HOW COILS ARE USED

6B

RADIO-TELEVISION-ELECTRONICS

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STUDY SCHEDULE NO. 6

☐ 1. **Introduction** .... Pages 1-2

Here we describe how coils are used, different types of coils, and basic coil action.

☐ 2. **Magnetic Circuits** .... Pages 3-7

Similarities between magnetic circuits and electrical circuits are brought out.

☐ 3. **Using Coils to Produce Voltage** .... Pages 7-12

You learn how flux linkages can be changed to produce voltage, and you study Lenz's Law of coils.

☐ 4. **Inductance** .... Pages 12-18

We take up the basic property of coils and learn about self-induced voltages and mutual inductance.

☐ 5. **Ohm's Law for Coils** .... Pages 18-28

You learn how to find the current in an ac circuit by using vectors or mathematics and you also study Kirchhoff's Voltage Law, the importance of phase, and what the Q of a coil is.

☐ 6. **Answer Lesson Questions.**

☐ 7. **Start Studying the Next Lesson.**

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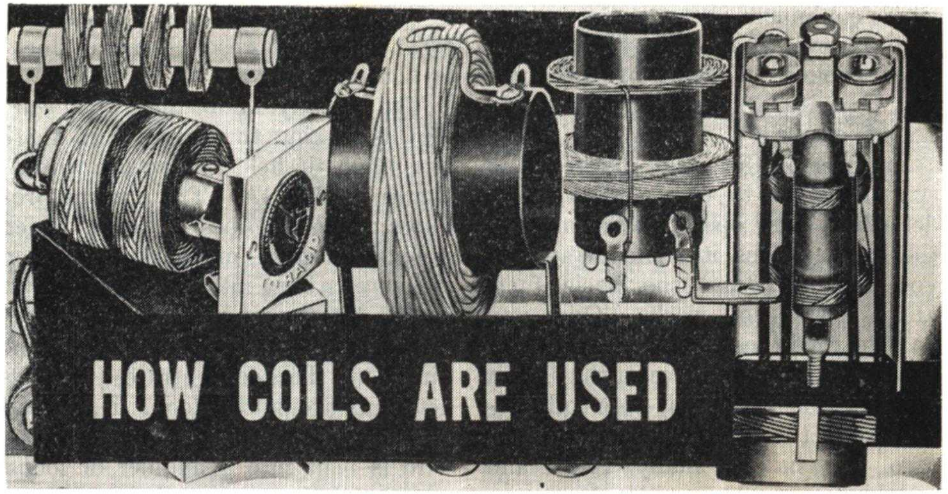


Photo above courtesy Miller Quality Products.

HOW COILS ARE USED

COILS are important to the electronic technician because they are used in all types of electronic equipment. They are used in many different ways to perform different jobs. Without them the modern miracle of electronics would not be possible; industrial electronic equipment uses coils; neither radio nor television would be possible if it were not for coils. Since you will find coils used in all types of electronic equipment, it is important for you to understand what they are used for and how they work.

HOW COILS ARE USED

You will find coils used with capacitors to select signals. You may have wondered how a radio receiver selects the one signal to which it is tuned and rejects the other signals from nearby radio stations. It is done by means of a combination of coils and capacitors.

Coils are used in power supplies. You already know that the output from a half-wave or a full-wave rectifier will be a pulsating dc current. Coils are used in conjunction with capacitors to separate the ac and dc components so that the dc can be used to operate the vacuum tubes or transistors in the equipment.

Coils are used to produce motion. You have already seen how a meter works. The motion of the pointer that indicates voltage, current, or resistance in a circuit is the result of interaction between the magnetic field set up by current flowing through a coil and the magnetic field of the permanent magnet in the meter. A motor operates on much the same principle as a meter.

Coils are used in transformers. You know that voltage can be stepped up or stepped down by means of a transformer. The transformer is nothing more than two or more coils wound on a common core.

TYPES OF COILS

There are many different sizes of coils. Small rf chokes have perhaps as few as two or three turns of wire and a diameter about like an ordinary pencil. Coils like these are used in high-frequency circuits where the signal may be over 100 megacycles (100,000,000 cycles).

Large coils wound on iron cores are found in some large pieces of electronic equipment. When coils are used in the power supply, they are called filter chokes. Chokes of this type may be quite large and may weigh 100 pounds or more.

In spite of the great difference in size of the two types of coils we have described, their operation is basically the same. Thus it is important for you to understand the basic facts about how a coil works. Once you have learned these facts you will know exactly what a coil does in the circuit whether it is a small air-core coil having two or three turns, or a large iron-core coil having many turns and weighing over 100 pounds.

COIL ACTION

In its simplest form a coil is nothing more than one or more turns or loops of wire, usually wound in a circular or helical (spiral) shape. Often the coils have certain other accessories such as a cylindrical cardboard or ceramic form, an iron core, or a metal shield or housing.

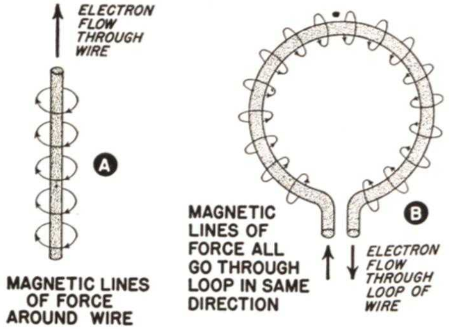


FIG. 1. When current flows through a wire, magnetic lines of force are set up around the wire as at A. When the wire is bent into a loop, the lines of force all go through the loop in the same direction, as shown at B.

You already know that when current is flowing through a wire there is a magnetic field around the wire as shown in Fig. 1A. The current produces magnetic lines of force, which are also known as magnetic flux. When the wire is bent into a loop as shown in Fig. 1B, the magnetic lines of force all go through the loop in the same direction. This concentrates the magnetic flux around the loop. If, instead of being bent into a single loop, the wire is bent into a number of loops, additional magnetic flux will be created, which will result in a stronger magnetic field.

The magnetic flux produced by the current flowing through a coil makes it possible to transfer energy from one circuit to another without any connecting wires. You have already learned a little about this when you studied transformers in an earlier lesson. Because of the flux, the coil offers more opposition to the flow of alternating current than it does to the flow of direct current. You will see in this lesson that this is extremely important. Once you understand why a coil offers more opposition to ac than to dc, you will have a good understanding of how a coil works.

Before going ahead with the study of coils there are several important things that you should know about magnetic circuits. To some extent this will be a review of what you have already learned, but you will also learn some additional material.

Magnetic Circuits

You already know that the magnetic lines of force produced by current flowing through a coil exist only as long as current flows. Once the current flow through the coil stops, the magnetic lines of force will disappear.

Another important fact is that the magnetic lines of force are complete loops, having no ends. They pass through and around the turns of the coil. Fig. 2 shows a coil with lines of force coming out of the left of the coil and going into the right end of the coil. Only two of these are drawn as complete loops, one above and one below. However, all the lines of force are actually complete loops. The three lines in the center that are not shown as complete paths also curve around from the left side of the coil and into the right side of the coil. We have not tried to draw all the magnetic lines of force that exist around a coil having a current flowing through it. The coil may have thousands of such magnetic lines each forming a complete loop and passing through all or part of the coil and radiating out from the ends of the coil. The path of these magnetic lines of force is the magnetic circuit of the coil. Although most of the lines of force will be concentrated near the coil, some will extend out quite some distance from it.

AIR-CORE COILS

Some coils are wound on a cardboard form. The purpose of a form of this type is simply to support the turns of wire making up the coil. The cardboard serves no useful purpose insofar as the operation of the coil is concerned. The actual core of the coil is simply air. This type of coil is referred to as an air-core coil. Thus, coils wound on a cardboard form and also coils of heavy, self-supporting wire are both called air-core coils.

IRON CORE COILS

Frequently a coil is wound on an iron or steel form or on a cardboard form with an iron or steel slug inside it. The iron or steel core makes a better magnetic circuit than air, and there will be a greater number and concentration of the magnetic lines of force. This means there will be more flux lines produced by the coil. This type of coil is called an iron-core coil. In coils designed for use in a power line or at audio frequencies, the iron-core is made up of thin strips of iron or steel called "laminations." These pieces of steel are fitted together to make a core, as shown in Fig. 3. As you can see, the core actually surrounds the coil as well as going through the center. Fig. 4 shows how such a coil is constructed. This type of construction is used rather than a solid iron or steel core because it is more efficient. You will learn more about this in a later lesson.

In high-frequency circuits a pow-

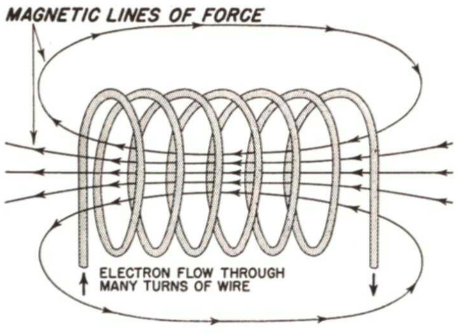


FIG. 2. When current flows through a coil, magnetic lines of force are produced. These are complete loops, passing through and around the coil.

dered iron core is often used. This type of core is made by pulverizing iron filings and mixing them with a binder to hold them together and to insulate the particles from each other. A core of this type called a slug, is often inserted in a coil by means of a screw so it can be adjusted in and out of the coil. This type of coil is shown in Fig. 5. The schematic symbol is shown beside it. Two or three lines drawn beside a coil indicate that it has an iron core, and the arrow indicates that it is movable. A coil with this type of core is called a slug-tuned coil.

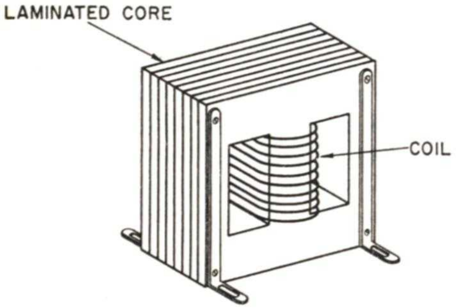


FIG. 3. Iron cores are frequently made of thin sheets of metal bolted together.

MAGNETOMOTIVE FORCE

The force that sends current around an electric circuit is called an electromotive force or voltage. The force that sends magnetic flux around a magnetic circuit is called magnetomotive force. It exists in every current-carrying coil.

The unit of magnetomotive force is the ampere-turn. If a coil has one turn and the current flowing through it is 1 amp, the magnetomotive force is 1 ampere-turn. If the coil has 10 turns and the current flowing is 1 amp, the magnetomotive force is the product of the two, or 10 ampere-turns. If a coil has 5 turns, and the current flowing through it is 5 amperes, the

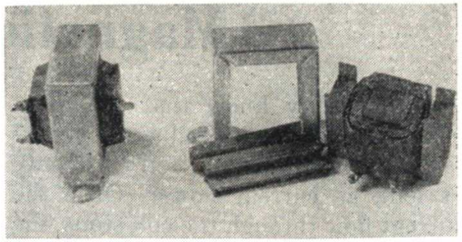


FIG. 4. Construction of an iron-core coil with laminated core.

magnetomotive force is 25-ampere-turns. Thus, to find the magnetomotive force in a coil, you simply multiply the current flowing through it in amperes by the number of turns on the coil. You can increase the magnetomotive force of the coil by increasing the current flowing through it or by adding more turns to the coil and keeping the current constant.

As an electronic technician it is very unlikely that you will ever have to calculate the magnetomotive force produced by a coil in a circuit. However, you should know what it is. It is essential to understand magnetic circuits in order to understand magnetic devices.

RELUCTANCE

You already know that every electric circuit has resistance. Resistance is the opposition to current flow in the circuit. Just as there is opposition to current flow in an electric circuit so also is there opposition to flux in a magnetic circuit. This opposition to flux is called reluctance.

FIG. 5. A slug-tuned coil and its schematic symbol.

Gilberts = Amp turns X 1.26
Amp. turns = Gilberts X 0.80

The reluctance in a magnetic circuit is distributed along the entire path taken by the flux. In other words, there is reluctance all the way around the path followed by each magnetic line of force both in the core and in the air. We can actually make a very close comparison between a magnetic circuit and an electric circuit. In Fig. 6A we have the magnetomotive force sending the flux around the magnetic circuit against the opposition offered by the reluctance of the circuit. In Fig. 6B, we have a wire connected across a battery. Here the electromotive force of the battery is forcing current around the circuit against the opposition or resistance of the wire. We have shown the whole length of the wire as a resistor. Here we see that the magnetomotive force is the equivalent of the electromotive force, the magnetic flux the equivalent of current, and the reluctance the equivalent of resistance.

We have a magnetic circuit that is similar to an electric circuit consisting of a resistor connected across a battery as shown in Fig. 7A. Here most of the resistance in the circuit is concentrated in the resistor, the resistance of the leads is small compared to that of the resistor. In the magnetic circuit of Fig. 7B, the iron core of the coil has an air gap. Most of the reluctance is concentrated in the air gap, the reluctance of the iron core is low in comparison to the reluctance of the air gap. One of the choke coils used in the power supply of a radio transmitter often has an air gap like this.

In an electric circuit if we lower the resistance or opposition, we can increase the current, and if we increase the resistance we reduce the current. Exactly the same situation exists in the magnetic circuit. If we lower the reluctance or opposition we increase the flux, and if we increase the reluctance we reduce the flux.

The reluctance in a magnetic circuit can be reduced by providing a better path for the magnetic lines of force to flow through. Magnetic materials such as iron and steel have a low reluctance, just as copper has a low resistance in an electric circuit. Therefore if a coil is wound on an iron core shaped like the one shown in Fig. 8, the magnetic lines will flow through the core as shown in the drawing. Because the iron has a low reluctance, there will be a much greater flux than there would be if the same coil had an air core. Thus the flux in a magnetic circuit can be increased by providing a path of a magnetic material for the magnetic lines of force to flow through. Making a frame like the one

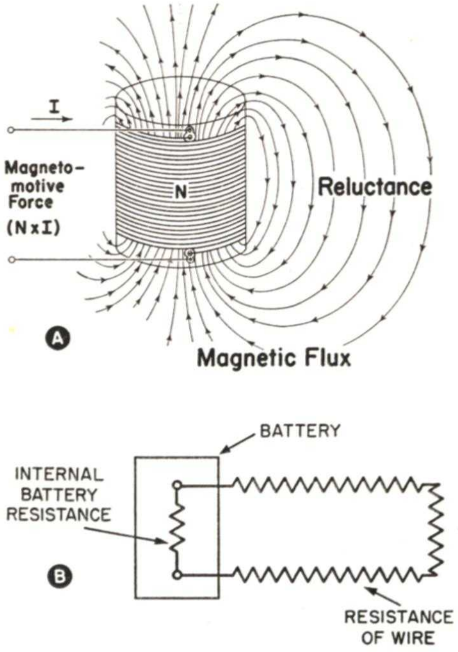


FIG. 6. Comparison between an electrical circuit (A) and a magnetic circuit (B).

shown in Fig. 8 of nonmagnetic material such as paper, glass, aluminum, or copper would not increase the flux, because these materials do not have a lower reluctance than air.

There are other factors that affect reluctance. Increasing the cross sectional area of the core will reduce the reluctance and increasing the length of the magnetic circuit will increase it.

PERMEABILITY

Silver, copper, and aluminum have different conductivities. Silver has the highest conductivity and is the best conductor, then copper and then aluminum. A copper wire has less resistance than an aluminum wire of the same size and length.

Similarly, different magnetic materials have different permeabilities. The permeability of a core material determines the total reluctance of the coil; when the permeability goes up, the reluctance goes down and vice versa.

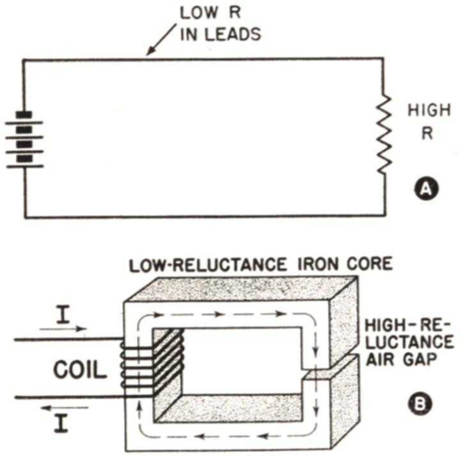


FIG. 7. In the electrical circuit at A, most of the opposition (resistance) to the current is in the resistor. The total resistance in the circuit is only slightly higher than the resistance of the resistor. In the magnetic circuit at B, most of the reluctance or opposition to the flux is in the air gap. The total reluctance in the circuit is only slightly higher than the reluctance of the air gap.

The permeability of air and all other nonmagnetic materials is considered to have the numerical value of 1. Magnetic materials all have higher permeability values than 1, ranging from about 50 all the way up to 10,000 or even higher for certain special alloys. Thus if the permeability of a material is 10, we can expect 10 times the magnetic flux through this material that we would have through air for the same number of lines of force.

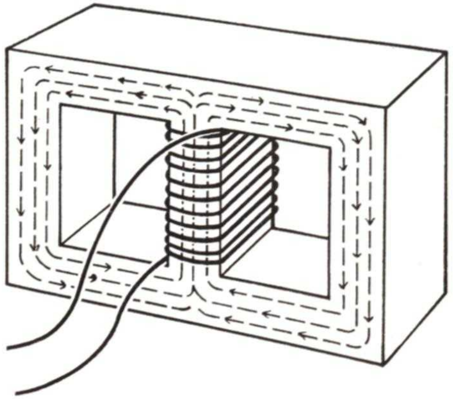


FIG. 8. There will be much greater flux if a coil is wound on an iron core like this than if the coil had an air core.

MAGNETIC FLUX

You already know that magnetic flux in a magnetic circuit corresponds to current in an electric circuit. In an electric circuit, current is equal to the voltage in volts divided by the resistance in ohms. In a magnetic circuit the flux is equal to the magnetomotive force divided by the reluctance.

In practical magnetic circuits you will not have to calculate the magnetic flux. Even if you performed this calculation it would be of no value to you. However, it is important that you understand what magnetomotive force, reluctance, and magnetic flux are, and how they are related to each other.

You can increase the amount of flux in a magnetic circuit either by increasing the magnetomotive force or by decreasing the reluctance.

You can decrease the amount of flux either by decreasing the magnetomotive force or increasing the reluctance.

Every change in flux is thus due to a change in either magnetomotive force or a change in reluctance.

Using Coils To Produce Voltage

Many electronic devices use coils to produce a voltage. A transformer is one such device. The voltage applied to one winding of a transformer causes a current to flow through it. This sets up a magnetic field, which in turn induces a new and completely separate voltage in another coil.

Another type of device may make use of a coil placed in the field of a permanent magnet to take a wave or signal other than an electrical signal and produce an electrical signal from it. Such a device is called a transducer. An example of a transducer using this principle is a dynamic microphone. A dynamic microphone uses coils placed in a magnetic field to convert an audio signal, which is actually a wave or vibration in air, to an electrical signal, which is the electrical equivalent of sound.

If you understand how a voltage can be induced in a coil, you will have mastered one of the most important points in understanding how coils work. To see how a voltage can be induced in a coil we must first learn something about flux linkages and then see how changing the flux linkages of a coil will induce a voltage in the coil.

FLUX LINKAGES

Let us see what we mean by flux linkages. Suppose we have a magnet that produces a single magnetic line of force. If this magnet is brought near a coil having one turn such as shown in Fig. 9A, we will have one magnetic line linking with or passing through a one-turn coil, and we will have one flux linkage. If we had ten turns on the coil and the one magnetic line of force passed through all ten turns, then we would have ten flux linkages as shown in Fig. 9B. However, if the single magnetic line passed through and linked only six turns of the 10-turn coil, as shown in Fig. 9C, we would have only six flux linkages. Thus the term "flux linkage" is an indication of the number of magnetic

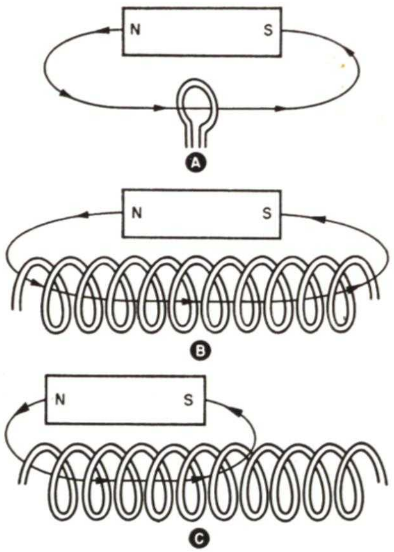


FIG. 9. How the number of flux linkages can be changed. In A there is one flux linkage; in B, ten; and in C, six.

lines of force passing through and linking the turns on the coil. If we have a magnet that produces 100 magnetic lines, and the entire 100 lines linked to a coil having 80 turns, the number of flux linkages would be 80 times 100, or 8000 flux linkages.

Changing Flux Linkages. Now let's look at Fig. 10A. Here we have a magnet with 10 magnetic lines of force, but actually only two of them are cutting through a coil with 5 turns on it, so we have a total of 10 flux linkages. As you can see, part of the flux is lost—it does not cut through the coil. This is called leakage flux or flux leakage. If we suddenly move the magnet to the position shown in Fig. 10B so that the magnet is placed inside of the coil and all ten lines cut through the five turns of the coil, we have a total of 50 flux linkages. When the number of flux linkages increases from 10 to 50 there will be a voltage induced in the coil. This voltage is known as an induced voltage.

If the magnet is then moved away from the coil so that the number of flux linkages is changed from 50 back to 10, we will again have a voltage induced in the coil.

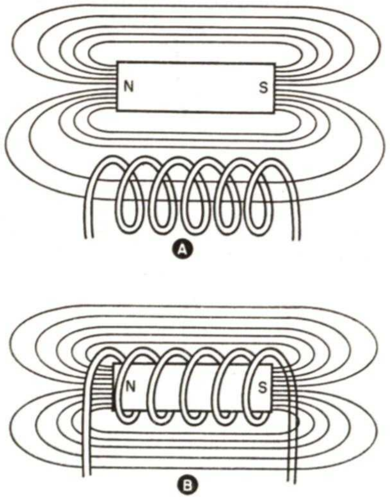


FIG. 10. In A we have 10 flux linkages; in B we have 50 when the same magnet is moved inside the coil.

In each of the two examples given, we had a change of 40 flux linkages. If we had a stronger magnet so that the number of lines of force was greater, and therefore the change in flux linkages was greater, we would have a greater voltage induced in the coil.

In moving the magnet either towards or away from the coil, the voltage that will be induced in the coil will depend upon the speed with which the magnet is moved. If the magnet is moved slowly so that the number of flux linkages changes slowly, the voltage induced in the coil will be small. However, if the magnet is moved rapidly so that the change in flux linkage occurs very quickly, the voltage induced in the coil will be higher. If it took one second to move the magnet so that the number of flux linkages changed from 10 to 50, we would get a certain voltage induced in the coil. The exact value is not important to this discussion. However, if we were to move the magnet so that the number of flux linkages was changed from 10 to 50 in 1/100th of a second, we would get exactly 100 times as much voltage as before. The faster the rate of change in flux linkages, the greater will be the induced voltage.

LENZ'S LAW FOR COILS

The voltage induced in a coil always acts in a definite direction. In other words, the voltage has a definite polarity. *This polarity at any given instant depends on just two things—on the direction of the original flux, and on whether the flux linkages are increasing or decreasing.*

The exact relationship between these things is expressed by a famous electrical law known as Lenz's Law. The law is named after the man who was first to realize that the direction in which an induced voltage will act can always be predicted before it is produced.

When the number of flux linkages is changed, a voltage will be induced. This induced voltage will have a polarity such that it will tend to send through the coil a current which opposes the change in magnetic flux. In other words, if the flux linkages are increasing, the induced voltage will tend to send a current through the coil and produce a magnetic flux which will oppose the original coil flux to try to keep it from increasing. On the other hand, if the flux linkages are decreasing, the induced voltage will be of such polarity that its current (if the coil circuit is complete) will produce a flux which aids the original flux and thus tends to prevent the flux from decreasing.

This is an extremely important law and perhaps can be better understood by referring to the circuits shown in Fig. 11. In Fig. 11A, we have a magnet with 10 flux lines cutting through a five-turn coil, which gives us 50 flux linkages. (We have shown only two lines of force). As the magnet is moved away from the coil, reducing the number of flux linkages, as shown in Fig. 11B, a voltage will be induced in the coil, and current will flow through the coil. Current flowing through the coil will set up a magnetic field which will aid the flux linkages already existing! As long as the number of flux linkages is changing, the induced voltage will be present and will cause the induced current to flow.

On the other hand, as the magnet is moved back into the coil to increase the number of flux linkages, a voltage will be induced in the coil with a polarity that will cause a current to flow and set up its own lines of flux to oppose the flux lines from the magnet as shown in Fig. 11C.

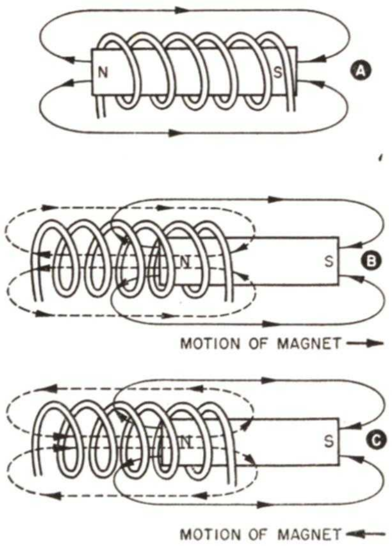


FIG. 11. Changing the number of flux linkages induces a voltage in the coil. The polarity of the voltage depends upon whether the number of flux linkages is increasing or decreasing.

Thus the polarity of the induced voltage is always such that it will produce a current (if the circuit is complete) that will produce flux lines that oppose the change in flux linkages producing the induced voltage.

METHODS OF CHANGING FLUX LINKAGES

There are three methods of producing changes in the flux linkages in a coil. They are: by cutting through magnetic lines of force; by changing the reluctance; and by changing the current flowing in the coil.

Cutting Lines of Force. You have already seen an example of this method of producing changes in flux linkages when you studied generators in an earlier lesson. You learned that when a conductor is moved through a magnetic field it cuts the magnetic lines of force, and a voltage is induced in the conductor. We get this induced voltage because the motion of the conductor changes the flux linkages as the conductor passes through the magnetic lines of force.

In a generator, instead of moving a single wire through a magnetic field, a coil is rotated in the magnetic field. As the coil is rotated, it moves through and cuts through the magnetic lines of force produced by a permanent magnet or an electromagnet, and a voltage is induced in the coil. The voltage induced in the coil will have a polarity such that the current that will flow when the coil is connected to an external circuit will set up a magnetic field in the coil which opposes the change in flux linkages producing the voltage.

Changing the Reluctance. Any change in the reluctance of a magnetic circuit will change the amount of flux which passes through the coil, thus changing the flux linkages through the coil and inducing a voltage. Remember, whenever there is a change in flux linkages, a voltage is induced.

An example of this method of producing a voltage is the variable reluctance phono pickup used in many record players. A simplified drawing of one is shown in Fig. 12. The needle, or stylus, is mounted on a cantilever spring, which moves between two coils. The other end of the cantilever spring is connected to the south pole of a permanent magnet. A T-shaped yoke connects the other end of the magnet to two pole pieces on which two coils are wound. The flux path is from the magnet through the yoke, and the two pole pieces, across the air gap to the cantilever spring, and through it back to the magnet. As the needle follows the record grooves, it moves from side to side, nearer one or the other of the two coils. As it does so, the air gap on one side decreases, so the reluctance on that side decreases, and the flux increases. At the same time, the air gap on the other side becomes wider, increasing the reluctance and decreasing the flux. Since the flux changes are in opposite directions, the voltages induced in the two coils will be of the opposite polarity. The two coils are connected in such a way that the two voltages are added in the output.

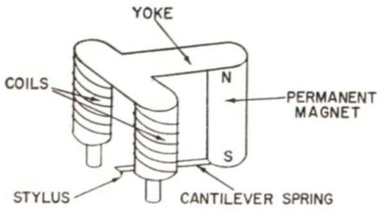


FIG. 12. A variable reluctance phono pick-up.

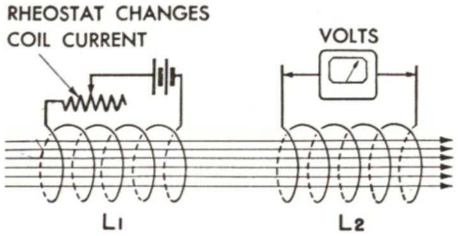


FIG. 13. When two coils are arranged as shown above, the flux produced by one passes through the other.

The change in flux linkages will induce a voltage in the coil.

Changing the Coil Current. When two coils are arranged as shown in Fig. 13, the flux produced by coil L1 passes through coil L2. As long as the current through L1 remains constant, the flux produced by this coil will remain constant, and there will be no change in the flux linkages in L2. However, if the current is changed by changing the setting of the rheostat, there will be a change in the flux produced by L1 and hence a change in the number of flux linkages in L2. This will induce a voltage in L2.

Of course, this not a practical way of inducing a voltage in L2 because the rheostat setting would have to be changed continually and at a rapid rate in order to induce any appreciable voltage in L2. However, if the plate current of a vacuum tube flows through L1, and a signal is applied between the grid and cathode of the tube as shown in Fig. 14, the varying signal applied between the grid and the cathode of the tube will cause the current flowing from the cathode to the plate of the tube to vary. Thus the current flowing through L1 will vary and this will cause the flux produced by L1 to vary. The change in flux produced by L1 will result in a change in the flux linkages through L2 and there will be a voltage induced in L2. This arrangement is actually used in many electronic circuits.

Still another application of this same principle is the ac transformer used on ac power lines shown in Fig. 15. Here, one winding called the primary winding, is connected directly to the ac power line. The ac voltage, which is a varying voltage, will cause a varying current to flow through the primary winding. As the current varies, the flux produced by the primary will change, resulting in a change in the flux linkages through the second winding, which is called the secondary winding. This change in flux linkages will induce a voltage in the secondary winding.

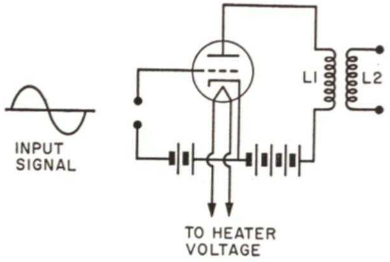


FIG. 14. Coils L1 and L2 are wound close together, often on the same coil form. The ac signal applied between the grid and the cathode of the tube will cause the current flowing from the cathode to the plate of the tube to vary. This varying current will flow through L1, resulting in a change in the flux produced by this coil, and hence a change in flux linkage through L2.

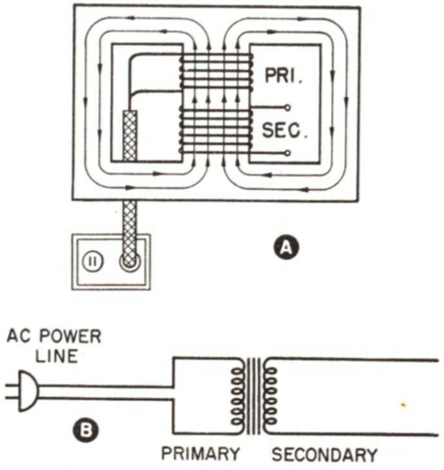


FIG. 15. A power transformer. The primary winding is connected directly to the power line. As the current through the primary winding varies, the flux produced by L1 will vary, resulting in a change in flux linkages through the secondary winding, inducing a voltage in the secondary.

SUMMARY

There are several important facts that you should remember from this section of the lesson. First, remember that a voltage is induced in a coil when the number of flux linkages changes. Either an increase in the number of flux linkages or a decrease in the number of flux linkages will induce a voltage in the coil.

Lenz's Law of coils is important. It states that the induced voltage always acts in such a direction that it tends to oppose the original change in flux linkages.

Changes in flux linkages can be produced by cutting through magnetic lines of force, by changing the reluctance in the magnetic circuit, or by changing the current flowing through the coil.

In the next section of this lesson you will learn more about coils. You will learn how the electrical characteristics of coils are expressed and also you will see why the opposition that a coil offers to the flow of ac through it is much higher than it is to dc. If you understand what you have already studied about the coils up to this point in your lesson you should have no difficulty with the rest of the lesson.

Inductance

In the preceding section of this lesson you learned that if the number of flux linkages cutting the turns of a coil changes, there will be a voltage induced in the coil. The exact amount of voltage that will be induced in the coil will depend upon how great the change in flux linkages is, and how rapidly it occurs. It will also depend upon the coil itself. The property of the coil that will govern or determine the voltage induced in the coil is called inductance. Saying the coil has inductance is just about the same as saying a resistor has resistance. Inductance is a basic property of a coil and it indicates how much voltage will be induced in the coil for a given change in flux linkages.

Before we go further with this idea of inductance, you should learn something about self-induced voltages.

SELF-INDUCED VOLTAGES

When a coil is brought near a magnetic field and the strength of the field is suddenly changed, there will be a change in the number of flux linkages through the coil. You know that this will result in a voltage being induced in the coil.

However, let us consider a coil that is placed by itself away from any external magnetic field. If a voltage source is connected to the coil, current will flow through the coil and this current will set up a magnetic field. The magnetic field produced by the coil will produce lines of flux. These lines of flux will link through the turns of the coil as shown in Fig. 16.

If the current flowing through the coil is suddenly changed, the strength of the magnetic field will change and there will be a change in the number of flux linkages passing through the turns of the coil. This will have exactly the same effect as changing the flux linkages produced by an external magnet would have. There will be a voltage induced in the coil and the voltage induced in the coil will be such that it will tend to oppose the change producing it. In other words, by changing the current flowing through the coil, the coil is able to induce a voltage in itself. This voltage is known as a *self-induced voltage.*

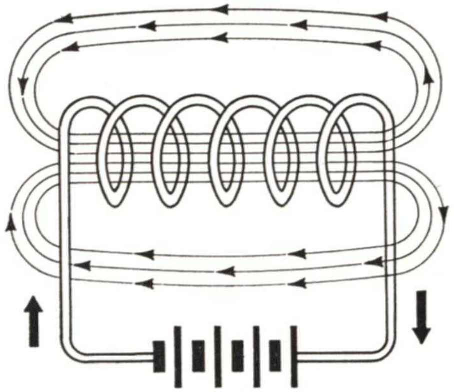


FIG. 16. If a voltage source is connected to a coil, current will flow through the coil, and a magnetic field will be set up.

It is important for you to realize that the induced voltage in a coil always opposes the change in the voltage which produces it. As an example, suppose in the circuit shown in Fig. 16 we increase the coil current by boosting the applied voltage. When we do this, we get an induced voltage in the coil which opposes the applied voltage and thus opposes the increase in applied voltage. The voltage will try to keep the current in the coil from increasing. If we increased the voltage applied to the coil very suddenly, we would immediately get an induced voltage that would try to prevent a corresponding increase in the coil current. However, the current flowing in the coil would gradually increase, and as it increased, the induced voltage would decrease until finally the current flowing through the coil would be limited only by the dc resistance of the coil, and at that time the current would become constant and the induced voltage would disappear.

UNITS OF INDUCTANCE

For a given change in flux linkages, the voltage that will be induced in a coil will depend upon the inductance of the coil. The unit of inductance is the *henry.* It is named after Joseph Henry, an outstanding scientist who did a great deal of experimenting with coils.

You need not remember the exact value of the henry as defined by scientists, but to give you an idea of what a henry is, we will define the unit. There are two easy ways to define it. If a current of 1 ampere flowing through an air-core coil produces 100,000,000 flux linkages, the coil has an inductance of 1 henry. Another way of defining the henry that can be used for both air-core and iron-core coils is as follows: If the voltage induced in a coil is one volt when the strength of the current flowing through a coil changes at a rate of 1 ampere per second, the coil has an inductance of 1 henry. In other words, if a coil has an inductance of 1 henry, a current change of 1 ampere per second will induce a voltage of 1 volt in the coil.

Large iron-core coils frequently have quite high inductances. You will find iron-core coils in electronic equipment having inductances of 20 or 30 henries. In some cases you may find iron-core coils having inductances ranging as high as 1000 henries.

However, most air-core coils have a very small inductance. For convenience in specifying inductance values of air-core coils and some small iron-core coils, two other units are used, the millihenry and the microhenry. Just as the milliampere is 1/1000th of an ampere, the millihenry is 1/1000th of a henry; just as a microampere is one millionth of an ampere, the microhenry is one millionth of a henry. The unit millihenry is frequently abbreviated mh and microhenry is abbreviated μh.

FACTORS AFFECTING INDUCTANCE

There are several factors that affect the inductance of a coil. As you might expect, one of the chief factors is the number of turns on the coil. You can expect a coil having 200 turns to have a higher inductance than a coil having 100 turns wound on the same type of core.

The inductance of a coil is also affected by the shape and size of the coil. As an example, an air-core coil wound on a round form six inches in diameter will have a higher inductance than a coil with the same number of turns wound on a form one inch in diameter. In the coil with the smaller diameter, many of the lines of flux will escape or cut through only a few turns of coil, or in other words there will be considerable flux leakage. On the other hand, in the larger coil more flux lines will cut through each turn of the coil, resulting in a greater number of flux linkages, which in turn will give the coil a greater inductance.

The inductance of a coil is affected by the core material. If a magnetic material is placed in the core of a coil, the magnetic path will have a much lower reluctance, there will be more flux and a much greater number of flux linkages than there would be in a similar coil without an iron-core. The exact material placed inside the coil also affects the inductance. The higher the permeability of the core material, the greater the inductance of the coil will be.

Before leaving this section of the lesson it should be pointed out that inductance is not limited to coils alone. Even a straight wire has some inductance, because when a current flows through the wire, a magnetic field is set up around the wire and the wire will be cut by magnetic lines. Of course, the inductance of a straight wire is much lower than it would be if the wire were wound into a coil, but nevertheless *every piece of wire does have inductance.* In most cases this inductance is so low it has no effect on the circuit performance, but in some ultra-high-frequency electronic equipment straight wires or tubing are actually used as "coils."

Because the most important property of a coil is its inductance, electronics men often call coils "inductors" or "inductances." The term inductance not only includes coils, but in the case of ultra-high-frequency equipment may include a straight piece of tubing that is to be used as the inductance in one of the circuits.

INDUCTIVE REACTANCE

You have learned that when a coil is connected to a voltage source as in Fig. 16, and the voltage is changed, there is a voltage induced in the coil that opposes the change in voltage. Now let us consider what happens when a coil is connected to an ac voltage source as in Fig. 17. Here the voltage is continually changing.

During the first quarter cycle when the ac voltage is increasing and has the polarity shown in Fig. 17, the polarity of the induced voltage will be as shown so it will oppose the ac voltage as it tries to increase. Thus, the induced voltage acts to oppose and limit the change in current in the coil. If there were no voltage induced in the coil, the current would increase as the voltage increased, and the actual value of current flowing at any instant would depend only on the voltage applied and the dc resistance of the coil. However, since the induced voltage is of the opposite polarity to the applied voltage, the induced voltage has the effect of opposing the applied voltage and limiting the current change in the coil. This self-induced voltage is known as "counter emf" or "back emf." The counter emf in a coil is the induced ac voltage that appears across the coil. This ac voltage drop is just the same as the voltage drop across a resistor caused by current flowing through the resistor. In other words, the counter emf is the ac voltage drop across a coil caused by the opposition that the coil offers to the alternating current. This opposition that the coil offers is not the same as resistance because it affects only ac, and not dc. The opposition is known as inductive reactance and it is measured in ohms.

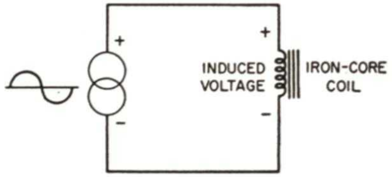


FIG. 17. A coil connected to an ac voltage source.

The amount of voltage induced in a coil will depend upon how rapidly the change in flux linkages occurs. When an ac voltage is applied to a coil, the speed with which the number of flux linkages changes depends upon the frequency of the ac voltage. Thus the change in flux linkages occurs more rapidly if the frequency is 100 cycles than it would be if the frequency were only 10 cycles. Therefore an ac current with a frequency of 100 cycles flowing through a coil will induce more voltage than a current of the same strength but a frequency of only 10 cycles. This means that the inductive reactance depends upon the frequency.

The inductive reactance of a coil can be determined by multiplying the inductance of the coil in henrys times 6.28 times the frequency in cycles.

Electronics technicians use symbols to provide a short convenient way of expressing this relationship. The symbol used for reactance is X. A small capital letter L following the X and written X_L is used to indicate inductive reactance. The letter f is used to represent frequency, and the letter L is used to represent inductance. Thus the expression for inductive reactance of a coil in ohms can be written:

$$X_L = 6.28 \times f \times L$$

The number 6.28 is two pi. Pi is the Greek letter π, (pronounced pie) which represents the number 3.14. You have probably seen this number before—it is used to find the area of a circle. Remember that the area of a circle is π times the radius squared. 2π is 6.28, which is a number that appears in many electrical formulas. Sometimes you will see the expression for inductive reactance written:

$$X_L = 2\pi f L$$

Now let's see how we use this formula to find the inductive reactance of a coil.

Example 1: Suppose we want to know the inductive reactance of a 50-henry choke at 100 cycles. The formula is:

$$X_L = 6.28 \times f \times L$$

Substituting 100 for f and 50 for L gives:

$$X_L = 6.28 \times 100 \times 50$$

Multiplying these numbers gives us 31,400 ohms. This is the inductive reactance of the coil at a frequency of 100 cycles. At a frequency of 50 cycles, the inductive reactance would be half this figure, and at a frequency of 200 cycles per second, the inductive reactance would be twice this figure. We say that the inductive reactance of a coil varies *directly* as the frequency. If the frequency increases, the reactance increases, and if the frequency decreases the reactance also decreases.

Example 2: Suppose we want to know the inductive reactance of a 10-henry choke at a frequency of 100 cycles. Substituting 100 for f and 10 for L gives us:

$$X_L = 6.28 \times 100 \times 10$$

Multiplying this gives us:

$$X_L = 6280 \text{ ohms.}$$

Notice that this is less than in the case of the 50-henry coil. Thus the inductive reactance also varies *directly* as the inductance of the coil.

Reducing the inductance reduces the reactance and increasing the inductance increases the reactance.

As an electronic technician you will seldom have to work on a problem of this type. However, it is important for you to remember that the inductive reactance of a coil varies directly both with the frequency and with the inductance of a coil.

You might wonder what the inductive reactance is of a small coil consisting of only a few turns. At low frequencies of a few hundred cycles, the reactance is so low that in most cases it can be ignored. However, when small coils are used in high-frequency circuits, their inductive reactance can be appreciable. Let's take as an example a 10-microhenry coil used at a frequency of 100 megacycles.

10 microhenrys is .000010 henry, and 100 megacycles (abbreviated mc) is 100,000,000 cycles.

$$X_L = 6.28 \times f \times L$$

$$X_L = 6.28 \times 100{,}000{,}000 \times .000010 = 6280 \text{ ohms.}$$

Thus, even though the reactance of the coil is quite small, at the frequency of 100 mc it has as high an inductive reactance as the 10-henry coil had at 100 cycles.

MUTUAL INDUCTANCE

When two coils are wound on the same iron core or when two air-core coils are placed near each other, some of the flux produced by one coil will cut through the turns of the other coil. Thus any change in the flux in one coil will induce an emf or voltage in the other coil. The two coils are said to be mutually-coupled through their magnetic fields.

You will study iron-core coils of this type in more detail later, when you study transformers. However, there are a few things that you should know about mutually-coupled coils now.

Air-core coils when they are wound on the same form placed near each other are generally called rf transformers. This type of coil is used at radio frequencies. Coils of this type may either be placed in a metal can to shield the coils from external circuits, in which case they are called shielded rf transformers, or they may be left unshielded.

The voltage induced in the secondary of two mutually-coupled coils depends upon the frequency of the primary current, the value of the primary current, and the coupling between the two coils. The coupling between the two coils is called the mutual inductance.

Mutual inductance is measured in henrys, just as the inductance of either the primary or the secondary of an air-core transformer is. The mutual inductance is usually represented in formulas by the letter M. The greater the value of mutual inductance, the greater will be the induced voltage in one coil when the current through the other changes.

Mutual inductance is defined in the same way as inductance—when a primary current changes at a rate of 1 ampere per second, if the voltage induced in the secondary coil is 1 volt, the mutual inductance is 1 henry.

Mutual inductance depends upon the size of both coils, the number of turns on each coil, and in the case of air core coils, it also depends on their relative positions and their distances apart.

COILS IN SERIES AND PARALLEL

When we consider coils connected in series or in parallel, there are two different cases to consider. The first and simplest is where the coils are located some distance from each other so that their magnetic fields do not affect each other. When the coils are connected together in series, as shown in Fig. 18A, the combined inductance is the sum of the individual inductances. In other words, the total inductance is obtained simply by adding the inductance of the individual coils. This should be easy to remember because in this respect coils are like resistors.

When coils are connected together in parallel as shown in Fig. 18B, the total inductance will be less than the inductance of the smallest coil in the group. Again, this is just like resistors connected in parallel—remember that when resistors are connected in parallel, the total resistance is always less than the resistance of the smallest resistor. Since resistors and coils are the same in this respect, you should have no difficulty remembering what happens when coils are connected in series or in parallel. It is unlikely that you will ever actually have to calculate the inductance of a number of coils connected together, but you should realize what happens to the total inductance in a circuit.

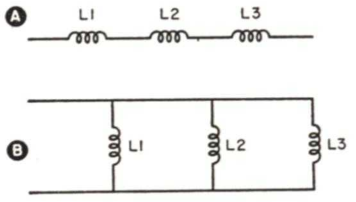


FIG. 18. Coils connected in series (A); coils connected in parallel, (B).

When coils connected in series are placed close together so that some mutual inductance exists, there is interaction between the coils, and the combined inductance can no longer be figured simply by adding the inductances of the individual coils. In this situation, we must consider the mutual inductance in the circuit and also how the coils are connected together.

Let's look at the first case, where the coils are connected in series so that the flux from one coil aids the flux from the other. In other words, the magnetic lines are flowing in the same direction. Here, if the inductance of the two coils is represented by L1 and L2 and the mutual inductance by M, the total inductance (L_T) of the two coils connected in series will be equal to:

$$L_T = L1 + L2 + 2M$$

If the connections to one of the coils is reversed, its magnetic field will oppose the magnetic field of the other. Here we find that the field of one coil is opposing the field of the other. Under these circumstances the total inductance of the two coils connected in series will be:

$$L_T = L1 + L2 - 2M$$

SUMMARY

You have studied a great deal of important material about coils in this section and it would be worthwhile to read the section over several times to be sure that you have understood everything covered.

You have learned that the electrical property that describes coils is called inductance, and that inductance is measured in henrys. A coil has an inductance of 1 henry when a current change of 1 amp. per second induces a voltage of 1 volt in the coil.

You learned that when the current flowing through a coil changes, there is voltage induced in the coil that opposes the change that produces it. This voltage is a self-induced voltage and is called counter emf or back emf.

Coils have a property called inductive reactance. Inductive reactance is the opposition that a coil offers to the flow of ac through it. Inductive reactance is measured in ohms and is somewhat similar to resistance inasmuch as it opposes the flow of ac through the coil.

When two coils are placed near each other, the flux lines of one coil will cut through the other coil, and the coils are said to be mutually-coupled. The amount of coupling is determined by the nearness of the coils to each other and the shape and size of the coils. This coupling is called mutual inductance. The mutual inductance of two coils is measured in henrys.

When coils are connected in series, the total inductance is equal to the sum of the individual inductances, and when they are in parallel, the total inductance is less than the inductance of the smallest coil. When mutually-coupled coils are connected in series, the total inductance is L1 + L2 + 2M when the magnetic field of the two coils aid each other; and L1 + L2 — 2M when the magnetic fields oppose each other.

Ohm's Law For Coils

You will remember from earlier lessons that the current that will flow in a circuit depends upon the voltage applied and upon the resistance of the circuit. This rule can be applied to ac circuits as well as dc circuits, but in an ac circuit, you substitute the total opposition offered to the flow of current for the resistance. In an ac circuit, the total opposition to current flow is called impedance and is represented by the letter Z. In this section of this lesson, you will study Ohm's Law for coils, you will learn what phase is and also what impedance is and how to find the impedance in ac circuits.

PHASE

Before you can understand why impedance is important in ac circuits you must understand what we mean by phase. Phase is important. It is something that you will run into all the way through your study of electronic circuits. Time and time again you will see the expressions, "in phase," "out of phase," and "phase shift." Since phase is so important, learning what it is now will simplify your studies later.

In a circuit made up only of resistance, if we increase the voltage, the current will increase immediately. Changes in current can be produced instantly by changing the voltage in the circuit. In other words, the current follows the voltage changes instantaneously. The current is in phase with the voltage. This idea simply means that changing the voltage will produce the same change in current flowing in the circuit.

You have already seen that this is not true of circuits containing coils. If you have a dc voltage source connected across a coil, the current that will flow will depend only on the dc resistance of the coil, in other words the resistance of the wire used to wind the coil. If you suddenly increase the voltage applied to the coil, there is immediately a change in the number of flux linkages cutting the various turns of the coil. This induces a voltage in the coil, and the induced voltage opposes the change in applied voltage. When the current changes because of the increase in applied voltage, it will be limited by the induced voltage as well as by the dc resistance. The inductance of the coil opposes the change in current through it—this effect is called inductive reactance. Gradually the current will increase from the value that it was originally to a higher value, if the voltage is increased. As the current increases, and finally reaches its new value, the self-induced voltage in the coil decreases until finally when the current becomes constant, the self-induced voltage in the coil will disappear.

Now let's look at an ac circuit where an ac voltage is applied across the coil. We are going to look at a 60-cycle sine wave such as shown in Fig. 19A as it is applied across a coil and consider what happens to the voltage at a number of instants as the sine wave goes through part of its cycle. Look at the voltage at the point marked A. At this instant the voltage is zero, but it is increasing at a very rapid rate. The actual rate at which the voltage is increasing can be shown by drawing a straight line that is tangent to the curve at Point A. (When we say it is tangent, we mean the side of the line touches the curve but does not intersect it.) Notice that at this instant, the line is going almost straight up and down as shown in Fig. 19B. This indicates that the voltage is changing very rapidly in a short period of time. Now look at the lines drawn tangent to the curve at Points B and C. Notice that at Point B, the line slopes more, showing that the voltage is not changing quite so rapidly, and finally the line drawn at Point C is horizontal, indicating that there is no change in the voltage. At this instant, the voltage is constant.

Now let's consider what will happen to the self-induced voltage of the coil at these three points. At Point A, the applied voltage is changing very rapidly and therefore there will be a very rapid change in the flux linkages in the coil. This means there will be a high self-induced voltage. At Point B where the applied voltage is not changing so fast, the change in flux linkages will be somewhat less than at Point A and as a result the self-induced voltage will not be as high as that at Point A. Finally at Point C, the voltage applied to the coil is not changing at all, and therefore there will be no change in the flux linkages and no self-induced voltage in the coil.

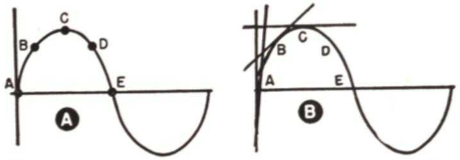


FIG. 19. A 60-cycle sine wave is shown at A. The lines drawn tangent to it at Points A, B, and C show the rate of change at those particular points.

Point A to Point C is called one-quarter of a cycle. We also call this 90 degrees. You know that there are 360 degrees in a circle and one-quarter of a circle is 90 degrees. A simple two-pole generator generating a 60-cycle sine wave will go through 90° in generating a quarter of a cycle. We therefore say that the ac voltage has gone through 90°.

Now looking at Fig. 19A, let's see what happens to the second quarter of the cycle. Starting at Point C again, since this is where the second quarter starts, the ac voltage is not changing. At Point D, the voltage is changing, it is decreasing at a fairly rapid rate. Finally at Point E the voltage passes through zero volts, and the voltage is decreasing at a very rapid rate.

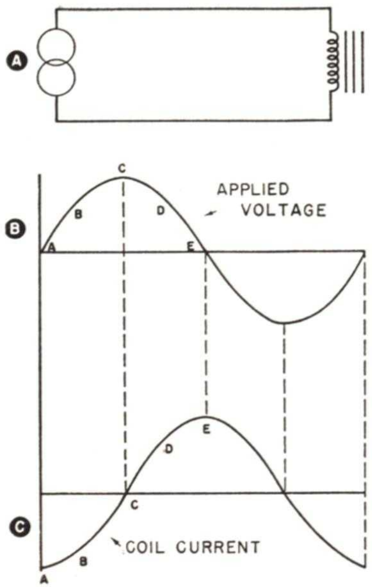


FIG. 20. Phase relationship between the voltage applied to a coil and the current through it.

Again let's consider what happens to the induced voltage at these three points. As before, at Point C where the applied voltage is constant there is no induced voltage.

At Point D where the voltage is decreasing, there will be a self-induced voltage and this voltage will have the polarity such that it tries to oppose the decreasing voltage. Finally at Point E, the self-induced voltage will be even higher because the number of flux linkages changing is at a maximum. Again, the voltage induced will try to oppose the decrease in generator voltage.

Now let's see what happens to the current flowing in a coil connected across a generator as the ac voltage goes through the cycle shown in Fig. 19. The coil and generator are shown in Fig. 20A. The generator voltage is shown in Fig. 20B and the coil current in Fig. 20C. At Point A, the actual voltage applied to the coil by the generator is zero. However, since the voltage is changing at a very rapid rate at this point, there will be a high induced voltage in the coil. The polarity of the induced voltage will be opposite to the polarity of the voltage applied by the generator because the induced voltage tries to set up a current to produce a magnetic field to oppose the change in flux linkages.

Since at this instant, the generator is not applying any voltage, but the induced voltage is at a maximum and has the opposite polarity, instead of current flowing from the negative terminal of the generator through the coil and back to the positive terminal, the induced voltage in the coil will push the current through the circuit in the opposite direction. This current will be high because the induced voltage is at its maximum value.

At Point B, the generator voltage is beginning to build up, and the induced voltage is beginning to go down. However, even though the generator voltage is building up, the voltage is still changing at a very rapid rate, even though it is not quite as rapid as at Point A. As a result the induced voltage is still higher than the applied voltage, and the generator voltage cannot completely overcome the induced voltage and so current continues to flow in the same direction as it did.

By the time the generator voltage reaches Point C, the current being pushed through the coil by the induced voltage will drop to zero, because the number of flux linkages is no longer changing because at this instant the voltage applied across the coil is not changing. If the voltage applied by the generator remained at this value, current would try to build up and flow from the negative terminal of the generator through the coil back to the positive terminal of the generator.

However, this situation exists only for an instant. As soon as the generator voltage reaches the value shown at C in Fig 20, the generator voltage starts to decrease. Once the voltage starts to decrease, there is a voltage induced in the coil that tends to oppose this change in voltage across the coil. This induced voltage aids the generator voltage and current starts to flow as shown in the second quarter of the cycle in Fig. 20C.

When the ac voltage reaches Point D, the voltage is decreasing at a rapid rate and it produces an even higher self-induced voltage, which causes the current to continue to increase even though the generator voltage is decreasing. Finally the generator voltage is changing at its maximum rate when it reaches Point E, and the self-induced voltage in the coil will be a maximum. Since this self-induced voltage is still opposing the change in the voltage applied to the coil, the current produced by the self-induced voltage will reach a maximum value and it will be flowing again in the direction shown at the end of the second quarter cycle in Fig. 20C.

Now let us stop and see exactly how the current follows the voltage produced by the generator. When the generator voltage was zero, but starting to increase in a positive direction, as at Point A, the induced voltage at the time was a maximum and had the opposite polarity to that of the generator. This caused a high value of current to flow in a direction opposite to what you would expect from the generator polarity. As the generator voltage built up to its maximum value, the induced voltage and current flowing through the coil gradually decreased until at the time the generator voltage reached a maximum voltage value, the current flowing in the coil reached zero. As the generator voltage applied to the coil began to decrease, the current flowing through the coil began to increase, and finally the generator voltage reached zero. At that instant the current flowing in the coil had reached a maximum value! Notice what has happened, the current is lagging behind the source voltage by one-quarter of a cycle, or 90°.

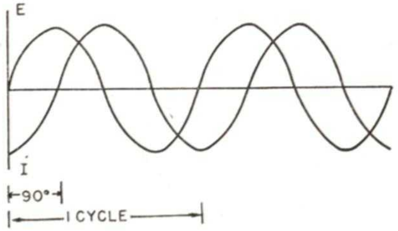


FIG. 21. Current through a coil, I, lags behind the voltage, E, by 90°.

If we draw the generator voltage in Fig. 20 and the current flowing in the circuit on the same diagram, it will look like Fig. 21. Notice here that one-quarter of a cycle, or 90 degrees, after the voltage reaches a certain point, the current reaches that point. Thus the current follows the voltage. Electronic technicians say that the current *lags* the voltage by 90°.

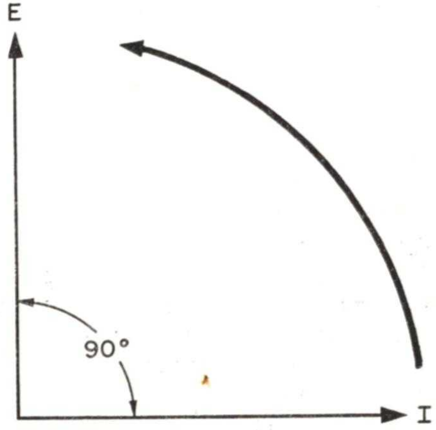


FIG. 22. The relationship between the current and voltage shown in Fig. 21 can be shown by means of vectors.

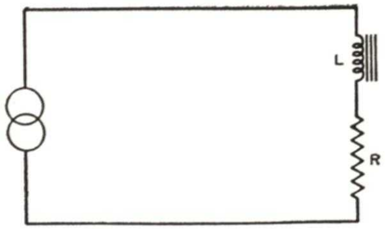


FIG. 23. A practical coil consists of both inductance and resistance. The circuit shown above could represent a coil alone or a coil and a resistor in series.

This relationship can be shown by means of a diagram, called a "vector diagram." This is a kind of graph in which arrows drawn from a common starting point are used to show the phase relationship between various quantities such as current and voltage, having the same frequency. The arrows are considered to be rotating counter-clockwise around the common starting point, and the angle between them represents the difference in phase.

Fig. 22 shows how we would show a 90° phase difference between voltage and current. The arrow, or vector, drawn horizontally represents the current. In a diagram such as this, the current vector is always used as the reference point. It is drawn horizontally and pointing to the right, and the other vectors are drawn in relation to it. The voltage leads the current by 90°, so the voltage vector is drawn 90° ahead of, or counter-clockwise from, the current vector.

The relationship between the voltage applied and the current flowing through a coil is a good example of what we mean by phase. The voltage and current are out of phase. The current lags the voltage by 90 degrees. However, if we consider the induced voltage, when the induced voltage is zero, the current is zero, and when the induced voltage is a maximum, current is a maximum. Here we can say that the induced voltage and the current are in phase.

In your study of electronic circuits, you will be concerned more with the applied voltage and current flowing than you will be with the induced voltage. Therefore, you must remember that the current that flows in an inductive circuit will lag the voltage by 90 degrees.

This relationship between current and voltage in an inductive circuit applies only when the circuit consists of pure inductance. Unfortunately there is no such thing as a purely inductive circuit. Coils have inductance, but coils also have resistance because they are made by winding a number of turns of wire on a form. The wire has resistance. This resistance cannot be eliminated, and therefore instead of having a circuit consisting of a pure inductance, in practical circuits, you actually have a circuit consisting of inductance and resistance.

The total opposition in an ac circuit is made up of the inductive reactance of the coil, and also of the resistance. We call the total opposition impedance. Now let's consider impedance.

IMPEDANCE

In a circuit where an ac voltage is applied across a coil, the voltage forcing the current through the coil must overcome both the inductive reactance of the coil and the resistance of the coil. The ac resistance of the coil is made up of the dc resistance of the wire used to wind the coil plus other losses that have the effect of increasing the resistance.

The practical way of studying how a coil behaves in an ac circuit is to consider the coil as being made up of a pure inductance with a resistor in series with it. This type of circuit is shown in Fig. 23. Here we can consider exactly what happens when an ac voltage is applied across a coil alone or we can consider what happens in a circuit consisting of both a coil and a resistor. Again, we simply lump together the resistance of the coil with the external resistor connected into the circuit.

FINDING THE CURRENT IN AN AC CIRCUIT

If you want to find the current flowing in this type of circuit when an ac voltage is applied, you must determine the total opposition that will be offered to the flow of ac current through the circuit.

There are several ways of finding the total flow of ac current in a circuit. We will introduce two ways here, you can use whichever way you consider the easier. As an example, let's find the current flowing in the circuit shown in Fig. 24. Here we have a coil with an inductance of 2 henrys. This coil is connected in series with a 1000-ohm resistor. The two are connected across a 60-cycle generator having an output voltage of 500 volts. The problem is to find the current that will flow in the circuit.

Vector Solution. First, we must find the inductive reactance of the coil. To do this we use the formula:

$$X_L = 6.28 \times f \times L$$

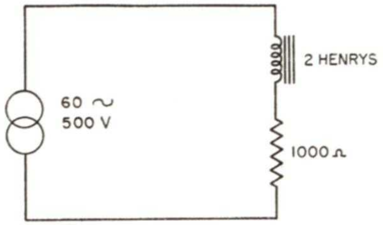


FIG. 24. There are two ways to find the current in the circuit shown above: by using vectors or by using a mathematical solution.

and substituting 60 for f and 2 for L we get:

$$X_L = 6.28 \times 60 \times 2$$

which equals 753.6 ohms. Since this is a practical problem, we simply call it 750 ohms.

Now we know that the inductive reactance of the coil is 750 ohms and the resistance in the circuit is 1000 ohms. You might at first think that we can obtain the total opposition to the ac current flow simply by adding these two together. However, this is not true—you cannot simply add inductive reactance and resistance. Let us see why. We know that when voltage is applied to an inductance, the current that flows will be out of phase with the applied voltage. When voltage is applied to the resistance, the current that flows will be in phase with the applied voltage. The inductance and the resistance have different effects on current.

Adding the effect of the two together can be done by means of vectors.

You have already seen how vectors can be used to indicate phase differences in quantities having the same frequency. Now we will see how they can be used to add similar quantities having the same frequency but a difference in phase.

As before, the angle between the vectors represents the phase difference between the quantities. The arrows are all drawn to the same scale, so that the length of the arrows indicates the amplitudes of the quantities to be added.

For example, suppose we wanted to show the relationship between two 60-cycle ac voltages A and B. A is 30 volts, and B is 40 volts, and they are 90° out of phase with each other. A is leading B. Fig. 25 shows how we would draw this, using a scale of ½-

inch equals 10 volts. We draw B, 2 inches long, and we draw A, 1½ inches long. Since A is leading B by 90° we draw it 90° counter-clockwise from B.

Now, suppose we wanted to find the sum of these voltages. We could not simply add 30 and 40, because of the difference in phase. This is where the vector diagrams will help us. We can add these two voltages, taking into account the phase difference, as shown in Fig. 26. We say we are finding the "vector sum" of the two.

To do this, we complete a rectangle by drawing lines parallel with the two vectors. Then we draw in a diagonal to the point where the two lines intersect. This diagonal represents the vector sum of voltages A and B. When we measure it, we see it is 2½ inches long. Since we used the scale of ½ inch to 10 volts, we see that the vector sum is 50 volts.

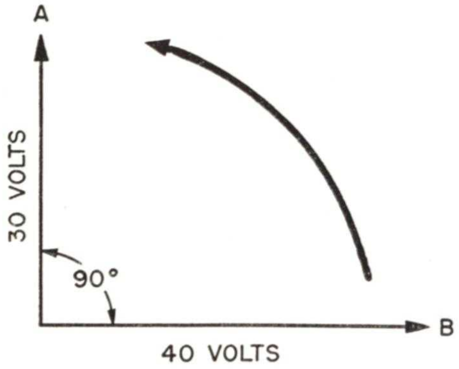


FIG. 25. In this diagram, the lengths of the arrows show the amount of voltage and the angle between them shows their phase relationship. They are considered to rotate counter-clockwise.

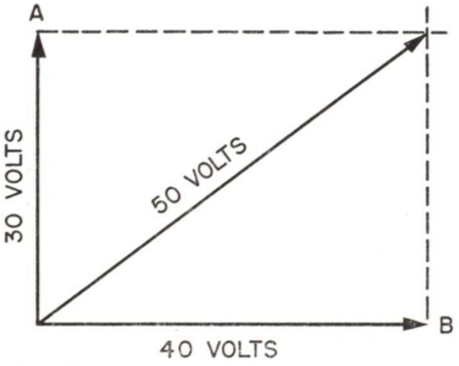


FIG. 26. How to find the vector sum of two ac voltages differing in phase.

Now let us see how we can apply this principle to find the total opposition or impedance in the circuit we have been studying. As we have already mentioned, when considering phase in a circuit, the phase of the current is always used as a reference. The current vector is drawn horizontally and pointing to the right, and voltage vectors are drawn in the positions corresponding to their phase relationship to the current. So the first thing we do is to draw an arrow to represent the current, as shown in Fig. 27. We do not know what the current is, so its length does not matter, but we do know it should be drawn horizontally and pointing to the right. The next step in our procedure depends upon an important fact—that the voltage across the resistor will be in direct proportion to its resistance. We also know that the voltage across the resistor will be in phase with the current, and the voltage across the coil will be 90° ahead of the current. Therefore, we can draw two vectors, one on top of the current vector to represent the voltage across the resistor, and one 90° ahead of (counter-clockwise from) the current vector to represent the voltage across the coil. We do not know what these voltages are, but since the voltage is in direct proportion to the resistance and reactance, we can draw the arrows using a scale that is in proportion to the ohmic values of the resistance and reactance and label the vectors R and XL.

FIG. 27. The current vector is drawn horizontally and used as a reference point for the other vectors.

First we draw a vector to represent the voltage across the resistance. If we use the scale of an inch to 500 ohms, the vector representing the voltage across the resistor will be 2 inches long. Since the current flowing through the resistor will be in phase with the voltage, we draw the resistance voltage vector and mark it R as shown in Fig. 28. Here you should notice that it is drawn right on top of the current vector. The current vector is not drawn to scale, but the resistance voltage vector is drawn 2 inches long.

FIG. 28. The voltage across a resistor is in phase with the current, so the vector for the resistor voltage is drawn on top of the current vector.

Next, we draw the vector for the voltage drop across the coil. Since we have a reactance of 750 ohms, this vector should be 1½ inches long. Since the coil voltage is 90 degrees out of phase with the resistor voltage, this vector is drawn as shown in Fig. 29 and labeled XL. Now we have a vector diagram that represents the voltage across the resistance and the reactance in the circuit shown in Fig. 24. Now to get the impedance, we draw dotted lines as shown in Fig. 30 to complete the rectangle. The vector representing the voltage across the impedance is drawn in as shown in Fig. 30 to the point where these lines meet, and the impedance is obtained by measuring the length of this vector. On the diagram we have drawn, the impedance voltage vector is 2½ inches long. Since we have used the scale of 500 ohms to the inch, the impedance in the circuit must be 2½ times this value, or 1250 ohms. This is the total impedance or opposition to current flow in the circuit. Now that we have this figure, we can quickly determine the current that will flow.

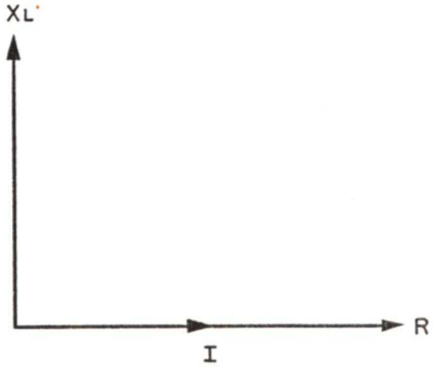


FIG. 29. The vector for the voltage across the resistance is drawn in at right angles to the resistor voltage vector.

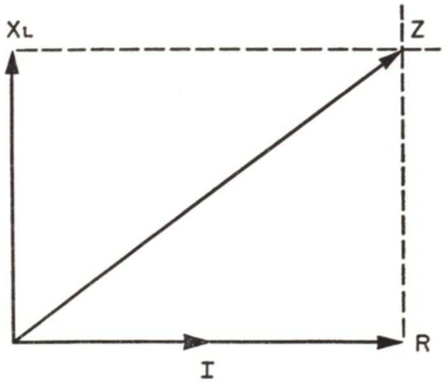


FIG. 30. The vector representing the voltage across the impedance is the vector sum of the other two.

To find the current we use Ohm's Law for coils. The current is equal to the voltage divided by the impedance. The letter Z is usually used to represent impedance. This can be expressed

$$I = \frac{E}{Z}$$

Substituting 500 volts for E and 1250 ohms for Z we get:

$$I = \frac{500}{1250} = .4 \text{ amp}$$

Mathematical Solution. Another method of solving for the impedance in an ac circuit is by means of the formula:

$$Z = \sqrt{R^2 + X_L^2}$$

The mathematical sign $\sqrt{\quad}$ means to find the square root. Therefore, you square the resistance and the reactance, add the two together, and then take the square root of the sum. Once you have the impedance, proceed as before to get the current. Again, this is not the type of problem that the technician will have to solve, but it is important to remember the general method of obtaining the impedance in a circuit of this type. If you know how to do square root problems, the mathematical solution is the simpler; if you don't, the graphical solution is the one to use. It is particularly important to realize that you cannot obtain the impedance simply by adding the resistance and the reactance together. The impedance in a circuit will always be somewhat less than the sum of the two because of the difference in phase.

KIRCHHOFF'S VOLTAGE LAW

You will remember that Kirchhoff's voltage law stated that the sum of the voltage drops in a complete circuit is equal to the source voltage. Now let's see how this applies to an ac circuit consisting of inductance and resistance.

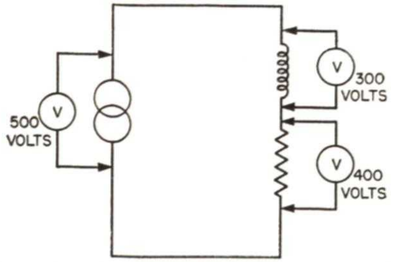


FIG. 31. **With a source voltage of 500 volts, we have 300 volts across the coil, and 400 volts across the resistor, but they are not in phase.**

Using the same example as before, we have already calculated the reactance of the coil at 750 ohms and we know the resistance of the resistor is 1000 ohms. We can use Ohm's Law in the form:

$$E = I \times R$$

to find the voltage drop across the resistor. In the case of the coil, the voltage drop is:

$$E = I \times X_L$$

To find the voltage drop across the coil, we simply multiply 750 by the current, which we have already determined as .4 amp. $750 \times .4 = 300$. Therefore the voltage across the coil is 300 volts. The voltage across the resistor is $1000 \times .4 = 400$ volts. Now look at Fig. 31 where we have indicated the voltages. We have 300 volts across the coil and 400 volts across the resistor, but our source voltage is only 500 volts. These are the readings we would actually obtain if we had meters connected as shown!

This may appear to be a contradiction of Kirchhoff's Voltage Law, but actually it is not. You must remember that the voltage across the resistor will be in phase with the current, but the voltage across the coil will not be in phase with the current flowing through it. The voltages that we have just determined are effective voltages. At any given instant the sum of the voltage across the coil plus the voltage across the resistor will be equal to the voltage across the generator. However, the effective voltage across the coil and the resistor if they are simply added together would give us more than 500 volts.

To add these two voltages we must again resort to vectors. The vector addition of these two voltages using a scale of 200 volts equals 1 inch is shown in Fig. 32. Notice that the vector representing the voltage across the resistor is drawn 2 inches long, and the one representing the voltage across the coil is drawn 1½ inches long. When we complete the vector diagram to find the sum, as before, we obtain a vector which is equal to the generator voltage of 500 volts.

The mathematical solution that we used before can also be used to obtain the source voltage. If we let the symbol E_G equal the source voltage we have:

$$E_G = \sqrt{E_R^2 + E_L^2}$$

If we substitute 400 for E_R, E_R^2 equals 160,000. Similarly E_L squared equals 90,000. Adding the two together we get 250,000; the square root of 250,000 is 500, so as before we find that $E_G =$ 500 volts.

Importance of Phase. A general knowledge of phase and vector diagrams helps you to understand the action of coils and capacitors in ac circuits and will make you a better-than-average technician. You will understand why you do certain things when making adjustments or repairs, instead of just blindly following instructions. It is the men who know the "How" and the "Why" who command the highest salaries in the modern world of electronics.

Later in your course, you will learn that the opposition of a coil, which we have called inductive reactance, can be balanced or cancelled by the opposition of a capacitor, which is called capacitive reactance, because the two are of opposite phase. You will see the importance of phase in many other practical examples. Phase, however, is not a subject you can grasp in one lesson; you will understand it better and better with each succeeding lesson.

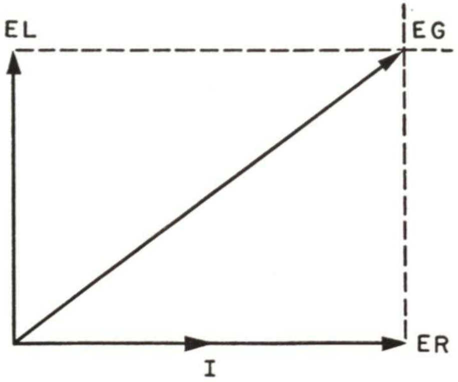


FIG. 32. **Finding the vector sum of ER and EL.**

Q OF A COIL

We mentioned that since a coil is wound of wire and wire has resistance, there is no such thing as a perfect inductance. All coils have both inductance and resistance.

As you might expect, when manufacturers make a coil, they usually try to keep the resistance as low as possible. Generally, the lower the resistance is in proportion to the inductive reactance of a coil, the better the coil. The relationship between inductive reactance and resistance is called the Q of the coil. This is represented by the formula:

$$Q = \frac{X_L}{R}$$

A high-Q coil is a coil in which the value of the inductive reactance is much higher than that of the resistance. Coils with a Q of 100 or more are quite common.

Since the reactance of a coil increases with frequency, you might expect the Q to increase with frequency. This is true up to a certain point, but R is the ac resistance of a coil and it increases with frequency also. As long as X_L increases with frequency faster than R, the Q of the coil will increase, but if R increases faster than X_L, the Q of the coil will decrease as the frequency increases so the coil cannot be used at high frequencies.

Q is particularly important in tuned circuits when coils are used with capacitors. You will see why this is so later when you study these circuits.

SUMMARY

This section of your lesson is almost too important to try to summarize. However, to help you to review, here are the important things you should understand.

You should have a general understanding of what we mean by phase. When the current in an ac circuit is increasing exactly in step with the voltage, and reaches the maximum value at the same time as the voltage reaches the maximum value and reaches its minimum value at the same time as the voltage reaches its minimum value, we say that the current and voltage are in phase. In a circuit consisting of a pure inductance the current will lag the voltage by 90 degrees. This means that it is one-quarter of a cycle behind the voltage.

Impedance is the vector sum of resistance and reactance. The impedance in a circuit will be greater than the resistance or the reactance alone. Impedance cannot be determined simply by adding the resistance and the reactance.

The voltage across a component in an ac circuit can be found by Ohm's Law. The sum of the individual voltage drops in an ac circuit is equal to the source voltage, providing we add these voltages vectorially. We cannot add them by means of simple arithmetic and expect their sum to be equal to the source voltage. If we could measure the source voltage and the voltage across each of the parts in the circuit at any instant, we would find that the sum of the voltage drops at that instant would be equal to the source voltage.

LOOKING AHEAD

You have now finished the study of the basic facts of resistors and coils. When you complete a similar study of capacitors in the next lesson, you will have a basic knowledge of these three important parts. In a later lesson you will learn more about how these three parts work together and what effect they have on ac signals. Remember that the ac supplied by the power company, audio signals, and radio frequency signals are all ac signals differing only in frequency and in some cases in wave shape. The important facts you learned about ac and coils in this lesson apply to all ac signals regardless of their frequency.

Most students are anxious to go ahead as quickly as possible with their course, particularly in the early lessons. However, do not be so anxious to go ahead with later lessons that you leave the earlier lessons without completely understanding them. The information given in these early lessons is basic and is information that you will use over and over again in more advanced lessons. If you do not understand how basic parts such as resistors, coils, and capacitors affect circuit performance, you will not be able to understand some of the later lessons.

Lesson Questions

Be sure to number your Answer Sheet 6B.

Place your Student Number on every Answer Sheet.

Most students want to know their grade as soon as possible, so they mail their set of answers immediately. Others, knowing they will finish the next lesson within a few days, send in two sets of answers at a time. Either practice is acceptable to us. However, don't hold your answers too long; you may lose them. Don't hold answers to send in more than two sets at a time, or you may run out of lessons before new ones can reach you.

1. If the reluctance of a magnetic circuit is increased, what will happen to the flux?

2. If the number of flux linkages cutting a coil decreases, a voltage will be induced in the coil that will tend to produce magnetic flux that will tend to prevent the original flux from decreasing. Is this statement true or false?

3. Explain what inductive reactance is.

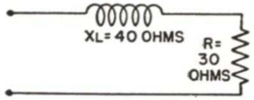
4. What is the inductive reactance of a 1-henry coil at a frequency of 100 cycles? $X_L = 2\pi F L$

5. If two 15-henry coils have a mutual inductance of 5 henrys, what is the total inductance when they are connected in series if the flux of one coil aids the flux of the other? 40 henrys $L_t = L_1 + L_2 + 2M$

6. Explain what is meant when we say "the voltage and current are out of phase."

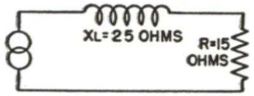
7. What do we mean by the impedance of a circuit?

8. What is the impedance of the circuit shown? (50)



9. If the frequency of a voltage source connected to a circuit consisting of a coil and resistor in series is increased, will the current flowing in the circuit increase, decrease, or remain the same?

10. If the current flowing in the circuit shown is 1 amp, find:
    (1) the voltage across the coil.
    (2) the voltage across the resistor.



SINCERE APPRECIATION PAYS

Have you ever watched a dog respond to a friendly pat as a reward for obedience? Have you noticed how a child glows with joy when praised for good behavior? Have you ever felt your own brain cells respond with increased effort when you praise them by saying, *"That's a fine piece of work, even if I did do it myself!"*?

Yes, everyone responds to sincere and merited praise. It is a tonic to both giver and receiver. It brings greater praise and appreciation back to you. It costs nothing more than a smile and a few sincere words, but it can truly achieve miracles in happiness and success, and put real money in your pocket.

Time spent in figuring how to give sincere and deserved praise is well worth while. Let people know that you appreciate *their* fine work, and watch the breaks come *your way*.

J E Smith