commutator and brush losses . . . . 1,249 "
276 Armature I^2R at 50° C . . . . 6,350 "
277 Shunt spools I^2R at 50° C . . . . 1,240 "
278 " rheostat at 50° C . . . . 500 "
279 Series spools I^2R at 50° C . . . . 490 "
280 " rheostat at 50° C . . . . 227 "
281 Friction in bearings and windage . . . . 1,000 "
Input . . . . 163,718 "
282 Commercial efficiency at rated load and 50° C . . . . 91.7 per cent
283 Inherent regulation, per cent . . . . 104 per cent

WEIGHTS

284 Armature magnetic core . . . . 1,330 lbs.
285 " teeth . . . . 140 "

286	Armature spider	1,000 lbs.
287	" shaft	
288	" end flanges	450 lbs.
289	" copper	450 "
290	Commutator segments	510 "
291	" spider	400 "
292	' rings	90 "
293	Other parts of armature and commutator	80 "
294	Armature complete, including commutator and shaft	4,450 "
295	Pole-pieces	2,509 "
296	Magnet-cores	
297	Magnet-yoke	3,794 "
298	Shunt coils	694 "
299	Series coils	306 "
300	Total spool copper	1,080 "
301	Brush-gear	533 "
302	Bed-plate and bearings	
303	Machine complete	12,400 net lbs.

DRAWINGS REQUIRED

304 Longitudinal cross-section.
305 End elevation.
306 Plan.
307 Diagram of armature winding.
308 Details of important features.
309 Efficiency curve.
310 Curve of regulation.
311 Curves for losses from no load to rated load.
312 8 × 10½-in. paper required for description of method of calculation.

Drawings to be made with pencil on brown drawing paper, then traced and blue-printed.

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