7

Motors, Generators, and Control

YOU DO NOT have to be an expert in motors and generators to work in industrial electronics. However, remember that much industrial electronic circuitry is used for controlling motor speeds and generator voltages. For that reason you should have a good basic understanding of how motors and generators work because it will better help you to understand their control.

Both dc and ac motors are used in industry and each has their special advantages and disadvantages. DC motors are very popular because their direction can easily be reversed and it is a simple matter to control their speed, especially at very low speeds.

By contrast, ac motors do not have a high torque development at very low speeds, so it is common practice to use some type of belt and pulley or transmission system to get satisfactory torque at low speed.

DC motors have a very high torque at start-up speeds. This is especially true of a series motor discussed in this chapter. For portable operations, dc motors are preferred because they can be operated directly from a battery. Also, generators or alternators can be used to charge a battery when it is away from any ac source. When near an ac source, a rectifier power supply can be used to provide the dc necessary for charging batteries.

The biggest disadvantage of dc motors in industry is that dc is not readily available. When dc motors are used in industrial processes, it is necessary to deliver the dc from a central source by using very large bus bars. That is expensive compared to delivering ac power to an ac motor.

AC motors, then, have the advantage that the power for operating them is readily available. These motors are economical and relatively simple to construct. They do not usually require brushes and commutators. Therefore, they require very little maintenance during their lifetime of operation.

By contract, dc motors must have their brushes periodically replaced. Failure to do that can be destructive to the commutator and that means additional maintenance problems.

There are certain types of ac motors that have a built-in speed control. As you will see in this chapter some motors have their speed directly controlled or dependent upon the frequency of the input signal.

CHAPTER OBJECTIVES

After studying this chapter, you will be able to answer the following questions:

- What is the basic construction of dc motors and generators?
- What is a series-wound dc motor and what are its advantages and disadvantages?
- How can a dc motor be used as a generator and how is this capability used to stop the dc motor?
- Why are capacitors needed for starting some types of ac motors?
- Which type of ac has a speed determined by the input ac frequency?

PHYSICAL LAWS AND EFFECTS RELATED TO ELECTROMECHANICAL DEVICES

There are some basic physical laws and effects that are important in understanding the operation of many electromagnetic devices. Some examples of those devices are:

- Transformers
- Motors
- Generators
- Relays
- Solenoids
- Hall devices
- Ferrite beads

Faraday's Law. Faraday's law states that any time there is relative motion between a conductor and a magnetic field, a voltage is induced in the conductor. Refer to Fig. 7-1. Here a conductor is positioned between two magnetic poles. If that conductor is moved vertically, a voltage will be induced across its ends because it is moving through the magnetic flux between the poles. If a conductor is moved horizontally, there is no voltage induced because it is not cutting across any flux lines.

The distribution of flux lines between the poles is also shown in Fig. 7-1. If the conductor is moved at an angle to the flux, the induced voltage will be less than for vertical motion and greater than for horizontal motion. A greater angle between the motion and the flux lines results in a higher induced voltage.

Faraday's law describes the amount of voltage induced. Mathematically, this equation is written as follows:

$$v = -N\,(d\phi/dt)$$

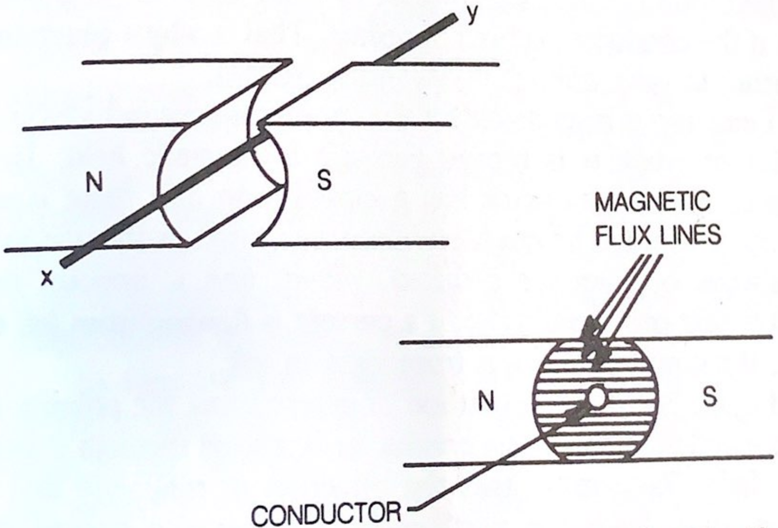

Fig. 7-1. Conductor XY is suspended between the magnetic poles. The side view shows the distribution of flux between the poles.

where N is the number of conductors moved through the magnetic field, and $d\phi/dt$ is the rate at which the conductor is cutting through the flux lines.

The higher the rate of cutting flux lines, the higher the value of $d\phi/dt$. You can see from the equation that you can increase the induced voltage by moving more than one conductor at the same time and connecting them so that their voltages add. Likewise, you can increase the voltage induced by increasing the number of turns.

Lenz' Law. The negative sign in the equation for Faraday's law is used to indicate that the induced voltage has a certain polarity. Specifically, if a connection is made across the ends of the conductor being moved, there will be a current flow. In this book we will define that current as being an induced current.

The induced current, like all currents, has a surrounding magnetic field. That magnetic field will always be in such a direction that it opposes the motion that produced it. This is a very important concept. It indicates that you have to do work (force × distance) to move the conductor through the magnetic field if that conductor is part of a closed current path.

Voltage is a unit of work. Technically, voltage is the amount of work done in moving a unit charge of electricity around a closed path. The amount of voltage generated is related to the amount of work done in generating it. If it is part of a closed-loop circuit, the amount of work required is greater than if the conductor is not connected. That is why a generator is harder to turn when it is delivering current.

Lenz' law is responsible for the countervoltage induced in a conductor when it is moved through a magnetic field. This assumes that a conductor has a closed loop and there is an induced current. The countervoltage generated in the conductor always opposes the induced current and it opposes the motion that produced it. So, if a current is flowing from left to right, the countervoltage is from right to left.

Figure 7-2 shows a method of determining the polarity of an induced voltage when a conductor is moved through a magnetic field. Remember that the direction of magnetic flux is always away from the north magnetic pole and toward the south magnetic pole.

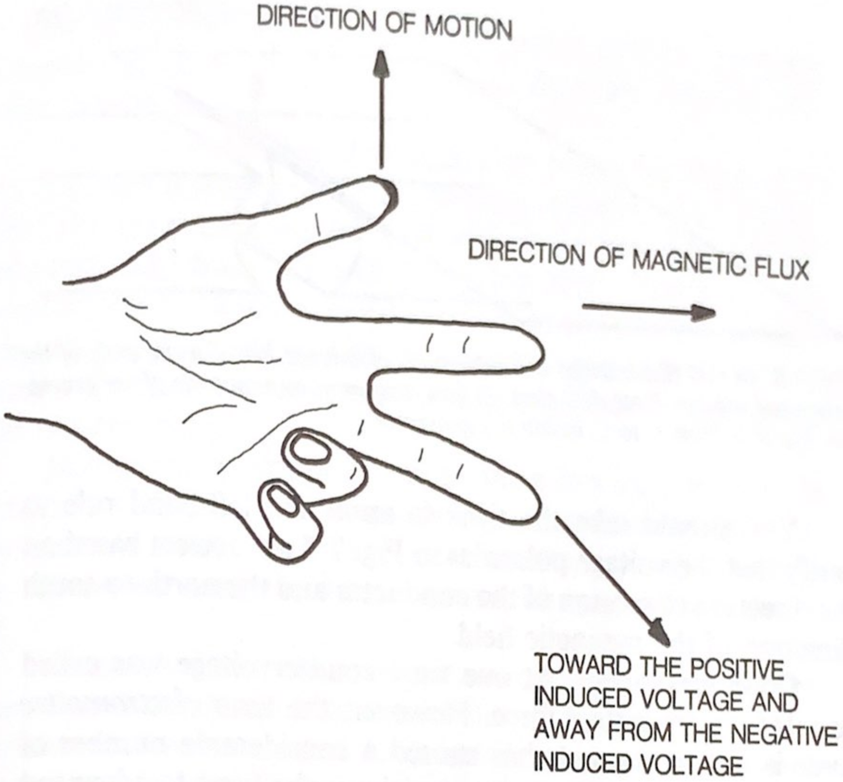

Fig. 7-2. The left hand rule shows the polarity of induced voltage when the conductor is moved in the direction indicated by the thumb. The hand is presumed to be inside the generator.

To summarize, voltage is induced when a conductor moves through a magnetic field. The voltage is directly related to the number of conductors and the speed that the conductors move relative to the flux line. Whenever voltage is induced, an induced current will flow, provided the ends of the conductor are connected in a closed circuit. The induced current always has a magnetic field that opposes the motion of the conductor. Furthermore, when the conductor moves and there is a closed circuit, there is a countervoltage that opposes the induced current. A countervoltage will always oppose any change in the magnitude of the current in an inductive circuit.

In Fig. 7-3 the conductor is being moved through the magnetic field and there is a complete path for current flow. Observe that the electron current flow is from − to + . If you are using conventional current flow, the direction of current will be reversed. However, the polarities of the induced voltage will be the same.

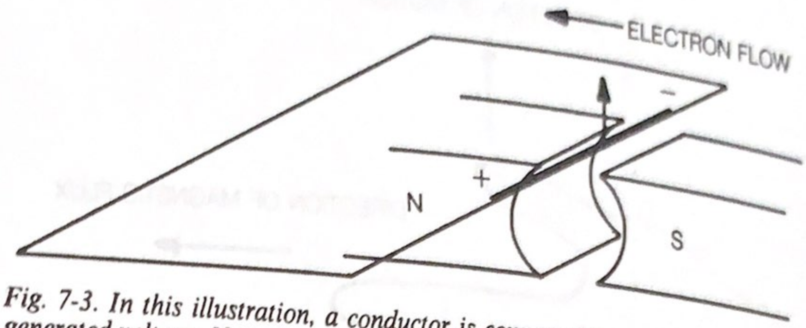

Fig. 7-3. In this illustration, a conductor is connected between the ends of the generated voltage. Note that electron flow is from – to + outside of the generator, but it is from + to – inside the generator.

You should take the time to apply the left-hand rule to verify that the voltage polarities in Fig. 7-3 are correct based on the direction of motion of the conductor and the north-to-south direction of the magnetic field.

Countervoltage. At one time countervoltage was called counter electromotive force. However, the term *electromotive force* is out of favor. It has caused a considerable number of problems with students and technicians who went to advanced work. Voltage is a unit of work. It is not a unit of force.

This is not an important point at the technician level, but in advanced work it becomes necessary to work with equations and to rationalize units. It is never possible to do that and come out with voltage as a unit of force. It always comes out as a unit of work.

Nevertheless, considering voltage a force that pushes electrons through the circuit is a very good model as long as you remember that it is only a model.

Figure 7-4 shows two conductors being moved simultaneously through a magnetic field. The original conductor (XY)

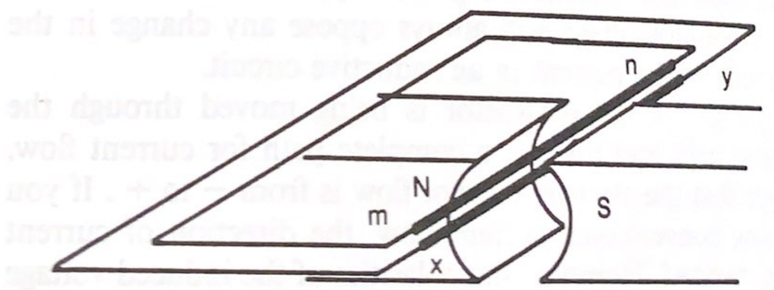

Fig. 7-4. Parallel conductors will result in a countervoltage.

is now in parallel with the new conductor (MN). There are complete paths for current to flow, so there are induced currents in both lines.

You will remember that whenever a current flows in a circuit, there is always an accompanying magnetic field. Therefore, the magnetic field for MN will cut across XY and the magnetic field from XY will cut across MN. Therefore, each conductor will induce a countervoltage in the parallel conductor inside the generator. That countervoltage will always be in such a direction that it opposes the flow of induced current in the external circuit.

In a typical motor or generator there is a large number of parallel conductors—each generating voltages in nearby conductors. So, every motor has a countervoltage generated inside it. Also, every generator has a countervoltage generated inside it.

Ampere's Law. One important concept that has been mentioned should be discussed further. It has been stated that whenever there is a current flow, there is always an accompanying magnetic field. That magnetic field circles the current. According to Ampere's law, the strength of the magnetic field is directly proportional to the amount of current flowing.

The left-hand rule is sometimes used to define the direction of the magnetic flux around an electron-current carrying conductor. If you (mentally!) grasp the conductor with your left hand so that your thumb points in the direction of electron flow, your fingers will circle the conductor in the direction of the accompanying magnetic field. That is always north-to-south.

Again, for conventional current flow you will use the right hand, pointing your thumb in the direction of conventional current flow. Your fingers will still grasp the wire in the direction of the magnetic flux.

The Motor Rule. So far we have discussed the generation of voltages and countervoltages when conductors are moved through a magnetic field. Now consider what happens when a current-carrying conductor is placed in a magnetic field. This is the principle upon which motors are based.

The magnetic field accompanying a current interacts with the magnetic field between the poles of the magnet. If the conductor is free to move it will do so.

The direction of motion of the conductor can be determined by the right hand motor rule. As with the left hand generator rule, this is another form of Flemming's rules. Flemming's rules were originally based upon conventional current flow.

Figure 7-5 shows how the right hand rule applies. Again, the forefinger points in the direction of magnetic flux. The electron current through the conductor is represented by the second finger. The thumb now points in the direction the conductor will move if free to do so. You can see that the conductor will move up, in the illustration of Fig. 7-6.

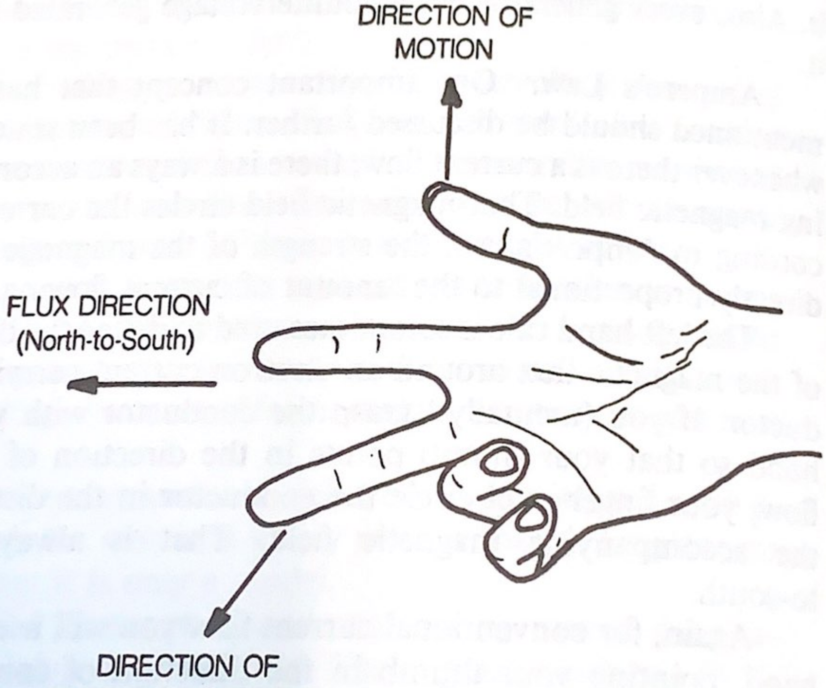

Fig. 7-5. The right-hand motor rule describes the direction that a current-carrying conductor will move when placed in a magnetic field.

Figure 7-7 shows two important models of current-carrying conductors in magnetic fields. To understand this model you should understand that magnetic flux lines always try to take the shortest possible distance. One concept compares them to rubber bands. You can stretch them out of their normal posi-

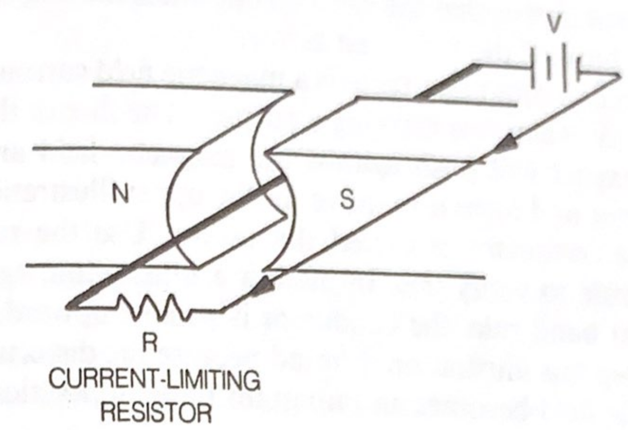

Fig. 7-6. An external power supply and a limiting resistor is used to move the conductor.

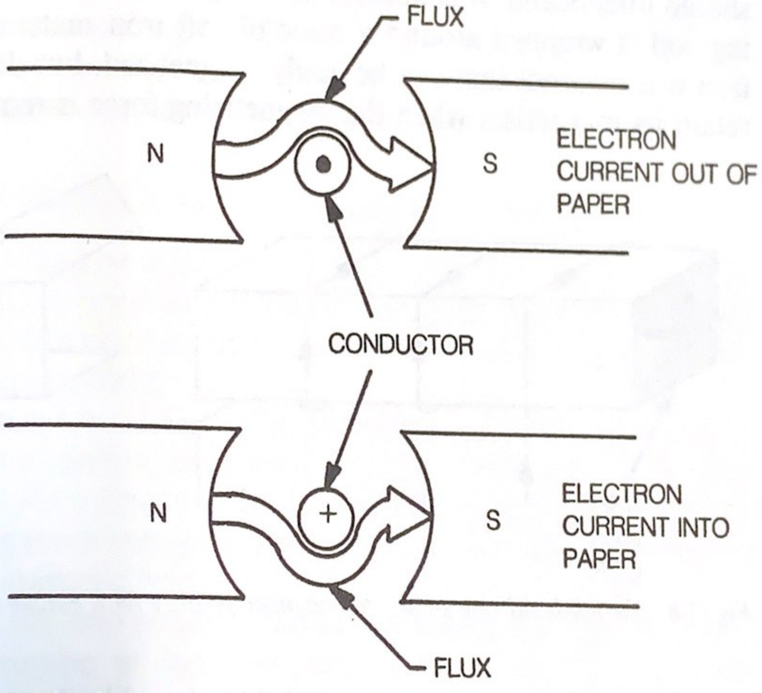

Fig. 7-7. Flux lines wrap around the current-carrying conductor and force it to move.

tion but they will always try to return to the position of least distance.

The symbolism in Fig. 7-7 is standard. A dot in the center of the conductor means that the electron current is moving toward you. (Think of the tip of an arrow.) The plus sign in the conductor means that the electron current is moving away from you. (Think of the tail of an arrow.)

Keep in mind that there is a magnetic field surrounding the conductor when it is carrying a current. The flux of the permanent magnet will push against the magnetic field around the conductor and force it to move. In the upper illustration of Fig. 7-7, the conductor is forced downward. Use the right hand motor rule to verify this. In the lower illustration, again using the right hand rule, the conductor is pushed upward.

Keep this illustration in mind because the distortion of the magnetic field becomes an important thing in practical motors and generators.

The Left-Hand Rule for Coils. Before leaving the subject of physical laws and effects, there is one more rule that you should understand. It is illustrated in Fig. 7-8. A current carrying coil is wrapped around a piece of soft iron material. Soft iron is a material that can be easily magnetized, but does not retain its magnetism when the magnetizing force is removed.

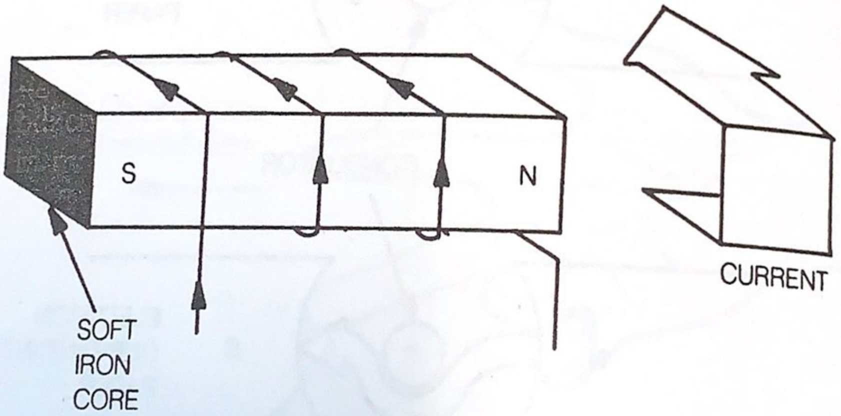

Fig. 7-8. The left-hand rule shows the magnetic polarity for a simple coil.

The direction of the magnetic field induced in the soft iron can be determined from the direction of the current in the coil. A left hand rule is used in this case. Grasp the coil (in your imagination only!) with your fingers pointing in the direction of electron current around the coil and your thumb will then point in the direction of the north pole of the induced magnetism.

For conventional current flow, the right hand rule is used. The electron current would then be reversed. The coil would be conductor means that the electron current is moving away from you. (Think of the tail of an arrow.)

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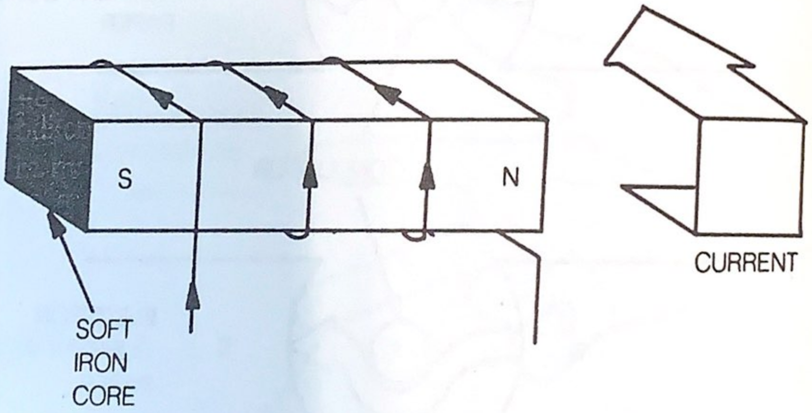

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For conventional current flow, the right hand rule is used. The electron current would then be reversed. The coil would be grasped with the right hand and the thumb would point in the direction of the north pole.

You may well wonder about the use of some of the physical laws and effects that were discussed in this chapter. Does an industrial electronics technician really need to know these things?

Actually, the rules, physical laws and the effects are primarily for improving your understanding of motors and generators. They are not necessarily things that you would apply in your job every day. This is not only true of the physical laws and effects in this chapter. In all chapters and in all books, technical theory is presented to help your understanding of the subject. Not every single sentence is directed to things you can do on your job. Instead, authors want to make it possible for you to have a better understanding of how the things work. If you know how things work, you will be better able to find out what is wrong when they are not working. From this point we will discuss some practical motor and generator ideas.

MORE PRACTICAL GENERATORS AND MOTORS

Consider now the illustrations in Fig. 7-9. Instead of being straight, the conductor has been bent into the shape of a loop. We will first consider what happens when this loop is turned in the magnetic field.

Using the rules given for generators, you will see that with a clockwise motion, the voltage induced in one side of the loop adds to the voltage in the opposite side of the loop. Therefore, twice as much voltage will be generated when the loop is turned in the magnetic field.

In the zero position, the loop is cutting through the maximum number of flux lines per instant of time. Therefore, the induced voltage is maximum. After the loop has been turned 90 degrees, the conductors of the loop are moving parallel to the flux lines between the poles. Since they are not cutting across conductors, there is no voltage being generated.

After the loop has passed the 90 degree position, the conductors again move through the magnetic field. If you keep track of the direction of the induced voltage in one side of the

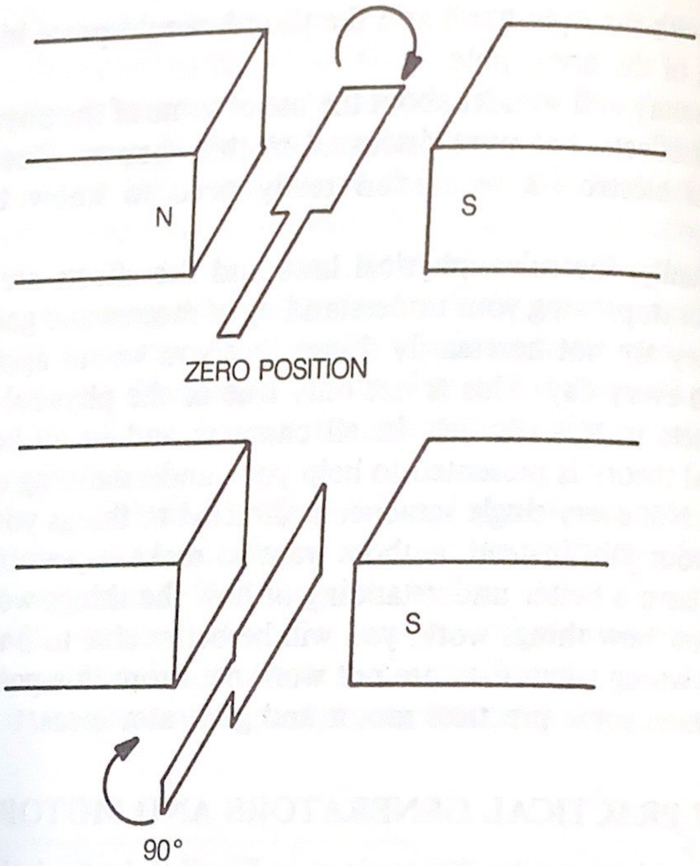

Fig. 7-9. The conductor between the poles is made into a loop. Two positions for the loop are discussed in the chapter.

loop you will see that it reverses after the loop passes the 90 degree point.

If the loop is turned at a constant speed you will get an ac voltage across the ends of the loop. That would be OK for an ac generator but since we want dc current here, the output of the loop will have to be rectified in some way. Of course, diodes could be used. In that case the device becomes an alternator, which is a dc generator obtained by an ac generator with a diode rectifier connected to its output. The alternator in cars is based upon this principle of operation.

Normally, the generator output is rectified by a mechanical rectifier. The mechanical rectifier is made of a commutator and carbon brushes.

The loop of wire of Fig. 7-10 is physically and electrically connected to a commutator. As the loop rotates, so does the commutator. In the positions shown, the maximum voltage is

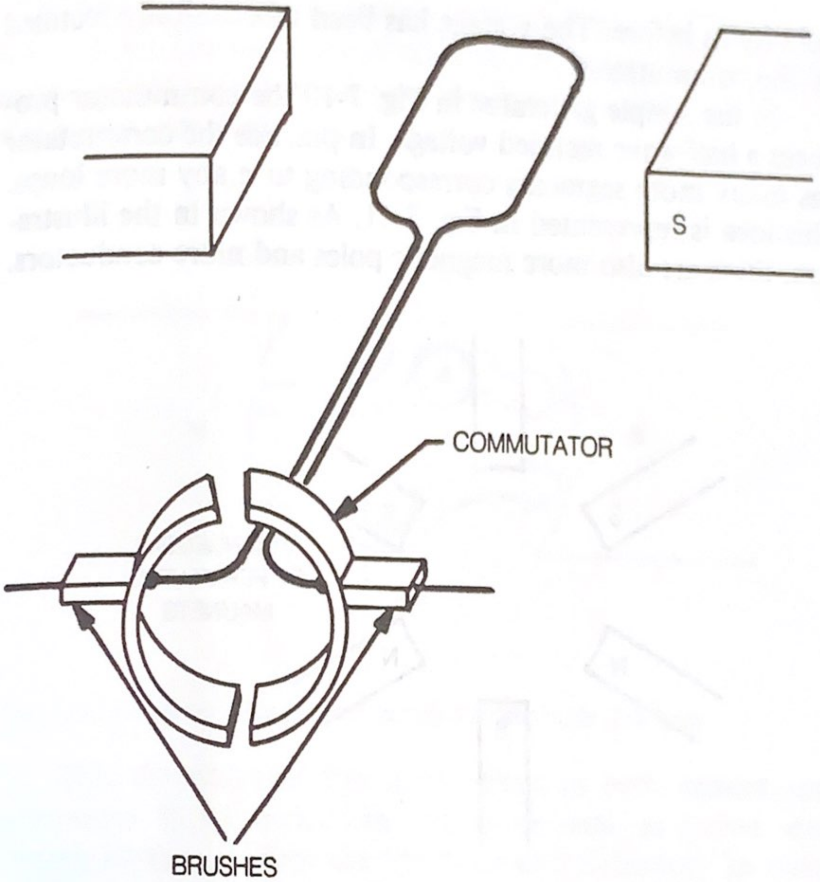

Fig. 7-10. The loop is connected to a commutator that acts as a mechanical rectifier.

being delivered to the commutator segments so, maximum output is obtained from the brushes.

If you mentally rotate the loop and commutator 90 degrees, while holding the brushes in their position, you will see that the brushes are connected to the slots in the commutator ring. In practice these slots are filled with a material that keeps the brushes in position. Brushes are pushed against the commutator segments by springs in order to get good contact.

As the loop continues to turn, the section that was originally on the left side in Fig. 7-10 is now on the right side. However, the commutator has switched this side of the loop to the right-hand brush. Likewise, the loop that was on the right-hand side is now on the left-hand side and the commutator has switched this side of the loop to the left side of the brush. The overall result is that the output voltages will have the same polarity as before. The voltage has been mechanically rectified by the commutator.

In the simple generator in Fig. 7-10 the commutator produces a half-wave rectified voltage. In practice the commutator has many more segments corresponding to many more loops. This idea is represented in Fig. 7-11. As shown in the illustration, there are also more magnetic poles and more conductors.

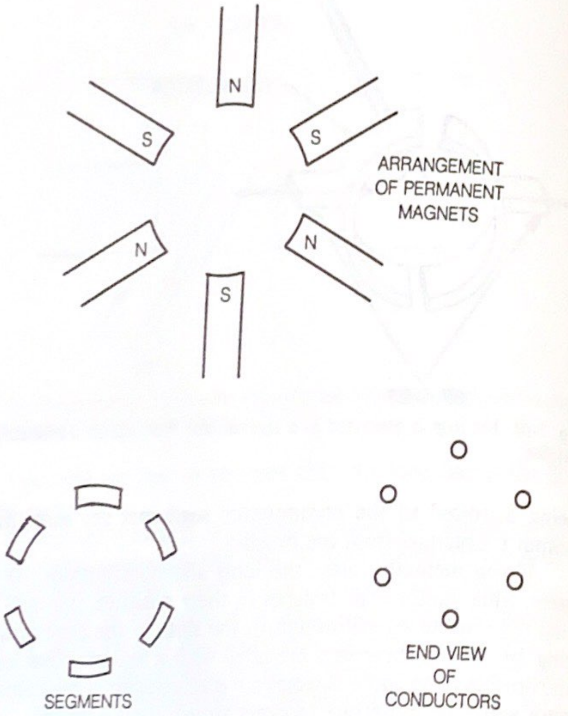

Fig. 7-11. There are usually more commutator segments, more poles, and more loops. This gives a smoother operation.

The overall result is that the output voltage at the brushes never actually drops to zero volts. The result is a dc voltage with a very slight ripple, dependent upon the number of commutator segments and loops.

Interpoles. The illustration in Fig. 7-7 has been upgraded in Fig. 7-12. The two ends of the loop are being rotated in the magnetic field. The distortions of the flux lines, due to each half of the loop, are illustrated.

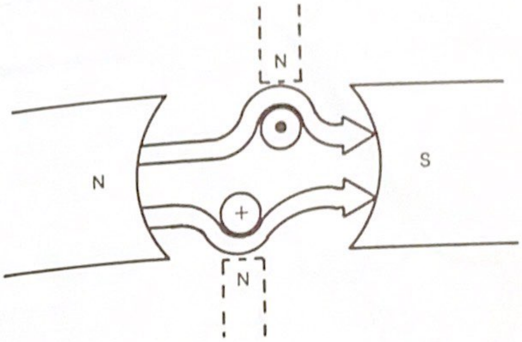

Fig. 7-12. Interpoles may be used to help straighten the flux lines.

This distortion of flux lines occurs in both motors and generators. In some cases interpoles are used, as shown with broken lines, to reduce the effects of flux distortion. In other words, the interpoles straighten the flux lines. If the flux remains in its normal position, there will be a greater force or greater voltage on the conductors when there are interpoles. These interpoles are normally connected inside the generator.

Instead of turning the loop between the magnetic poles to produce a generated voltage, it is possible to apply a voltage through the commutator segments. That is how dc motors are made. The basic concept is illustrated in Fig. 7-13.

The rotating loop and commutator segments are mechanically fixed to the shaft of the motor. As the loop and segments turn, the motor shaft turns. The motor shaft is not shown. For the position shown in Fig. 7-13, the maximum turning force—or *torque*—will be produced.

When the loop has turned 90 degrees, the segments in the commutator reverse the currents in the two loop halves. The motor continues to turn.

In practice, a motor of the type in Fig. 7-13 will work, but it does not have the smooth operation usually required for dc

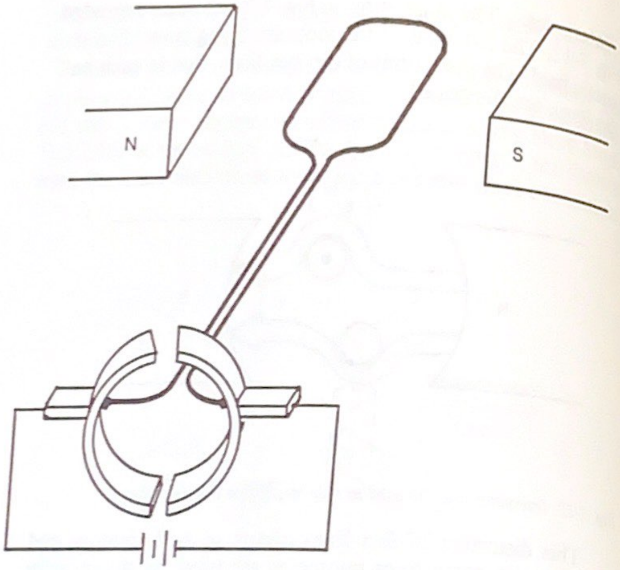

Fig. 7-13. This is the basic principle of operation for a dc motor.

motors. So, the motor is modified as shown in Fig. 7-11 to include a number of magnetic poles, conductors, and commutator segments.

DC Motor-Generator Action. From the similarity in the illustrations in this chapter, you can see that dc motors and generators have the same basic construction. A permanent magnet dc motor will produce a voltage at its terminals if its shaft is rotated. Conversely, the permanent magnet dc generator will run like a motor if a voltage is applied to its terminal.

This concept is sometimes used to test generators. A dc voltage is applied to see if a generator will rotate like a motor.

Likewise, motors can be checked to see if they will produce a dc output when their shaft is rotated. These are just quick checks in a troubleshooting procedure. They do not tell you anything about the condition of the motor or generator.

The similarities between motors and generators are also used to other advantages. Suppose, for example, a dc motor is turning at high speed and it becomes necessary to stop it quickly. If you short its terminals together, after removing the applied voltage, a countervoltage is induced in the conductors and an induced current flows that opposes the rotation. This procedure is called dynamic braking. A motor can be stopped very quickly using this technique.

Another method for stopping a dc motor quickly is to reverse the polarity of voltage applied to its terminals. This method is called plugging.

In some battery-operated equipment the technique is slightly modified. When the motor is running at full speed, it is doing its normal work. When the motor is stopped, the countervoltage is used to charge the battery, thus insuring a longer time interval between major charges.

Motor/Generator Excitation. A magnetic field is absolutely necessary for the operation of these types of generators and motors. In dc applications the magnetic field is constant. It may be produced in any of three ways.

First, it can be produced by a permanent magnet. In today's technology, permanent magnets can produce very strong fields and they do not deteriorate with time as in earlier days.

The second method of producing a magnetic field is called self-excitation. When a generator is self-excited, it means that the dc produced by the generator is not only delivered to the external terminals but is also used for producing the magnetic flux. This situation is illustrated in Fig. 7-14.

With the switches in the position shown, the output of the generator commutator delivers a current through the field coil. Since this current is in series with the armature, this is a series-wound generator. The important point is that the coil current is produced by the generator itself. This same technique can be used for shunt and compound-wound generators.

The third method of producing the magnetic flux occurs when the switches are set opposite from what is shown in Fig. 7-14. Now, an external power supply (V) is used to produce current in the coil. This is called a separately excited motor or generator field.

In this illustration, a variable resistor limits the amount of current through the coil. When the motor is first started, the coil

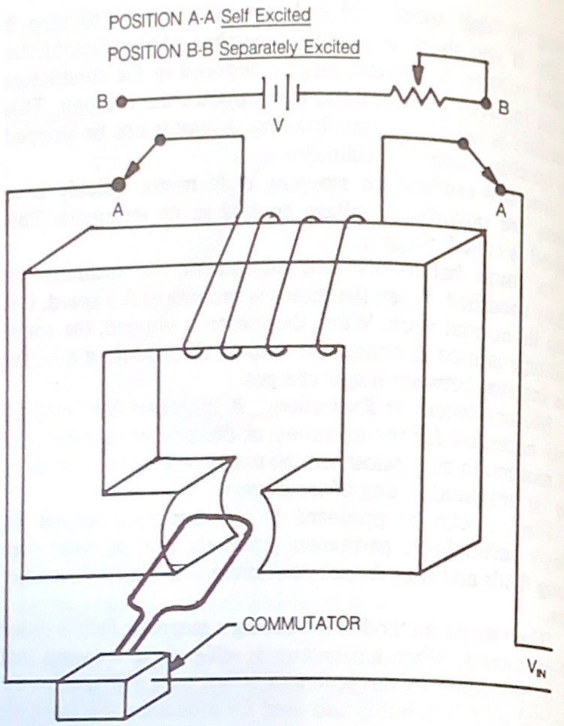

Fig. 7-14. Different methods of excitation.

current must be very low because they is very little opposition to current flow other than the resistance of the coil and the resistance of the rheostat in series with the coil.

When the motor or generator is operating at full speed, a countervoltage is generated in its coils. That countervoltage opposes the current through the field coil, so the resistance in series with the coil of Fig. 7-14 must be decreased in order to make full use of this separate excitation.

If the variable resistor is set in one position, it is not possible to get a good compromise between the maximum possible current in the coil when the motor or generator is running and the minimum current when it is first starting. Therefore, the variable resistor must be operated manually as the motor or generator is brought up to speed.

A variable resistor is not an efficient way to do this. Instead, it is a common practice to use manual starters to bring the motor or generator up to its full capability. This is primarily applied to motors, but theoretically it could also be used for generators.

Operation of a Manual Starter. The manual starter in Fig. 7-15 is one example of how manual circuits can be used to start a motor and bring it up to its maximum speed. Electronic starters are also available that accomplish the same thing.

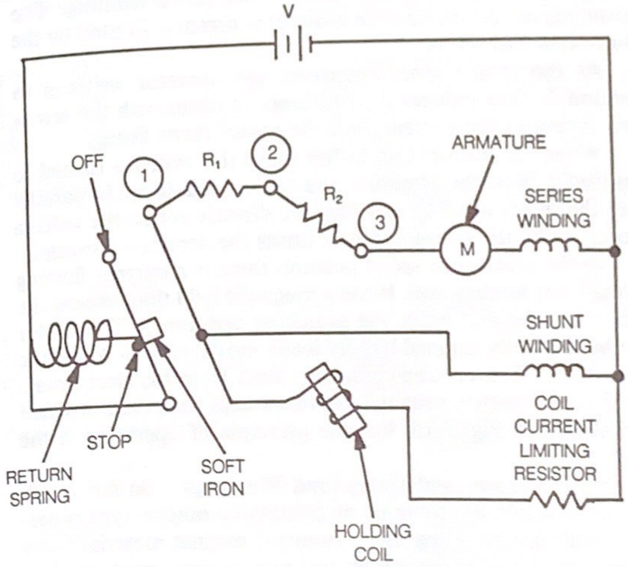

Fig. 7-15. A simplified starter circuit is used to explain starter operation.

When a motor first starts to turn, there is very little opposition to the current flow through the armature because there is no countervoltage. As the motor speed builds, the armature countervoltage develops and increases. This countervoltage opposes the supply voltage and power to the motor. It is necessary to provide some limitation to armature current during startup. The most common method of doing this is to use a manual starter.

We will describe a simple manual starter to establish the principle of operation. Refer to Fig. 7-15. The arrow represents a manually turned switch. It is sitting against the stop in the off position. A return spring provides tension to hold it against the stop. Notice that there is a soft iron cube mounted on the manual switch.

When the switch is turned to position 1, current flows through the shunt winding. It also flows through R1 and R2, through the armature, and through the series winding. The motor begins to turn and the armature current is limited by the two resistors in series.

As the motor speed increases, the operator switches to position 2. That reduces the resistance in series with the armature, increases the current, and the motor turns faster.

When the motor is up to full speed the switch is turned to position 3. Now the armature and series winding are in parallel with the shunt winding and they are directly across the voltage source. Only the countervoltage limits the armature current.

In the maximum speed position there is a current flowing through the holding coil. It has a magnetic field that attracts the soft iron cube and holds the switching position 3. The motor can be manually stopped by physically moving the switch to the off position. This requires pulling it away from the electromagnet. Manual starters usually have more steps than the simplified one shown in Fig. 7-15, but the principle of operation is the same.

Series, Shunt, and Compound Windings. So far, much of the discussion has centered on permanent magnet type generators and motors. Long life permanent magnet materials now make these types of generators and motors very practical. But, the amount of voltage generated and the amount of turning free (or torque) for the motors is limited by the amount of magnetic flux available. As a general rule it is possible to get a greater amount of flux using an electromagnet compared to the flux available in a permanent magnet having the same size.

For a generator, the current for the electromagnet can be obtained from the generator itself in a self-excited device. There are a number of ways to connect the electromagnets. The coils for these electromagnets are called the field coils. The rotating loop between the magnetic poles is called the armature. Figure 7-16 shows the possibilities.

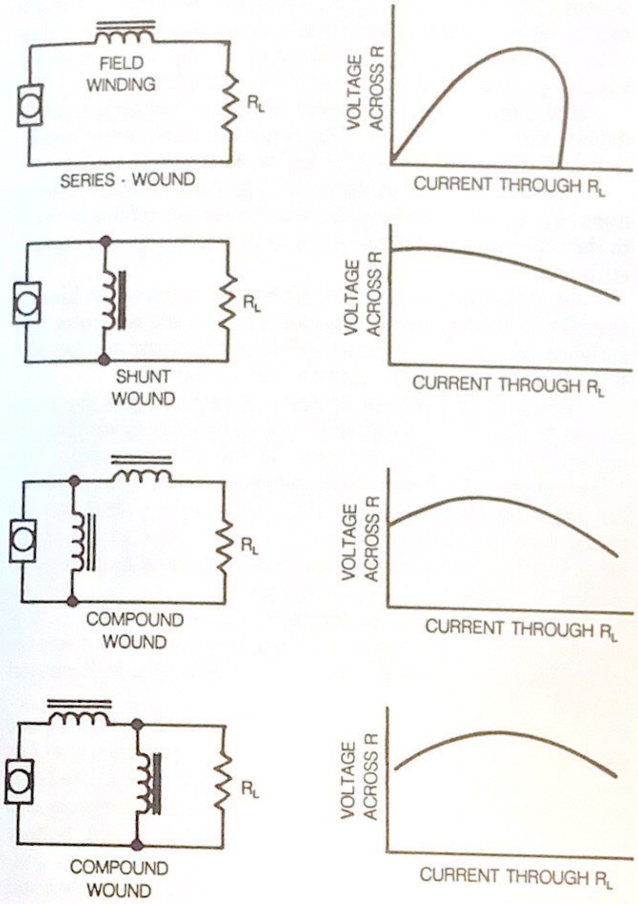

Fig. 7-16. For the various connections of field windings, you can see that the generator output is greatly influenced by the construction of the generator.

If the field coil is connected to the armature in such a way that the same current that flows through the coil also flows through the load resistance, you have a series-wound generator.

You will remember from an earlier discussion on power supplies that regulation is a measure of how well the output of a battery power supply or generator maintains its current and its output voltage for various amounts of current. For the series-wound generator you can see that the regulation is very poor.

In the shunt-wound generator, the field winding is in parallel with the load resistance. This produces much better regulation and this is the way typical self-exciting generators operate.

The next two figures illustrate compound wound connections. By suitably choosing the electromagnetic characteristics of the series and shunt coil, it is possible to get special characteristic curves.

As a technician you would not be able to tell which kind of compound windings are being used and how the generator was designed except that its output does not produce the normal series or shunt generator characteristic curves.

Windings in Practical Motors. Consider again the illustration in Fig. 7-16. If you replace the load resistors with batteries, the device becomes a motor instead of a generator. The same names apply. For example, when the battery current flows through both the armature and the field, it is a series-wound motor. Likewise, if the battery current runs through the armature and field and they are connected in parallel across the battery, it is called a shunt-wound motor.

As with the generators, the method of winding the electromagnetic field connecting it with the armature has an important influence on the operation of the motor. This is illustrated in Fig. 7-17.

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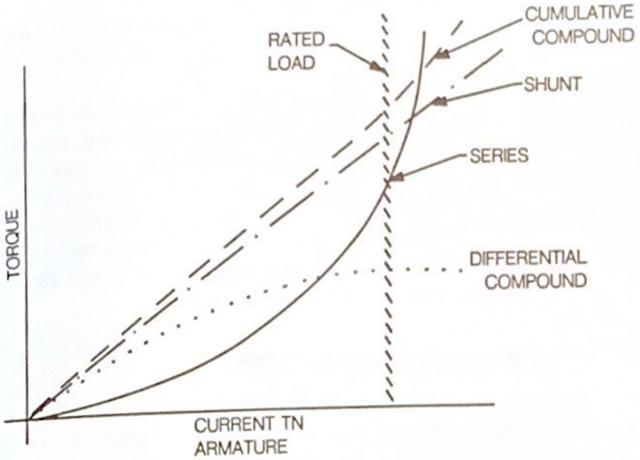

Fig. 7-17. The amount of torque generated in a motor is greatly influenced by the construction of the field windings.

As with the generators, the method of winding the electromagnetic field connecting it with the armature has an important influence on the operation of the motor. This is illustrated in Fig. 7-17.

Consider, first, the characteristic curve of the series-wound motor. You can see that as the current increases, the speed and torque of the motor increase very rapidly. Series-wound motors have a very high starting torque. An important problem with them is that if you connect the series-wound motor across a battery without a load, it will continue to go faster and faster until ultimately it will reach a speed at which it will destroy itself. For this reason these motors must never be connected without a mechanical load.

Look at the more nearly constant torque and current characteristics of the shunt-wound motor. This motor will not run itself to death in normal operations without a load. There is one problem, however, you should be aware of. If the field winding opens, there will only be a small amount of magnetic flux left in the soft iron material used for making the field. That small amount of flux will be sufficient to cause the motor to turn. The important thing is that there will be very little countervoltage and very little opposition to the turning. In that case the shunt-wound motor will behave like a series-wound motor. It will run faster and faster until it ultimately destroys itself unless it is connected to a mechanical load.

As with generators, it is possible to get special effects by the way the series and shunt field windings are combined in a dc motor. Again, you probably will not know how the windings are made unless you are a motor technician. As an electronic technician you are primarily interested in what happens if the windings do not work. Remember: if the shunt winding is open, the motor will act like a series wound motor, and if the series winding is open the motor will not run at all.

AC GENERATORS AND MOTORS

AC generators and motors are less complicated than their dc counterparts. They do not require commutators. In most cases they do not have brushes. Remember that brushes are made of carbon—the same material used to make resistors. Therefore, they cause heat dissipation and a voltage drop. Those losses can be avoided in most ac generators and motors.

AC Generators. Figure 7-18 shows a simple method of generating an ac voltage. Here, a permanent magnet is rotated between the field poles. In this case the poles are made of soft iron and are wound with two coils in series.

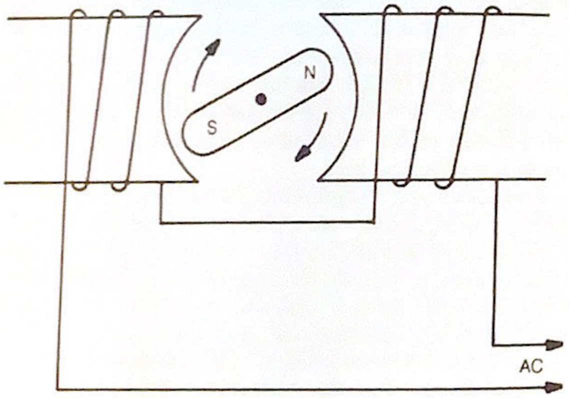

Fig. 7-18. This simple system will generate an ac voltage.

As the magnet turns, the flux induced in the soft iron is first in one direction and then in the opposite direction, depending upon the positions of the permanent magnetic poles. The frequency of the ac will depend upon the speed at which the rotating magnet is turned.

In more sophisticated ac generators, an electromagnet is rotated rather than a permanent magnet. Connection to the internal rotating electromagnet is through slip rings. They are illustrated in Fig. 7-19. Brushes deliver the direct current necessary for the electromagnet.

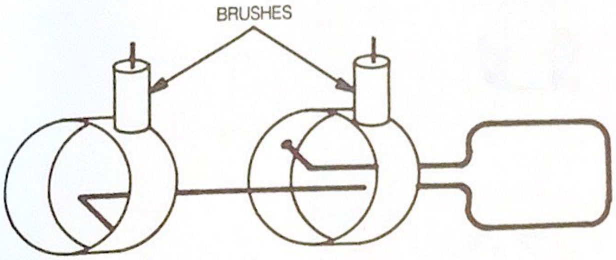

Fig. 7-19. Details of slip-ring construction.

In another type of ac generator, a conducting loop is rotated between north and magnetic south poles and the resulting ac is delivered through slip rings and brushes to the outside world.

As you can see, the construction of an ac generator is quite simple. The most efficient design is the rotating electromagnet (Fig. 7-18) with the ac taken from the generator without the need for slip rings or brushes.

AC Motors. Many types of ac motors make use of a rotating magnetic field which is followed by a soft iron or permanent magnet core material. In one of the most popular types, a rotating combination of conductors—called a *squirrel cage*—is used as an armature.

Figure 7-20 shows the concept of a rotating field. In the first illustration, the permanent magnet is aligned with block A which is presumed to be a soft iron material. Because of their proximity, the soft iron has an induced magnetic field from the

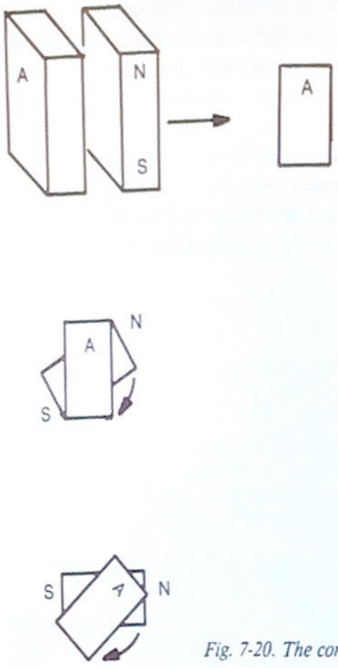

Fig. 7-20. The concept of rotating magnetic field.

permanent magnet. Therefore, both blocks have magnetic fields.

When the permanent magnet starts to turn, the magnetized soft iron will begin to follow it. The shaft of the motor is connected to the rotating soft iron bar.

The Rotating Magnetic Field. There are several ways of getting a rotating magnetic field. One way is to use two-phase power as shown in Fig. 7-21. The waveforms are 90 degrees out of phase. The result is that the north pole of the induced magnetism will rotate; in other words, each pole becomes a north magnetic pole as its ac voltage reaches its peak. Therefore, there is a rotating north magnetic pole.

There is also an accompanying south magnet pole opposite to the north pole. The overall result is a rotating field. Visualize the north pole moving from one pole to the next in sequence as

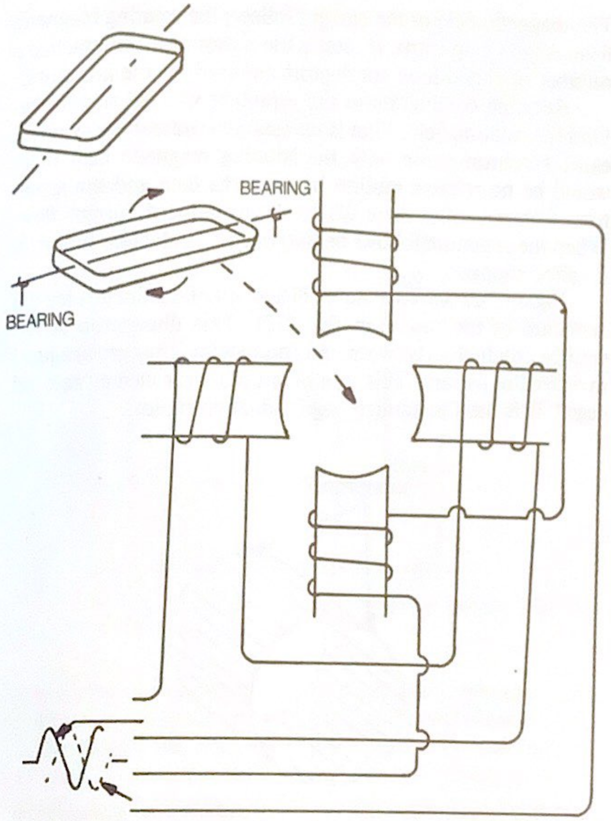

Fig. 7-21. Two-phase current can be used to produce the rotating field.

the two waveforms reach their peak. Then, corresponding south poles appear on the opposite poles.

When you place a piece of soft iron in the center of this simplified motor, it will have an induced magnetic field. That, in turn, causes it to rotate with the magnetic field.

Instead of a piece of soft iron, a conducting loop can be placed in the rotating field. It will turn if free to do so. The reason is that the moving field induces a current in the loop.