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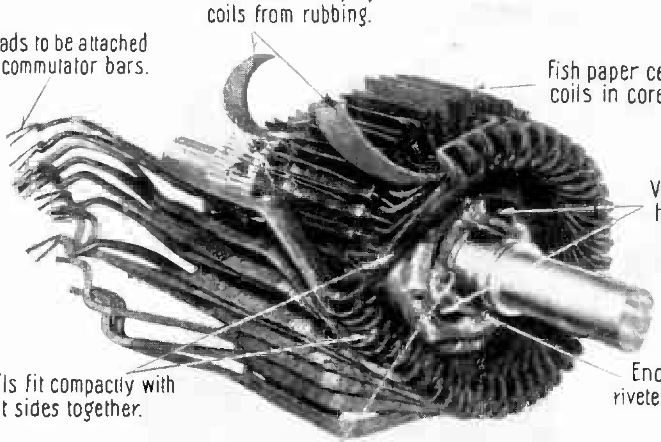


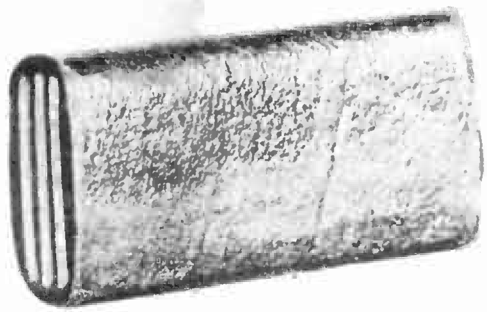
Partially Wound Armature

D-C MOTORS

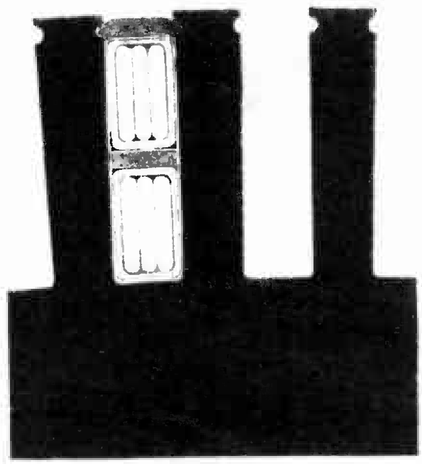
VOL.10,No.8

Dewey Classification R100

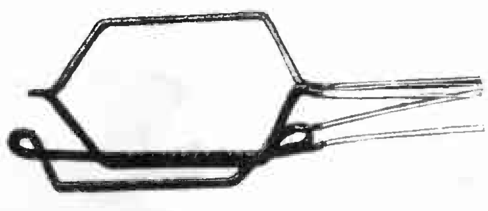
SECTIONAL VIEWS OF ARMATURE COILS
IN D.C. MOTORS



Section Through Armature Coil



Section Through Coils
and Slots



Complete Armature Coils

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D-C MOTORS

A study of the action of d-c motors is largely a study of magnetic and electromagnetic principles and, therefore, if the student is not thoroughly familiar with these subjects it is suggested that they be reviewed at this time.

THE PURPOSE OF THE D-C MOTOR

What is an electric motor and what is its purpose? The motor is a machine so designed and constructed that the electric power applied to it will be changed into mechanical power. Just what does that mean? Suppose we explain it as follows, taking for our explanation a trolley car. Over the track on which the car runs you notice a wire which is stretched from pole to pole. From this wire the trolley car pole collects current, as shown in Figure 1, and conducts it to the electric motor of the car causing the motor armature to revolve. The armature is geared to the wheels of the car.

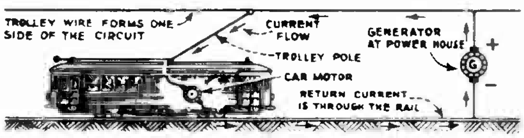


Figure 1

The current, after passing through the motor, is conducted through the wheels and passes into the rails, thence to the ground where it returns to the powerhouse generator. This simple explanation will serve to show you that electrical energy is converted into mechanical energy when the car moves.

THE PARTS OF A D-C MOTOR

In the electric motor there are three essential parts. The first part is the field pole, which is a piece of soft iron made into a particular shape for a definite purpose. On this field pole is wound a certain number of turns of wire making it an electro-magnet. The second part, known as the armature, is another electro-magnet made so that it can be revolved between the field poles. The third is a device called a commutator which leads the current into the armature windings.

In Figure 2 is shown a motor having four field poles of alternate north and south polarity. The armature bears a number of individual coils of wire which carry the current for magnetizing it.

That we may better understand the theory of why this armature revolves when placed in a magnetic field we are going to consider an armature coil of a single turn of wire, placed in the simple magnetic field provided by two magnet poles of opposite polarity.

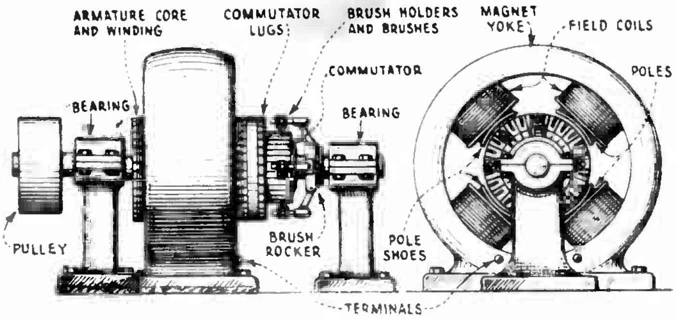


Figure 2

Referring to Figure 3, we show what is, in effect, a single electromagnet formed by the frame of a motor and the field poles. This magnetic structure is the first essential part of the motor. when current flows through the coils which surround the field poles a strong magnetic field is created (as shown by the dotted lines) which fills the space between the two pole pieces. The magnetic lines of force complete their circuit through the frame of the motor, which we see in this case provides two parallel paths.

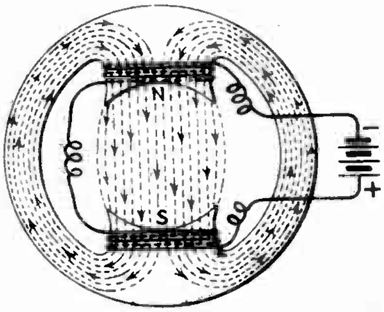


Figure 3

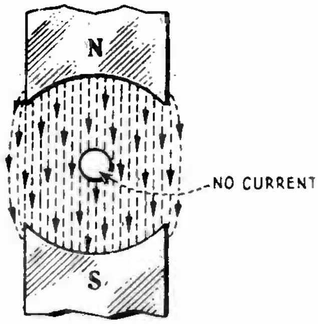


Figure 4

To further aid us in studying the motor action we will use only the field magnets and the space where the armature revolves, as in Figure 4. Here you notice a circle in the center of a field which represents only one side of an armature coil. Note carefully that the lines of force of the field are moving from the N to S pole of the magnets in a uniform manner, that is, they appear to be moving in straight lines ending on the S magnet very nearly opposite to the point at which they left the N magnet. This proves to us that although the armature coil is in the center of the field, the field has not been influenced by the presence of the coil.

This is the natural course a magnetic field assumes; it tends at all times to move in a straight line and should anything happen to divert it from this course it will endeavor to regain its natural state at the expense of whatever attempts to change it.

Now consider what happens if we remove the battery from the field windings; the magnetic lines of force cease to exist between the two pole pieces. Now let us connect the battery to the ends of the armature conductor which is shown between the poles in Figure 4. A magnetic field springs up at once about the armature conductor. In Figure 5 the circle marked with the cross indicates the conductor, and denotes that the current is moving through the wire away from you with its resultant field indicated by the arrowed lines.

Keeping the armature wire connected to the battery, let us now reconnect the field windings to the battery. As shown in Figure 6, the field of the armature wire is opposing the field of the magnets on the left side and moving with the magnet field on the right side of the wire. The lines of force between the north and south poles of the magnet are effective in a downward direction as shown in the figure. On the left side of the wire, they meet the lines of force caused by the current in the wire, and these are effective in an upward direction. This tends to neutralize or weaken the field at the point A.

At point B, to the right side of the wire, the lines of force due to the magnet poles are effective in the same direction as those due to the current in the wire. This causes a concentration or bunching of the lines of force at the right side of the wire, which is an increase in the field strength there. These distorted or

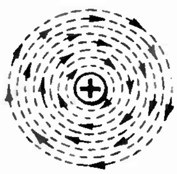


Figure 5

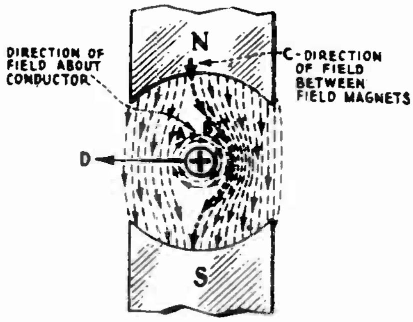


Figure 6

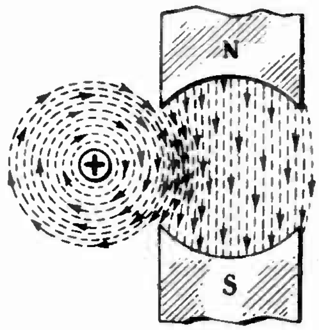


Figure 7

bent out lines of force act as taught rubber bands and at any instant tend to straighten themselves. This can only happen by the current-carrying wire moving away from the point where the lines of force are most concentrated, and toward the point where they are less concentrated. The wire will move in the direction shown by the arrow D.

This movement will continue until the wire has moved out of the magnet field as shown in Figure 7, or until it has moved so far that the pushing force which remains is too weak to overcome the natural friction between the wire and whatever supports it in position.

LEFT HAND RULE

There is a very handy rule for determining in just what direction the armature wire will move. Turn Figure 6 so that the normal left side of the page is toward you, and it is flat on a table with the Figure 6 exposed. Place the middle finger of the left hand on the crossed circle representing the current flow away from you. With the middle finger perpendicular to the paper, extend the forefinger in the same direction as the lines of force of the magnet, that is, toward the pole marked S. Keeping the thumb horizontal, stretch it out. You will find that it points in the direction of motion as shown by the arrow D in Figure 6. This rule should be practiced and memorized. It will help you somewhat to use the following memory trick:

Center finger	Forefinger	Thumb
Current direction	Flux direction	Toward?

The three fingers used are to be held at right angles to each other during this practice.

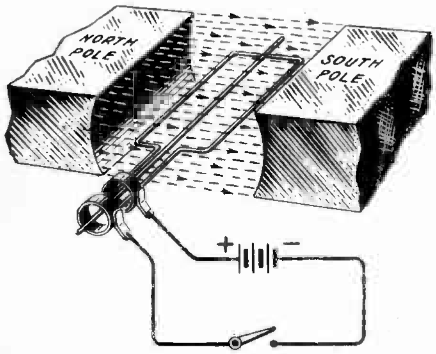


Figure 8

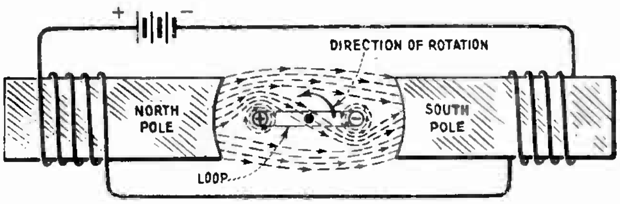


Figure 9

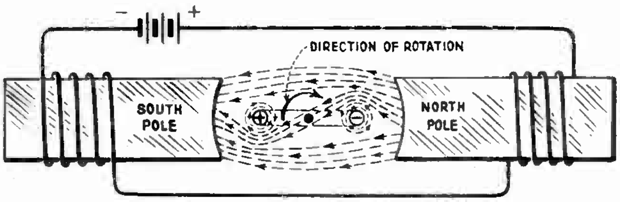


Figure 10

Let us study Figure 8 in order to understand more thoroughly how rotation of an armature takes place. You recognize the field magnets at once. A complete loop of wire (armature coil) has been drawn to show why a rotating movement is secured from the previously described simple displacement to one side (Figure 6). The loop is secured to an axle which passes through the center line of the loop, and centrally located with respect to the pole pieces. The loop is free to rotate about the axle, but not able to move in any other direction. Study the field as it leaves pole N in Figure 9. The small arrows show a bunching of lines of force over the top of the left wire of the loop, thus the magnetic field of the wire has added itself to that of the field magnets, making a strong concentration of lines above the wire. Underneath that wire its field is moving against the field of the magnets, thus weakening the field at this point. At the right-hand wire of the loop the opposite effect is evident. The concentration of lines of force is below the wire. We have stated that the loop is free to rotate on its axis. Applying the left-hand rule to both sides of the loop, we find that the left wire of Figure 9 will move downward and the right wire move upward. It is apparent that the loop will then turn in the direction shown by the arrow, or counter clockwise.

CONTROL OF DIRECTION OF ROTATION

Remembering the left-hand rule and the fixed relations between the fingers, it is seen that the direction of motion can be reversed by a reversal of either the field flux direction or the armature current direction, but not both. In Figure 10, the direction of current flow in the armature loop is the same as for Figure 9. The connections of the field windings to the battery have been reversed, and this reverses the polarity of the field magnet. The rotation is now clockwise as shown.

In Figure 11, the current in the armature wires has been changed in direction. Figure 12 has the same field polarity as Figure 9, but opposite armature current direction, so the directions of rotation are opposite. Figure 13 has the same field polarity as

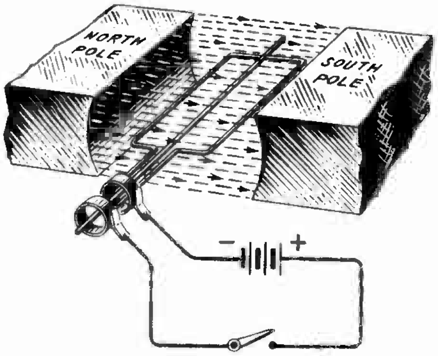


Figure 11

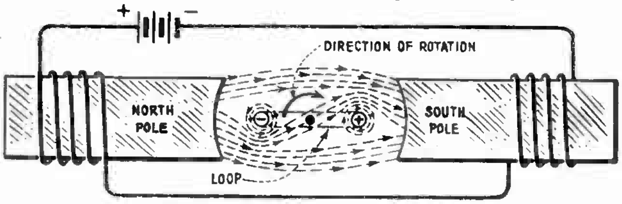


Figure 12

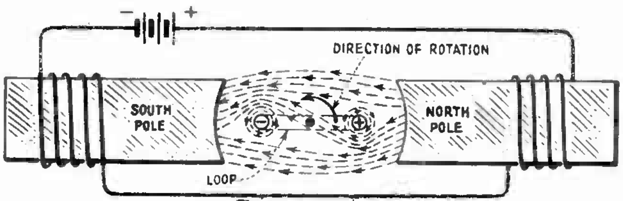


Figure 13

Figure 10, but opposite armature current direction, so the directions of rotation are opposite.

LIMIT OF ROTATIONAL MOVEMENT

The illustrations so far have shown merely in what direction the armature loop will turn when current passes through it in the presence of a separate magnetic field. To understand how far the loop will go we must return to the fundamental principle shown in Figure 6. We see here that the force exerted on the wire moves it out of the field of the poles, if it is free to move. In Figure 12, etc., the forces exerted on the two sides of the loop are such as to try to move the two sides of the loop out of the field and in directly opposite directions. But they are bound together at a fixed distance by their mechanical construction. Therefore, each wire will move as far from the center line of the field flux as it can. The limit of this movement is reached when the plane of the armature loop is perpendicular to the direction of the field flux. Then each wire is as far as it can go, with the arrangement disclosed to you up to this point. Maybe the rotational movement of the loop will have given it a certain momentum which carries it beyond that point. The wires will have then been carried on around a little way into the more intense sections of the field, and will be pushed back until they are in the neutral position; in Figures 12 and 13, for instance, the loop would come to rest in a vertical line.

COMMUTATION

In explaining the theory of the motor up to this point, we have used illustrations in which the armature received current from the battery through two wiping contacts resting on two separate rings (Figures 8 and 11). In Figure 14 we show a single ring split into two parts. These parts, called "segments", are insulated from the shaft and from each other. Each segment is connected to one end of the armature loop. The segmented ring is known as a "commutator". Pressing against opposite points of the commutator are two conducting strips, making a wiping contact with the commutator, and they are generally called "brushes". These are so mounted that each changes contact from one segment to another when the loop is at right angles to the lines of force. It will be remembered from our

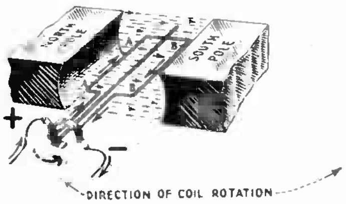


Figure 14

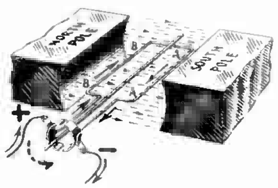


Figure 15

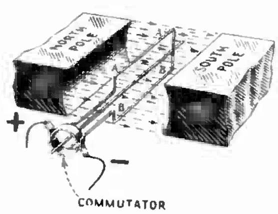


Figure 16

previous discussion that this is the limit to which the loop can turn with the armature current unchanged in direction. The momentum of the loop carries it across the neutral position a little ways. If the original direction of armature current were maintained the loop would then be thrust back into the neutral position. However, the direction of the armature current through the loop was changed by the commutator and brush arrangement when the loop crossed the neutral position. So instead of being pushed back, the loop is pushed forward in the same direction in which it started. (You may check this statement by applying the left-hand rule to Figure 15). It is now due to make a half-turn before coming into the next neutral position which is shown in Figure 16, and here again its momentum carries it across until the commutating action has again changed the direction of the armature current. This continuous pushing in one direction causes the armature loop to speed faster and faster until a steady speed has been reached.

COUNTER ELECTROMOTIVE FORCE

If we forget for the moment that the motor we are studying is rotating because of an electromotive force applied to the armature windings, we can consider the machine as though it were being rotated by some external source of mechanical power, such as a steam engine. In this case the machine becomes a generator, which is treated fully in a separate lesson. It is sufficient for our present purpose to state that when the armature loop is made to rotate in the magnetic field provided, the cutting of the lines of force by the two sides of the loop causes electromotive forces to be generated in them. The direction of these electromotive forces is opposite, as considered from the point of an observer outside the machine; the direction is the same considered from the standpoint of the series path provided by the loop itself. The electromotive forces generated in the two sides of the loop are, therefore, additive in their effect at the terminals of the loop (commutator segments). By the application of Fleming's Right-Hand Rule for the determination of the direction of an electromotive force induced in a moving conductor, we find that this is opposite in direction to the applied electromotive force from an external source which supplies the armature current and makes the rotation possible. The generated e.m.f. is, therefore, known as the counter e.m.f., sometimes called the back e.m.f. Its effect is very important in motor operation; it causes the effective or working electromotive force to become considerably less than the applied electromotive force. Just what the difference is, of course, depends on the numerical value of the counter e.m.f., and this depends on a number of factors, among which we can mention (1) the strength of the field, (2) the length of an armature conductor measured perpendicular to the field, (3) the number of complete turns in the loop, and (4) the rotating speed of the loop.

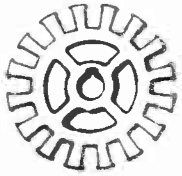


Figure 17

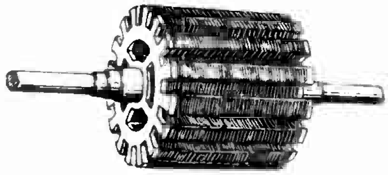


Figure 18

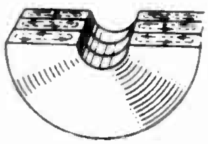


Figure 19

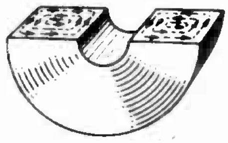


Figure 20

ARMATURE CONSTRUCTION

The armature core of the motor is made up of thin stampings of a good grade of soft iron or steel as shown in Figure 17. A number of these stampings are used to make up the armature core, and this core is then called a "laminated" core. Figure 18 will serve to show you how the armature core looks when all these individual discs have been placed, one against the other, making the completed core. The discs are held in place by various methods. In small motors, bolts are sometimes employed which run through the discs; in others, lock nuts which are threaded to the shaft, and in some makes a collar is shrunk on the shaft holding the discs in place under great pressure.

The armature is made up of laminations to reduce eddy current losses brought about when the armature revolves in a magnetic field. The induced currents within the revolving metal represent a part of the energy being used to operate the motor and do no actual good. In fact an armature constructed of one solid piece of metal would have eddy currents produced in it of such magnitude as to cause the armature to become very hot. This heat represents a large waste of energy. The armature coils absorb a considerable portion of this heat which causes damage to the insulation and overheats the bearings. It is then advantageous to see that such eddy currents are kept to a minimum. The losses are very materially reduced by building up the armature of thin discs of soft iron. By using laminations the magnetic conductivity of the core is reduced and the circulating eddy currents are confined to each disc, thus preventing these undesirable currents from becoming large enough to heat the armature excessively. The insulation between laminations is merely the coating caused by oxidation.

Figure 19 represents an iron core cut in half with the laminations purposely enlarged to show how the eddy currents are confined to each disc. Figure 20 represents a solid iron core showing how the eddy currents would move through the entire core.

When the armature coil is passing under one magnetic pole the eddy currents flow in one direction, but as soon as the armature comes under the influence of a magnetic pole of opposite polarity these currents are reversed in direction.

When the armature is revolving at high speed the eddy currents are rapidly reversed in direction thus causing friction between the molecules of the iron. Friction creates heat which, if allowed to become excessive, not only raises the temperature of the copper conductors, but may cause the insulation of the conductors themselves to burn. This rapid reversal of the molecules creates what is known as "hysteresis losses" and is considered as one of the harmful effects to be avoided in armature design and construction.

The slots along the outside of the laminated core carry the coils of wire on the armature, held in place by small pieces of wood which fit into the slots in the core, preventing the coils from being thrown out of the slots by centrifugal force. A cross section of how this is done is shown in Figure 21.

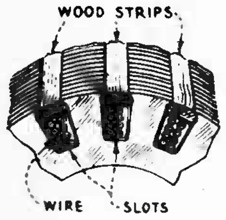


Figure 21

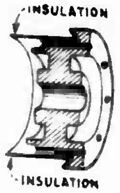


Figure 22

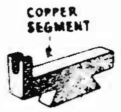


Figure 23

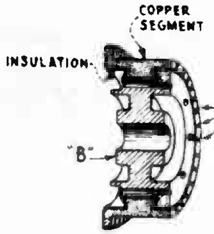


Figure 24

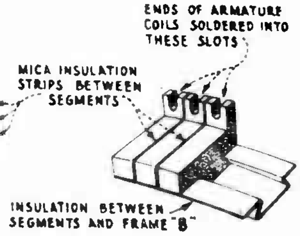


Figure 25

COMMUTATOR CONSTRUCTION

The commutator, the next and third essential part of the motor, is a very ingenious device. First we will see how the commutator is constructed. Figures 22 to 30 inclusive show the construction of the commutator. Figure 22 shows a locking ring which holds the segments in place. It is one solid piece of iron or steel cast in the shape shown. The commutator requires great care in assembling even though the principle of assembly is simple. The following building up process will give you the idea of how the parts are assembled. Figure 22 shows the part we begin with, the first requirement being to insulate the part. On this insulated section are then placed the copper segments which are insulated from each other; Figures 24 and 25 illustrate the alternate arrangement of mica strips and copper segments. After the required number of segments have been placed on the section and insulated perfectly, both from the holder and from each other, the locking ring, Figure 26 is moved into place as shown in Figure 27. The segments are locked into place by tightening the threaded studs which run through the locking ring, into the section, as shown in Figure 28. Figure 29 illustrates the segments as they would appear with a section cut out of a finished commutator, while Figure 30 is the finished commutator ready for fitting to the armature shaft and connection to the armature windings. The beginnings and ends of the armature coils are brought out and soldered into the slots of the segments as shown in Figure 25.

This completes the three major parts of the motor. Our next problem is to assemble these parts into a completed machine.

COMPLETE ASSEMBLY

Now let us consider one armature coil wound on an actual armature. In Figure 31 we can trace the position of this coil from the copper segment on which the top brush rests, across the armature core around the back of the core (as illustrated in Figure 32) into the armature slot on the opposite side of the core; and finally out where the end is taken to a copper segment of the commutator diametrically opposite the segment from which the coil started. Ordinarily coils are wound in all of the slots, but they have been omitted here to enable you to easily trace the position occupied by the one shown on the core. The continual rotation and speed of the motor is dependent upon a great number of coils as you will learn later.

In Figure 33 is shown a typical brush holder and brush, which rests on the rotating commutator and is connected to the power line used to supply the armature with current. For a view of a complete machine you are referred back to Figure 2 at the beginning of the lesson which shows a four-pole machine having four brushes. Two poles at opposite sides of the armature have North polarities; the other two poles, also opposite each other and in between the first

Figure 26

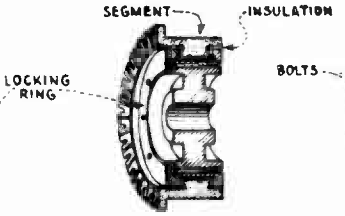


Figure 27

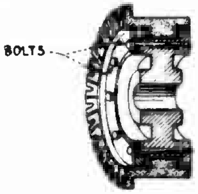


Figure 28

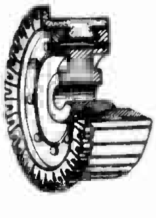


Figure 29

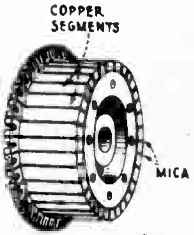


Figure 30

pair, have South polarities. We find also that the brushes are grouped into pairs, each brush being cross-connected to the one on the opposite side of the commutator. The positive power lead is, therefore, connected to the commutator at two places by two of the brushes; the negative lead to two other places on the commutator by the remaining brush pair.

A motor of this type may have six or any other <u>even</u> number of poles, and there will always be the same number of brushes as there are poles, if the power is supplied by a two-wire line.

TYPES OF ARMATURES

Armatures may be divided into three classes according to the core shape and the method of winding the wire on it. The classes are as follows:

1 - Drum Armatures
2 - Disc Armatures
3 - Ring Armatures

DRUM ARMATURES

This type is distinguished by having the entire winding external to the core, as shown in Figures 31 and 32. The core is of a cylindrical or drum shape. Each of the active wires is wound on the external surface of the drum in a direction parallel to the shaft. Such a wire is connected to another active wire by means of a connecting wire which is also external to the core.

DISC ARMATURES

The core for this type consists of a disc, and the active armature conductors are spread out radially on the flat sides of the disc. Armatures of the disc type are very seldom met with in modern practice.

RING ARMATURES

A ring-shaped core is used, and it is wound with a number of coils. Each coil consists of a number of turns of wire wound in and out aroung the ring. Figure 34 gives approximately the placement of a winding consisting of eight coils. This illustration is convenient for us to review the commutator action which it is so necessary for you to understand.

Tracing the current from the battery we see that it flows from the positive side to brush A, thence to commutator segment #1. At point K the current divides; part goes through coils 7-8-1-2 to point K1, thence to segment #5, and through brush B returns to the negative side of the battery. The other part of the battery current goes from point K through coils 6-5-4-3 to point K1, and hence to the negative side of the battery through segment #5 and brush B.

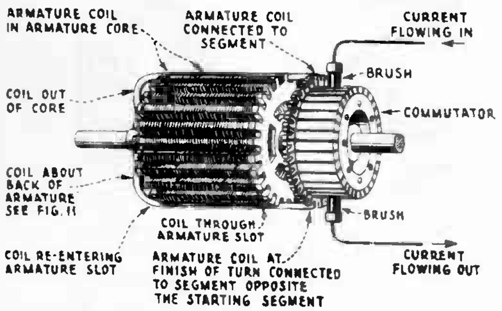


Figure 31

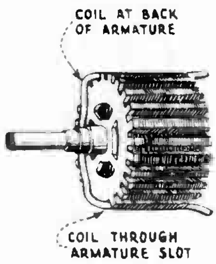


Figure 32

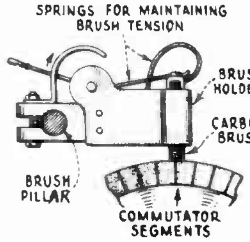


Figure 33

While the illustration does not show it, let us state that all the coils are wound around the armature ring in the same direction. When current enters coil 7 it sets up a North pole in the core ring near point K, and a South pole at that end of coil 7 which is next to coil 8. The current in coil 8 sets up a North pole at the end adjacent to coil 7, and a South pole at the end adjacent to coil 1. Likewise coils 1 and 2 set up magnetic poles in the same direction. This actually means that all the coils 7-8-1-2 and each turn of them works in the same direction to establish magnetic lines of force which make a North pole in the ring at point K, and a South pole in the ring at point K1. Taking the other path from K, the current through coil 6 goes through it in the opposite direction from that through coil 7,and sets up at point K a North pole also, making a South pole in the core on the side toward coil 5. The current passing through coil 5 sets up a North pole on the side toward coil 6, and a South pole on the side toward coil 4. This principle holds for coils 4 and 3. Therefore, the magnetizing effects of the coils 6-5-4-3 are additive, and the lines of force in that half of the ring are concentrated. Their direction is such as to also establish a North pole at K and a South pole at K1. We see then that the magnetizing effect of all the coils combined is the same as though a strong permanent magnet were used with its axis practically at right angles to the line of direction of the flux between the two field poles.

In accordance with your previous study of magnetism, such a magnet would tend to turn and get in line with the direction of the field poles, the North pole of the armature being attracted to the South field pole, and vice versa. But since we are using a commutator on a wound armature we get a more continuous effect. As segment #1 turns up to the right, and segment #5 turns down toward the left, we find that segments #2 and #6 have come under brushes A and B respectively. The current through coil 7 has been reversed and it now has a North pole at its left end where it previously had a South pole. Likewise coil #3 now has a South pole at its right end, where it previously had a North pole. We see then that the North pole of the armature ring has been shifted to a point between coils 7 and 8, and the South pole to a point between coils 3 and 4, with the armature rotated one-eighth of a turn. Therefore, the relation between the direction of the field flux and the armature flux is the same as before, and the turning effect continues.

The commutator is of course the secret of the continual motion produced. It keeps the directions of the current through the various coils such that the combined effect of all the coils is the same at all times as far as directions of magnetic forces are concerned.

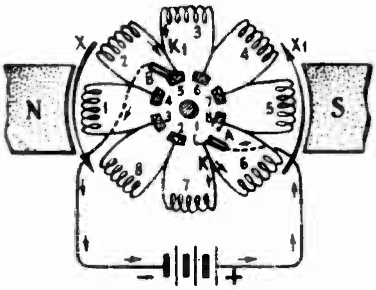


Figure 34

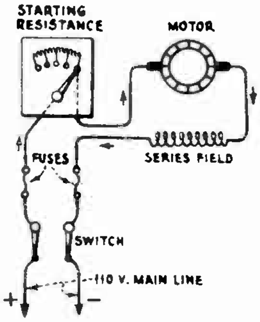


Figure 35

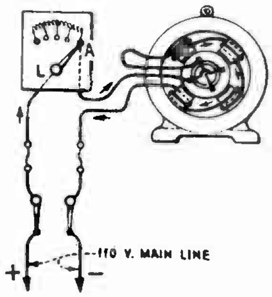


Figure 36

TORQUE AND SPEED

The motor is designed to produce a turning motion as a result of a twisting force which we call TORQUE, and on this torque depends the work the motor is capable of doing. We are interested not only in the work which can be done, but also in the SPEED of the motor in revolutions per minute. The formulas for these are as follows:

Speed: $n = \dfrac{E_a}{\Phi Z'} = \dfrac{V - I_a R'}{\Phi Z'}$ revolutions per minute

Torque: $T = 7.05\, Z' \Phi I_a$ lb. - ft.

where: E_a = counter e.m.f.

V = line voltage

Φ = field strength or flux

Z' = a factor which depends on the number of poles, the length and the number of the armature conductors.

I_a = armature current

R' = the sum of the armature resistance and any other resistance in series with the armature and the line.

These equations are important for our understanding of the operating conditions of various types of motors.

TYPES OF MOTORS

There are three types of direct current motors used in radio practice. They are the series, shunt, and compound.

The different types are used according to the work they have to perform.

The series motor, although not found extensively in radio use, will be briefly explained here in order to enlighten you on the field winding connections. This motor is used mostly in electrical hoisting equipment and in electric traction work. It derives its name from the fact that the field coils are connected in series with the armature.

The series motor connection is shown in Figures 35 and 36; it is noted that all the current for the motor flows through the armature circuit and the field circuit in succession. Inspection of the equation for the speed of a motor shows that the speed of the series type must decrease rapidly with increasing load. When a load is thrown on the motor the twisting force or torque must increase, and from an equation above this can happen only through increasing either the field flux or the armature current. In the

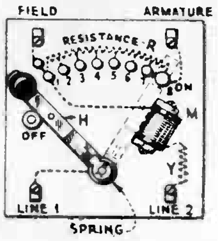


Figure 37

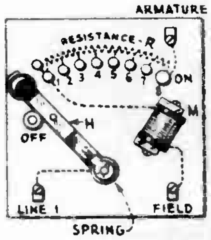


Figure 38

series motor the field flux is proportional to the armature current, so we see that the current will increase to supply the additional power required. Now look at the equation for speed; we have decreased the value of the numerator (above the line) by increasing the IR which is to be subtracted from the line voltage V; we have increased the denominator (below the line) because the field flux is increased in proportion to the current. These two things combine to make an appreciable decrease in the motor speed.

On the other hand, if the machine is designed to run at a certain speed when connected to some minimum load which can be increased, if that minimum load is entirely removed, as by the slipping of a pulley belt off the pulley of the motor, the decrease in work performed will so decrease the armature current that the machine will speed up to a dangerous extent. We, therefore, find a series motor should be coupled to its load either by direct shafting or by sturdy gears, and never by a belt.

SHUNT MOTOR

This type of motor is used where a close regulation of speed is required under loads which are constantly varying. The field coils of the shunt motor are wound with many turns of fine wire, thus making the resistance of the field coils high. This allows only a small current to flow of more or less constant value no matter how much current is flowing in the armature circuit. This is illustrated in Figures 39 and 40. When a load is thrown on such a motor we can interpret its action also in terms of the two equations given you. Looking at the equation for speed, we find again that the IR drop in the armature is increased, decreasing the value of the numerator, and the motor, therefore, slows down slightly under load. This decrease in speed is appreciably less than it would have been for a series motor, in which the field strength would also have been increased by an increase in armature current.

Caution should be exercised in the operation of this type of motor regarding the speed control; the regulation of the speed may be accomplished by the use of a variable resistance in series with the field coil, or by a resistance in series with the armature circuit. The field circuit must not be opened thereby cutting the current off suddenly. If the field circuit suddenly opened the field would become very weak and the motor would operate by the residual magnetism in the field magnets. The armature would increase its speed because sufficient counter e.m.f. could not be generated to reduce the applied e.m.f. and the armature might possibly be torn apart if abnormally high speed were attained. Precautions to guard against an open field will be described later under motor control.

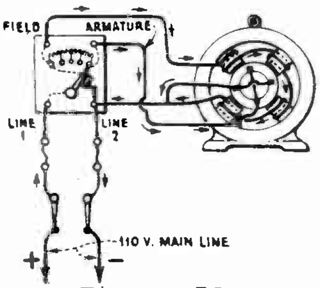


Figure 39

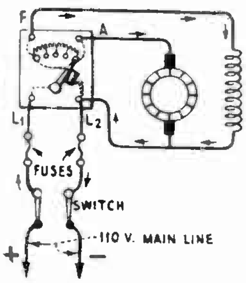


Figure 40

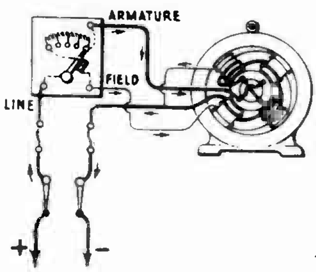


Figure 41

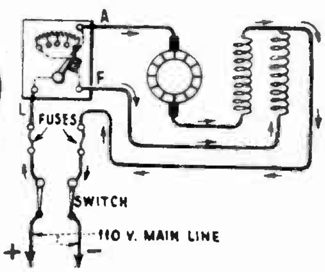


Figure 42

COMPOUND MOTOR

The purpose of this type of motor is to obtain constant speed under all load conditions. It differs from the two types just described because the field is composed of two sets of windings, a series and a shunt winding, as shown in Figures 41 and 42. Most of the field flux is due to the shunt winding. The series winding is so connected that its field flux opposes that due to the shunt winding. Under this condition, when a load is applied the armature current increases, and from the speed equation we see that this decreases the numerator (top part) of the term. At the same time the armature current flowing through the series field winding has increased its opposition to the field flux created by the shunt winding. The net result is a decrease in the strength of the field, which is part of the denominator (lower part) of the term in the speed equation. By design, the decreases in the upper and lower parts of the term are made proportional, and the speed of the motor remains constant. It is even possible to so proportion the strengths of the shunt and the series fields that the speed of the motor is increased somewhat when a load is applied.

When the field due to the series winding bucks the field due to the shunt winding, the motor is said to be differentially compounded. It is, of course, possible to change the connections of either the series or the shunt field winding which will make the two fields add. The motor is then said to be cumulatively compounded. With this type the speed falls considerably with increasing load. Its characteristics may be said to be intermediate between those of the shunt and the series motor. One particular advantage of the cumulatively compounded motor over the series motor is that the former will not"run away" when the normal load on the machine is suddenly removed, but will instead increase its speed to a definite safe limit.

In a compound motor the shunt winding may be connected across the line, in which case it is called a long shunt. It may, on the other hand, be connected right across the armature terminals, (short shunt) and in this case the shunt field current passes first through the series field winding where it has little extra effect as it is small compared to the full armature current passing through the series winding. One terminal of the shunt winding always connects to that side of the armature which goes straight to the line. The other terminal of the shunt winding may connect to the side of the armature which goes to the series winding, or it may pass over the series winding and connect to the second line wire. The first of these methods is the short shunt and the second is the long shunt.

STARTING A MOTOR

The resistance of an armature coil is very low and to place the line voltage, of say 110 volts, on an armature coil when it is not in motion would be the same as connecting a short wire around the terminals of a battery; that is to say, the armature would cause a short-circuit on the 110-volt line. In our study of the motor, however, we discovered that as soon as an e.m.f. was applied to the commutator segments through the brushes, current moved into the armature coil and the coil at once was forced to move.

In this starting of the motor armature the current taken by each coil is more than is required to drive it. If you connect an ammeter in the circuit it may read 25 amperes at first, but as the armature gains speed, you will see the ammeter needle gradually drop back until, when the armature is revolving at full speed, the meter may only read 4 or 5 amperes.

Now why did the current drop from 25 to 5 amperes? At the start the armature coils were practically a short circuit, which allowed an excessive current to flow; but as this excessive current flows in the coils for a very short period of time no damage is done in the case of a small motor.
As the motor armature begins to revolve its coils act similar to those of a generator, that is, an electromotive force is developed in the coils, called counter e.m.f. This counter e.m.f. opposes the current which is causing the armature to revolve, and by virtue of this opposition limits the amount of current flowing in the armature. As the speed increases this back or counter e.m.f. becomes greater and greater, allowing less and less current to flow into the coils.

This continues until the full speed is reached when the back e.m.f. may, for instance, reach a voltage of 105 volts. If there is 110 volts applied and 105 "bucking" or opposing it then, 110 − 105 = 5 volts, which will be the total e.m.f. forcing current through the armature coils. Suppose the resistance of the armature is one ohm. By Ohm's Law $I = \frac{E}{R}$. $I = 5 \div 1 = 5$ amperes, or the total current flowing in the armature when it is up to full speed. By Ohm's Law figure out what the current flow would be in the armature coils if the armature did not rotate.

$$I = \frac{E}{R} \text{ or } I = \frac{110 \text{ volts}}{1 \text{ ohm}} = 110 \text{ amperes.}$$

This would certainly place a short in the line and cause the fuses to blow, thus protecting the armature coils from burning. Therefore, you can realize the importance of c.e.m.f. as applied to the motor; it acts to regulate the current.

So far the motor has merely been revolving without driving any machinery. Suppose now the motor is connected to a load; the motor will momentarily slow down and the counter e.m.f. will at the same time become less, and more current will flow into the armature windings. Now disconnect the load; the speed of the armature increases and so does the counter e.m.f. thus reducing the current flowing into the armature. Any variation in the speed of the armature will cause a variation in the counter e.m.f.

This counter e.m.f. then acts to automatically regulate the flow of current into the armature when the load on the motor is varied.

Motors such as we are going to use require some means of controlling the e.m.f. applied to the armature at the time of starting the motor, therefore, a resistance is placed in the motor line to regulate the current flow to the armature coils. When the normal speed of the motor is reached this resistance is cut out of the circuit.

This regulating device is called a starting box and is shown in Figures 35 and 36. Further explanation of starting boxes will be taken up later in this lesson.

MOTOR STARTING BOXES

Controlling the start and stop of electric motors and generators is accomplished by either the manual type of control or by the automatic or remote control. The modern radio transmitter is equipped with the latter type so that the operator may start and stop the apparatus from the operating table. Other methods require that the motor generator sets be started and stopped by manipulating the lever of the starting rheostat.

The starting resistance of direct current motors, as explained, controls the current flowing in the armature of the machines. A further control of this applied current to the armature is effected by the counter e.m.f. developed by the armature after it begins to rotate. The starting resistance may be cut out of the circuit gradually as speed is attained. As the resistance of the armature is low the starting resistance is necessary to limit the current to a safe value until the armature has attained its full speed.

Figure 37 illustrates what is known as a four-terminal starting box while Figure 38 shows the three-terminal box.

The difference between the two starting boxes is in the connection of the holding magnet in the circuit. In Figure 37 the holding magnet is connected in series with the resistances Y and R and across the 110-volt circuit as shown. The starting box of Figure 38 has the holding magnet connected in series with the shunt field of the motor and resistance R.

Figure 39 illustrates the method of connecting a shunt motor to a four-terminal starting box. Figure 40 is a schematic diagram of the same motor and box.

Figure 41 shows the proper connections for a compound wound motor and a three-terminal starting box with a schematic diagram shown in 42. When it is desired to start a motor with this type of control the starting arm H, Figure 38 is moved slowly across the contacts. When the armature is on contact Number 1 current flows from line 1 to the starting arm through the arm to resistance contact 1, through all the resistance coils to contact 8 where it is led to the terminal marked armature and from there to the motor armature. As the arm is slowly moved over the contacts the resistance is gradually cut out. When arm H reaches the holding magnet M and rests on contact 8 all the resistance is out and current flows directly from line 1 to the armature.

The magnet M holds the arm H which is made of soft iron, in the running position as shown by the dotted arm in Figure 37. This magnet is connected to the first contact and it receives full voltage at first, but as the arm moves over the contacts less e.m.f. is im-

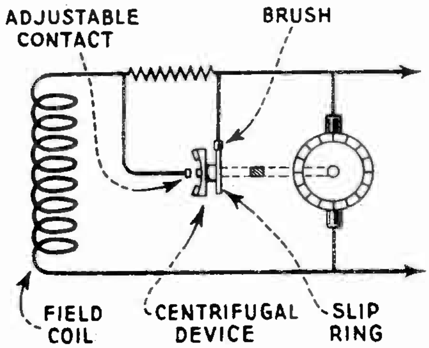


Figure 43

pressed across the magnet windings due to the increased resistance through R as the arm is moved to full running position. Hence, when the arm is in full running position, just enough current flows through the magnet windings to attract and hold the arm. The resistance protects the magnet winding from heating.

If the shunt field circuit or the line switch is opened for any reason the magnet current is cut off and the arm is pulled back to the "off" position by a spring located in the shaft supporting the handle.

AUTOMATIC SPEED CONTROL

In some uses of motors an evenness of speed is desired which must be better than can be achieved merely by the design of the motor itself. Mechanical principles are then brought to bear on the problem, as in the case of a small motor which is used to move the film in a sound picture projection machine. Steadiness of speed is essential here as any speed change will change the musical pitch of the sound program being picked off the film.

In Figure 43 is shown the schematic wiring of such a machine. It is shunt wound, and a resistance is placed in the lead from one side of the line to one side of the field winding. The effect of the resistance is to decrease the current which would otherwise flow through the winding. At one end of the motor shaft is a centrifugal device consisting of two fly-weights secured by hinges to a disc on the end of the shaft. At the center of the spring which joins the fly-weights there is a contact, connected to a slip ring on which rests an ordinary brush. When the motor is not running the spring holds the fly-weights in toward the shaft. As the motor picks up speed, the centrifugal force tends to throw the weights out away from the shaft, which action is resisted by the spring holding the weights together.

Opposite the contact which is central to the fly-weights, there is another contact and this latter can be adjusted by means of a dial so that its distance from the moving contact can be changed. The two contacts will touch when the machine has reached a certain speed which is sufficient to extend the fly-weights away from the shaft enough to thrust the moving contact over against the fixed one. This operation places a short across the resistance which is in series with the field winding, the field strength is increased and the motor slows down, as previously described. The slowing down of the motor makes the fly-weights draw in closer to the shaft and this opens the contacts again. The resistance is once more inserted in series with the field winding, weakening it so that it speeds up again slightly.

The success of such a device depends on a very accurate design and a sturdy construction, so that very small changes in speed will operate it to cause an effect which will be opposite to the change.

EXAMINATION QUESTIONS

1. What are the principles underlying the operation of electric motors?

2. What is the function of an electric motor?

3. Name the essential parts of a d-c motor.

4. (a) What is the purpose of the armature?
   (b) How is it constructed?

5. What is the meaning of torque?

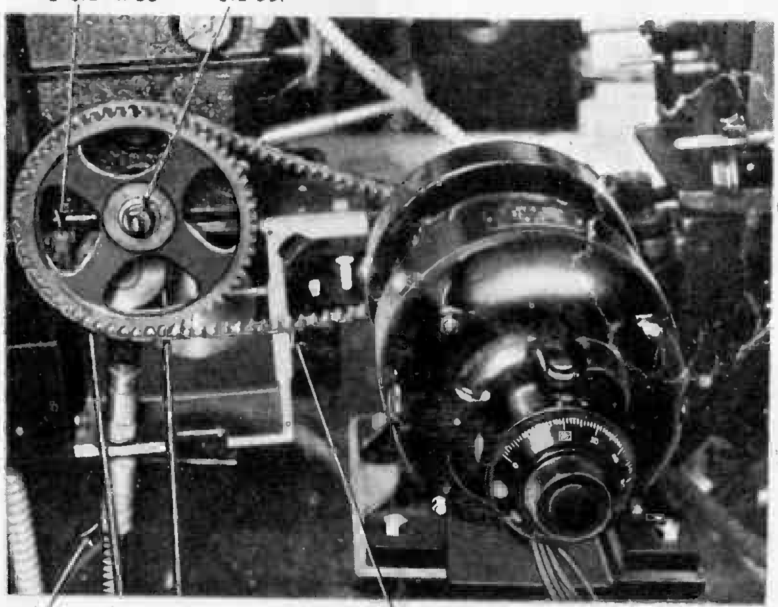
6. Give an equation for torque, and explain what each symbol represents.

7. What advantage has a cumulatively compounded motor over a series motor?

8. What is the purpose of the commutator? How is it constructed?

9. How is the speed of a shunt motor regulated?

10. Explain the action of a motor starter.



DC Motor Drive in a Sound Motion Picture Machine