Electronics

Radio

Television

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COILS IN ELECTRONICS CIRCUITS

ASSIGNMENT 16

COILS IN ELECTRONICS CIRCUITS

We have learned that there are but a few fundamental circuit components about which we need to become familiar in order to understand electronics circuits. These are: resistors, amplifying elements (transistors and vacuum-tubes), cells and batteries, coils, and capacitors. We have already discussed the first three of these, and this assignment will be devoted to the fourth one, **coils.**

We have already learned the schematic symbols for the various types of coils and have found that a coil carrying current is surrounded by a magnetic field. Since, it is the magnetic field which surrounds a coil carrying a current that permits coils to play a very important part in electronics circuits, let us review briefly what we have learned about a magnetic field. A magnetic field is a field of force which surrounds a magnetic body. The magnetic field can exert force on other bodies located in this field.

The Magnetic Field

There are two basic methods for obtaining a magnetic field. One of these methods is through the use of permanent magnets. The second method is more important in electronics, and results from the fact that **a magnetic field is produced when an electrical current flows through a conductor.** The effect is much stronger if the conductor is wound into the form of a coil. We have learned that in any magnet, either the permanent type or the electromagnetic type (this is the way we refer to a coil carrying current), that there is a North magnetic pole at one end and a South magnetic pole at the other end. The magnetic field of force, often called the magnetic flux, is assumed to go from the North pole of the magnet to the South pole. Each line of flux is a continuous line. That is, **each** line leaves the North pole and goes all of the way around to the South pole. There are no incomplete lines of flux.

Now that we have refreshed our memory on the subject of the magnetic field, let us return to our main topic: coils.

Coils

Coils are frequently used in electronics circuits not only for their ability to produce a magnetic field, but because of the effects the coil has on the remainder of the circuit. Let us examine typical coils very carefully and see what these effects are.

Several typical electronics and television coils are shown in Figure 1. The coil shown in Figure 1(A) is a type frequently used in transmitters, and is made of very heavy wire. Notice that it has few turns, and that these turns are widely separated, or "spaced". Because this wide spacing reduces the possibility of voltages arcing across from one turn to the next, this type of coil can be operated at very high voltages. The large wire gives the coil greater mechanical strength and sturdiness than smaller wire would and it also has a lower d-c resistance. Also, as we shall see later on, there is another reason for using large wire. This reason is the "skin effect" phenomenon.

Figure 1(B) illustrates a coil which is used in radio receivers. This coil is wound with many turns of fine wire.

Figure 1(C) is a special type of coil called an RF choke. Later on we shall see how it gets its name.

The coil illustrated in Figure 1(D) is wound around a core of magnetic material, probably iron or some alloy of iron. You will recall that this core will greatly increase the total amount of magnetic field produced by the coil. This coil is called an iron-core choke.

What A Coil Does

It is quite easy to get a good idea of the effect coils will have when used in electronics circuits. For example, if we take a coil of wire and connect it to a battery so that an electron current flows through it, we know that a magnetic field will be produced. Also, we know that we will have a North magnetic pole at one end of the coil and a South magnetic pole at the other end of the coil.

Since this resulting magnetic field can be used to attract small particles of iron to the ends of the coil, it is not unreasonable to suppose that a certain amount of work had to be done in order to produce this field. From all our experience we know that it is impossible to produce anything without expending time and work. The same thing is true in this case. Work is done in building up the magnetic field about the coil. After the field has been built up, it contains potential energy; that is, it possesses the ability to do work. Let us repeat this statement for emphasis: **Work is done in building up a magnetic field about a coil, and after the field is built up, it possesses potential energy.**

We found in a previous assignment, that if we were to move a conductor through a magnetic field, that a voltage would be induced in the conductor. Likewise, we found that if the conductor were held stationary and the magnetic field were moved across it, that a voltage would be induced in the conductor. This illustrates a very important point concerning a coil. If a magnetic field around a coil is moved, there will be a voltage developed across the coil.

To illustrate just how the magnetic field around a coil acts, let us consider the circuit shown in Figure 2(A). This is a very simple series circuit containing a battery, a switch, a coil, and a resistance. This resistance may not be an actual resistor, but there is always some resistance present in any circuit. The battery will have some internal resistance, the connecting wires will have some resistance, and of course, since the coil is made of wire, it will have some resistance. We can "lump" all these resistances together into a single resistor for purposes of analyzing the circuit, and assume that the coil has zero resistance.

Of course no current will flow in the circuit before we close the switch, and with no current flowing through the coil there will not be a magnetic field around the coil. However, when we close the switch, current will begin to flow and a magnetic field will **begin to build up** around the coil.

Here is the important point. It will take a certain amount of **time** and **work** to **produce the magnetic field.** When we first close the switch all of the battery voltage is needed to start producing the magnetic field around the coil. When current begins to flow in the circuit, we will begin to have a voltage drop across the resistance in the circuit. This will leave less than full battery voltage across the coil. The magnetic field (and current) will build up more and more slowly as less and less voltage is available across the coil. Figure 2(B) is a graph of the voltage and current associated with this coil. The solid line shows the current which is flowing, and the dotted line shows the voltage **across the coil.**

The current will continue to increase until all of the battery voltage is being used as an **IR** voltage drop across the resistor. **Voltage** is needed across the coil only during the time that the **magnetic field is building up.** The final value of current will be:

$$I = \frac{E}{R} = \frac{6}{3} = 2 \text{ amperes.}$$

Study Figure 2 (B) carefully and then consider the next statement. When we first closed the switch we had zero current and all the battery voltage was acting on the coil. Finally, when the current had reached its maximum value, all of the battery voltage was acting on the resistor, and the voltage across the coil was zero. Let's repeat this statement. When the voltage across the coil was maximum, there was no current flowing, and when the current flow was maximum, the voltage across the coil was zero. If for example, it took four seconds for the current in the circuit to reach its maximum steady value, we can definitely say that the voltage across the coil was at its maximum value four seconds before the current through the coil reached its maximum value. Certainly we can say that the current through the coil **lagged** behind the voltage across the coil.

We have seen that it takes time and work to build up a magnetic field. Because of the effect of the magnetic field, the current will always **lag** behind the voltage when we energize a circuit containing a coil.

Inertia

As far as an electronics circuit is concerned, this effect of a magnetic field is primarily an "**inertia**" effect. If we were to look up the word "inertia" in a dictionary, we would probably find a definition something like this: That property of matter which tends to keep it at rest if already at rest, or keep it in motion if it is already in motion; that is, the opposition to a change of any form.

Let us picture two large trucks of the same make and size standing at a red traffic light. One of the trucks is empty and the other is very heavily loaded. The light turns green and both drivers start off as rapidly as possible. Of course, the empty truck will accelerate more rapidly than the loaded truck since some of the work done by the engine of the loaded truck is needed to overcome the inertia of the heavy load.

If both trucks were moving down a highway at the same rate of speed, the heavy truck will be the hardest to stop since the **inertia** of the heavy load will tend to keep it moving.

Compare this analogy with the action of the circuit containing a coil shown in Figure 2.

In the loaded truck, the inertia of the load opposed any change in motion. In the electrical circuit the "inertia" of the coil opposes any change in current.

In electronics circuits you will find coils used in connection with alternating currents and voltages. You will want a clear understanding of the inertia effect when voltage and current are constantly changing in magnitude and periodically changing in direction.

When does the inertia of the heavy load in the truck become noticeable? Only when we try to start, stop or change the speed of the truck. Similarly, the inertia effect of the magnetic field in and around a coil becomes noticeable only when we try to start, stop, or change the amount of current through the coil, and thereby change the amount of magnetic field around the coil. As you know, in alternating current circuits, the current and voltage are changing continually, and therefore this inertia effect will be present constantly in a-c circuits.

To understand this inertia effect in an a-c circuit, look at Figure 3.

We have a 50 pound steel block mounted on ball-bearing wheels. There will be very little friction (resistance) when we move the block from side to side. We have a handle on top which we may grasp with our hand in order to move the block from side to side.

Suppose you take hold of the handle and move the block back and forth to the left and right. Since you are only moving the block back and forth in your mind, you won't get tired if you continue to move the block back and forth while we discuss what is taking place.

As the block travels back and forth, it is standing still at two different times during each cycle or oscillation. When the block moves to the limit of its travel to the left or right it stands still **for an instant** before reversing its direction. Are you applying any force to the handle at the time the block is standing still? Yes, definitely. For example, when the block is at its limit of travel to the right you are making the maximum effort of pull to the left.

When is the block moving most rapidly? Just as it passes its original position. Are you applying any force to the block at the time the block is moving most rapidly? No. Follow the block during one half cycle as it moves from extreme right to extreme left. The block is standing still for an instant at the right. You pull to the left as hard as you can to start the block moving to the left. By the time the block reaches the center of travel, (its original position), it is up to maximum speed. As soon as it passes a little to the left of center you will have to start pulling to the right to slow the block down. At the instant the block is at the center of its travel, it is moving most rapidly. You are not applying any force to the handle. The block is coasting.

Because of the **inertia** of the heavy steel block, the **movement** of the block

lags behind the **force** applied to the handle by ¼ of a cycle. You are applying maximum force to the right while the block is standing still at the left, yet it is not until one quarter cycle later that the block is moving most rapidly to the right. If, as in electrical work, we divide our complete cycle (left to right and back again to left) into 360°, we can say that movement lags behind the applied force by 90°.

In this example, the force applied to the block is equivalent to the force in an electrical circuit, or the voltage, and the movement is equivalent to the electric current. In the block, the motion lags the force by ¼ cycle; in an a-c circuit containing a coil, the current lags the voltage by ¼ cycle, or 90°.

How a Coil Acts in an A-C Circuit

Figure 4(A) shows a coil connected across the output of an oscillator, or a-c generator. The oscillator will produce a voltage (or force) that is periodically changing in direction. This force produced by the oscillator is trying to move a current back and forth through the coil. In this circuit, the electron **movement** (or current) will **lag** behind the applied force (voltage) by ¼ cycle because of the inertia of the magnetic field. This corresponds, in an electrical circuit, to the force and motion of the block in Figure 3. In the case of the block the inertia caused the motion to lag behind the force by ¼ cycle.

In Figure 4(B), we have plotted the voltage across the coil and current through the coil on the same time axis. The current is shown lagging behind the voltage by ¼ cycle or 90 electrical degrees. The voltage reaches its maximum value 90 degrees before the current reachs its maximum value. The voltage falls to zero 90 degrees before the current falls to zero and so on.

The inertia of the magnetic field prevents the current from rising to a maximum as rapidly as the voltage rises to its maximum. The inertia of the magnetic field keeps the current moving in one direction even after the voltage has begun to increase in the opposite direction.

The ability of a coil to produce this inertia effect is called **inductance**.

Thus, we see that the voltage and current in a **pure** inductance are 90° out of phase. **The current lags the voltage by 90°**, or to state the same thing in a different way, the voltage leads the current by 90°. In Figure 4(C) we see the vector representation of this condition. We said that the 90° phase condition resulted when the coil was a pure inductance. That is, when it had no resistance. Since any coil must be wound with some sort of a conductor it must have resistance. Therefore, a pure inductance can never actually exist. Actually, this phase angle of 90° can be approached very closely by winding a coil with large wire. A phase angle of as close to 90° as possible is desirable, since it is to obtain this out-of-phase condition that most coils are used. If we did not want this out-of-phase condition, we would not use coils in electronics circuits.

To further illustrate this out-of-phase condition of the current through a coil, and the voltage across the coil let us consider this same subject from a different viewpoint. Near the first of this assignment it was emphasized that if a conductor was moved through a magnetic field, a voltage would be developed in the conductor. Such a voltage is called an **induced voltage.** We have learned that an induced voltage can also be produced by having the conductor remain stationary, and by having the magnetic field move across the conductor.

Now let us refer to Figure 5. The magnetic field in this case is supplied by permanent magnets, but could be supplied by electromagnets. As the conductor is moved through the magnetic field, a voltage will be produced across this conductor. Instead of saying that the conductor is moved through the magnetic field, it is simpler to say that the conductor moves across, or "cuts", the magnetic lines of force. The important point is, that when the conductor cuts the magnetic lines of force, an emf or voltage is produced across the conductor. The polarity of this voltage is determined by the direction in which the lines of force are cut. If a voltmeter were to be connected across the ends of the conductor, it would be found that the polarity would be one way when the conductor was moved downward, and would be the opposite way when the conductor was moved upward. The amount of voltage produced is determined by the rate at which the conductor cuts the lines of force. If the conductor is moved twice as fast, and therefore cuts twice as many lines of force in a given time, the voltage will be twice as great. Remember this point: **the amount of voltage produced is dependent upon the rate of cutting the lines of force.** The greater the number of lines of force cut in a given time, the greater the voltage produced. We know that the same results occur if the conductor remains stationary, and the magnetic field is moved.

One other point concerning the induced voltage is that the polarity is always such that the effect produced will oppose the original motion. If the two ends of the conductor in Figure 5 are connected together through some conducting medium, such as a piece of wire or a resistor, a current will flow through the conductor. The conductor is in a magnetic field, and when passing current, a force will be developed which will tend to cause the conductor to move. The direction of this force is always opposite to the direction of motion of the conductor. Notice that the **induced voltage always opposes the action which caused it.**

To understand what effect this action has on a coil, examine Figure 6. In this illustration a coil carrying current is shown. Let us assume that a steady amount of current has been flowing for some time and a steady value of magnetic field exists around the coil as shown. Now let us assume, that through some means, the current is caused to decrease. With a decreasing current, the amount of magnetic field, or lines of flux, around the coil will decrease. Therefore, some of the lines of force shown in Figure 6 will collapse. In so doing, they "cut" the conductors which form the coil, and an emf is **induced** into the coil. Likewise, if the current is increased in the coil, more lines of force will build up, and the expanding lines of force will cause an emf to be induced in the coil. This process is called **self-induction,** since the current change in the coil is producing a voltage change in that same coil. The polarity of this voltage is such that it will oppose the applied voltage, and is sometimes called **back-emf.** In accordance with the action illustrated in Figure 5, the amount of voltage induced is proportional to the rate at which the lines of force cut the conductor which, in this case, is proportional to the rate of change of current. That is, the **faster the current changes,** the greater the voltage. Notice, the amount of voltage **is not** proportional to the amount of current, but is proportional to **how much the current changes** in a given period of time.

Let us study the sine wave of current shown in Figure 7, to discover where the greatest change occurs for a given period of time. For convenience, a sine wave of current which has a maximum of 1 ampere was chosen, but a sine wave with any other maximum would behave in a like manner. The time axis has been marked off in equal divisions of 30°. To find the amount of change in current for equal amounts of time, all we have to do is find the values of current at 0°, 30°, 60°, 90°, etc., and subtract the smaller from the larger. By referring to Figure 7 we could fill out the following chart:

DEGREES	CURRENT	DEGREES	CURRENT
0	0	210	—.5
30	.5	240	—.866
60	.866	270	—1.000
90	1.000	300	—.866
120	.866	330	—.5
150	.5	360	0
180	0		

To find the amount of change we merely subtract successive readings. We find that the following changes in amount of current occur:

0 to 30° Change, .5A	30° to 60° Change, .366A	60° to 90° Change, .134A
90 to 120° Change, .134A	120° to 150° Change, .366A	150° to 180° Change, .5A

The same changes occur on the negative alternation. Let us look at these figures to find where the **maximum change** occurs for a given time. We find that it **is not** at the maximum values of the sine wave, but is in the region from 0° to 30°, 150° to 180°, and on the negative half cycle, it would be from 180° to 210°, and 330° to 360°. If we were to divide the time-axis into smaller time intervals than 30°, and repeat this process, we would find that the maximum change in current, for a given time interval, occurs as the sine wave passes through zero, and that at 90° and 270° there is an instant when the sine wave is actually not changing at all.

If we apply this to the self-induction process shown in Figure 6, we will see what all this discussion has led around to. The maximum voltage is induced when the **greatest rate of change** is taking place. We have just proven that the greatest rate of change occurs as the sine wave passes through zero.

Therefore, the maximum **induced** voltage in the coil will occur at 0°, 180°, and at 360° on the **current** sine wave.

Refer again to Figure 4(B) and study the wave forms of the current and voltage. Doesn't the **maximum voltage** occur each time the **current wave passes through 0 amperes**? Also, notice, that when the current is not changing (at the maximum current points), the induced voltage is zero. The voltage and current shown in Figure 4(B) are 90° out of phase.

This entire explanation is not dealing with a different phenomenon than was explained by the moving block; instead, it is explaining the same phenomenon in a different way. Both explanations show that if a coil is connected into an a-c circuit, the **current flowing through the coil will lag the voltage across the coil.**

Since a current which is not changing will produce a fixed magnetic field and will therefore, cause no lines of force to "cut" the conductor, an inductance has no effect on a direct current. If however, a pulsating d-c is applied to an inductance, it will be acted upon by the pulsations.

Unit of Inductance

The unit of inductance is the **henry.** It is named after the American scientist Joseph Henry, who experimented with coils in the early part of the nineteenth century. **A coil has an inductance of one henry when an average rate of change of one ampere per second causes an induced average voltage of one volt.** In electronic circuits, inductances ranging from a few microhenries to about 100 henries will be encountered. The abbreviation for henry is (H). The term millihenry (mH) of course, means 1/1000 of a henry and the term microhenry (μH) means 1/1,000,000 of a henry. The letter L is used to represent inductance in a formula, just as R stands for resistance in Ohm's Law.

It should be emphasized, that the value of the inductance in henries does not determine the phase angle between the voltage across a coil, and the current through it. A **pure** inductance of one microhenry (if we could obtain one) would produce the same phase shift, 90°, as a pure inductance of 100 henries would. The difference between the two sizes is in the **amount** of current they will pass for a given a-c voltage. We shall elaborate on this statement presently, but before doing so, let us find what physical properties will affect the amount of inductance a coil possesses.

Physical Properties Which Determine the Amount of Inductance

The inertia effect of a coil is due to its magnetic field. The stronger the magnetic field about a coil, the larger will be its "inertia effect" or inductance. Anything which will affect the amount of magnetic field produced by a coil, for a given amount of current, will affect its inductance.

A quick review of Assignment 8 will show what must be done if we want to have a large magnetic field produced by a given amount of current in a coil.

To increase the magnetic field about a coil we can:

(1) Wind the turns of the coil closely together to make all of the magnetic field encircle the entire coil.

(2) Use a great number of turns in the coil.

(3) Introduce a magnetic core in the coil.

It would seem from the above, that we should always use a core of some magnetic material, as fewer turns of wire would be required. This is not always the case, though. At high frequencies, the losses produced by the magnetic cores become excessive, and for this reason, high frequency coils do not use magnetic cores. Inductances used in circuits operating at the power or commercial frequencies, 25, 50 and 60 cycles per second (Hertz), all use iron cores. Inductance used in audio frequency circuits also use iron cores, but inductance used in radio frequency circuits employ air-cores. Typical examples of radio frequency coils are the transmitting coil and the receiving coil shown in Figure 1. A coil wound on any non-magnetic material, for example, bakelite, glass, paper, etc., is said to be an air-core coil, since these materials have the same permeability as air. The next assignment will be devoted to the study of iron core coils and transformers.

Computing Inductance

It is sometimes rather difficult to determine the inductance of an iron core coil if only its physical size and number of turns are known, but it is a simple matter to compute the inductance of an air core coil if these properties are known.

Figure 8 shows a cross sectional view of three common shapes of air-core coils. The shape of the coil will effect the inductance, and if you wish to determine the inductance of a coil, you should select the shape of coil which most closely corresponds to the coil in question. You can measure the dimensions of the coil with a ruler. The formula to be used with each shape is given directly below the coils illustrated in Figure 8.

The coil shown in Figure 8(A) is a single layer coil. The coils shown in Figure 8(B) and Figure 8(C) are multi-layer coils. The coil in Figure 8(B) has a length which is much greater than the depth of the winding, while the one in Figure 8(C) has a depth of winding greater than the length of the winding. In the formulas the dimensions are in inches, (A) is the radius of the coil to the center of the winding, (B) is the length of the winding, (C) is the depth of the winding, and N is the number of turns. The answer L, will be in **micro-henries.**

To illustrate the use of these formulas in determining the inductance of a coil, let us assume we have a single layer coil, as shown in Figure 8(A) which has 20 turns, a length (b in the formula) of 3 inches and a radius (a in the formula) of 1 inch. To find the inductance we would substitute the known values in the formula given below the coil, 8(A).

$$L = \frac{a^2N^2}{9a + 10b}$$

$$L = \frac{(1)^2\ (20)^2}{9(1) + 10(3)}$$

$$L = \frac{1 \times 400}{9 + 30} = \frac{400}{39} = 10.3 \text{ micro-henries.}$$

Thus we find that the inductance of this coil is 10.3 micro-henries. This would normally be written, 10.3μH.

Suppose you wish to determine the inductance of the coil shown in Figure 9. The coil is known to have 200 turns. With a ruler, measure the three dimensions as shown. It is evident that the shape of the coil corresponds more nearly to the coil shown in Figure 8(B) than either of the other two coil shapes. The formula of 8(B) will therefore be used. These are the dimensions:

$$a = \frac{9}{16} \text{ inch or .562 inch}$$

$$b = \frac{3}{4} \text{ inch or .75 inch}$$

$$c = \frac{1}{2} \text{ inch or .5 inch.}$$

N, of course, is 200, since we have 200 turns in the coil.

The inductance of the coil equals:

$$L = \frac{.8a^2N^2}{6a + 9b + 10c}$$

$$L = \frac{.8 \times (.562)^2 \times (200)^2}{6(.562) + 9(.75) + 10(.5)}$$

$$L = \frac{.8 \times .316 \times 200 \times 200}{6 \times .562 + 9 \times .75 + 10 \times .5}$$

$$L = \frac{10{,}112}{15.1}$$

$$L = 670\ \mu H.$$

Thus we see that it is a simple matter to find the inductance value of air-core coils if the dimensions and number of turns are known.

Inductive Reactance

When we studied resistors earlier in the training program, we found that a resistor opposes the flow of current. We measured this opposition in ohms. For all practical purposes, the opposition offered to the flow of a current by a resistor, is the same whether the current is d-c, low frequency a-c, or high frequency a-c.

An inductance also opposes the flow of current, but the **amount of this opposition is dependent upon the frequency.** A pure inductance would offer no opposition to the flow of a direct current, but would offer a certain amount to a low frequency a-c current, and would offer much more opposition to the flow of a high frequency a-c current. This is because a **high frequency current is changing much more rapidly.** The opposition offered by a coil to the flow of current is also measured in ohms, but to avoid confusion with resistors, we speak of opposition offered by a coil to the flow of an a-c current as ohms of **reactance.**

Ohms of resistance are usually represented by the letter R.

Ohms of reactance for coils are usually represented by the symbol X_L (Read X sub L), X stands for reactance. The subscript L tells that we are speaking of the reactance of a coil since L is the letter used to represent inductance.

In determining the **ohms of reactance** of a coil, we must take into account not only the inductance of the coil, but also the **frequency** of the current.

The following formula is used to determine the **inductive reactance** (ohms of reactance) of a coil:

$X_L = 2\pi fL$ 6.28 x frequency x inductance = inductive reactance in ohms

where π = approximately 3.14
f = frequency in cycles per second (Hertz)
L = inductance in henries.

Suppose we have a circuit as shown in Figure 4(A), with the output from an a-c generator connected to a 5 henry coil. The a-c generator frequency is 1 cycle per second. What is the opposition to the flow of current offered by this coil? We substitute the known values in the formula:

$X_L = 2\pi fL$
$X_L = 6.28 \times 1 \times 5$
$X_L = 31.4$ ohms.

The inductive reactance of this 5 henry coil operating at 1 cycle per second (1 Hertz, or 1 Hz) is 31.4 ohms.

Suppose we were to change our oscillator frequency to 5 Hz. The oscillator voltage and current through the coil will vary five times as rapidly and the magnetic field must be built up five times as often as before.

Therefore, the opposition, or **inductive reactance** will be five times as large as before. Putting the known values in the formula we have:

$$X_L = 2\pi fL$$
$$X_L = 6.28 \times 5 \times 5$$
$$X_L = 157 \text{ ohms}$$

This is the same coil as before, but its opposition is greater because the **frequency** of the a-c is higher.

Let us find what the **inductive reactance** of this same coil would be if we increase the frequency to 5000 Hz.

$$X_L = 2\pi fL$$
$$X_L = 6.28 \times 5 \times 10^3 \times 5$$
$$X_L = 157 \times 10^3$$
$$X_L = 157{,}000 \text{ ohms.}$$

From this we see that the frequency is very important when finding the opposition offered by a coil to the flow of an a-c current, for a given coil will oppose the flow of a high frequency current more than it will oppose a low frequency current.

Let us solve a similar problem dealing with a radio frequency coil. Assume the coil in question has an inductance of 4 microhenries and the frequency is 800 kilocycles per second (800 kilohertz, or 800 kHz).

$L = 4$ microhenries or 4×10^{-6} henries

$f = 800$ kHz or 800×10^3 or 8×10^5 Hz

$$X_L = 2\pi fL = 6.28fL = 6.28 \times 8 \times 10^5 \times 4 \times 10^{-6} = 201 \times 10^{-1} = 20.1 \text{ ohms.}$$

This problem illustrates the practical value of powers of 10.

For practice, find the inductive reactance of the following coils. (1) 9 mH, 3,000 Hz (2) 30 H, 120 Hz (3) 40 μH, 20 megacycles per second (megahertz, or MHz).

Finding The Current Through A Coil

To find the current flowing in a circuit containing resistance, we use the formula: $I = E/R$. To find the current flowing in an a-c circuit which has reactance, we use the following formula: $I = E/X_L$. Since we are still dividing volts by ohms (omhs of reactance in this case), the answer will be in amperes.

Suppose we had a 10 henry choke connected across the 110 volt, 60 Hz a-c power line and wanted to find the current flowing through the choke. First we find the inductive reactance.

$X_L = 2\pi fL$
$X_L = 6.28 \times 60 \times 10$
$X_L = 3768$ ohms.
Then we find the current.
$I = \frac{E}{X_L}$
$I = \frac{110}{3768}$
$I = .0292$ amperes or 29.2 mA.

This is the rms value of the current since the 110 volts was the rms value of voltage.

Finding The Voltage Across A Coil

To find the amount of a-c voltage drop across a coil if the current and inductive reactance are known we use the formula:

$E = I \times X_L$

To illustrate the use of this formula let us find the voltage drop across the 4μH coil at 800 kHz, if there are 2 mA of current flowing.

We have already found the X_L of a 4 μH at 800 kHz to be 20.1 ohms.

$I = 2$ mA or, .002 amperes or 2×10^{-3} amperes.
$E = I \times X_L$
$E = 2 \times 10^{-3} \times 20.1$
$E = 40.2 \times 10^{-3} = .0402$ volts or 40.2 mV.

R-F Choke Action

We can now see why the R-F choke shown in Figure 1(C) is called an R-F choke. The inductance of such a coil is usually about 2.5 millihenries. Let us find the reactance of this coil at some radio frequency, 6000 kHz for example. We know that:

$L = 2.5$ mH $= 2.5 \times 10^{-3}$ H
$f = 6000$ kHz $= 6$ MHz $= 6 \times 10^6$
$X_L = 2\pi fL$
$X_L = 6.28 \times 6 \times 10^6 \times 2.5 \times 10^{-3}$
$X_L = 6.28 \times 15 \times 10^3$
$X_L = 94.2 \times 10^3 = 94{,}000$ ohms (approx.)

This demonstrates that the reactance of this coil is high, 94,000 ohms at this radio frequency of 6000 kHz. This reactance is so great that it will **practically** pass no RF current. Actually, of course, it will pass a very small amount, but for all practical purposes it will **choke** off the flow of RF current.

Assume, for example, that there were 10 volts of RF at 6000 kHz, applied to the choke. Let us find just how small the current would be.

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

$$I = \frac{10}{94,000} = \frac{10}{9.4 \times 10^4}$$

$$I = \frac{10 \times 10^{-4}}{9.4} = 1.06 \text{ x } 10^{-4}$$

$I = .000106$A, or 0.106 mA.

We see that this coil would pass only a very small RF current. However, if a low-frequency voltage is applied to it, it will not have this "choking" effect. To demonstrate this point, find the reactance of this coil at 100 Hz. Then find how much current would flow through it if 10 volts at this frequency were applied.

Do you agree that this coil is a **choke** at radio frequencies, but is not a choke at lower frequencies? Do you now understand why it is called an RF choke?

For chokes to be effective at low frequencies, 100 Hz or so, the inductance must be several henries. Typical chokes for this frequency are 30 henries to 100 henries. To obtain this large inductance, iron-core chokes are used. Figure 1(D) illustrates such a choke.

Finding The Inductance Of A Coil

Let us find out what process we should use to find the inductance of a coil if we have given the frequency and the inductive reactance. For example, what is the inductance of a coil whose reactance is 600 ohms at 2000 Hz?

$X_L = 600$

$f = 2000$

$\pi = 3.14$

$L =$ unknown, to be found

First we will rearrange the formula to get L on the left side of the equal sign and all other terms on the right side. You will recall that this process was outlined in Assignment 14. We proceed as follows:

$$X_L = 2\pi fL$$

$$\frac{X_L}{2\pi f} = \frac{\cancel{2\pi f}L}{\cancel{2\pi f}}$$

$$\frac{X_L}{2\pi f} = L \text{ or,}$$

$$L = \frac{X_L}{2\pi f}$$

Now we have the formula with L on the left of the equal sign and all other terms on the right. To solve our problem, we substitute our known values in this equation:

$$L = \frac{X_L}{2\pi f}$$

$$L = \frac{600}{6.28 \times 2000} = \frac{60 \times 10^1}{12.56 \times 10^3}$$

$$L = \frac{60 \times 10^1 \times 10^{-3}}{12.56} = \frac{60 \times 10^{-2}}{12.56}$$

$$L = 4.8 \times 10^{-2} = .048 \text{ henries or } 48 \text{ mH.}$$

For practice, use this same method for finding the inductance of a coil whose inductive reactance is 1000 ohms at a frequency of 30,000 Hz.

Circuits with Coils and Resistors in Combination

Figure 10(A) shows a circuit consisting of an a-c generator, or oscillator, whose frequency is 2000 Hz, and whose voltage is 3 volts. Connected to the output of this generator is a coil whose reactance **at this frequency** is 600 ohms, and a 300 ohm resistor. We wish to find the amount of current which will flow through the coil, and the resistor, and we also wish to know the amount of current supplied by the generator.

The resistor and coil are connected **in parallel.** One fact about parallel circuits which we should recall from our Ohm's Law studies is, that in a parallel circuit, the same voltage is applied to each branch. In this case we know that the 3 volts of the generator is applied to each of two loads, the coil and the resistor. We can very easily find the current through each of them.

To find the current through the resistor we use the formula, $I = E/R$.

$$I = \frac{E}{R} = \frac{3}{300} = .01 \text{ ampere or } 10 \text{ mA.}$$

To find the current through the coil we use the formula, $I = \frac{E}{X_L}$

$$I = \frac{E}{X_L} = \frac{3}{600} = .005 \text{ amperes or } 5 \text{ mA.}$$

It would seem at first glance that the current supplied by the oscillator would be the sum of these two currents, or 15 milliamperes, but such is **not** the case. Remember, that the resistor current is **in phase** with the oscillator voltage, but that the current through the coil **lags** the oscillator voltage by 90°. Vectors for these two currents, in relation to the oscillator voltage are shown in Figure 10(B) and (C). Figure 10(B) shows the resistor current **in phase** with the oscillator voltage. Figure 10(C) shows the coil current lagging the oscillator voltage by 90°. We learned in the assignment on a-c theory how to find the resultant value of two out of phase currents. This is illustrated in Figure 10(D). The voltage vector is used as the reference, since the oscillator voltage is common to both the resistor and the coil. The resistor current, I_R is in phase with the voltage vector E. The coil current vector I_L **lags** the voltage vector by 90° and therefore lags the resistor current by this amount. The coil current is only one half as great as the resistor current, so this vector is only one half as long as the resistor current vector. The two currents are added vectorially in Figure 10(D), by completing the parallelogram and drawing the diagonal. The resultant current I_T is found to be approximately 11.2 milliamperes. This is the current which must be supplied by the generator. A protractor applied to the vector diagram would show that I_T, the current supplied by the generator, lags the generator voltage by approximately 27 degrees.

In Figure 11(A) we have a resistor and a coil connected in series across the output of an oscillator. Since the resistor and the coil are in series, the **same current** will flow through each of them. How much voltage will the oscillator have in order to force 20 milliamperes of current through the circuit?

The voltage drop across the resistor will be:

$$E = I \times R$$

$$= .02 \times 100 = 2 \text{ volts.}$$

The voltage drop across the coil which has a reactance, **at this frequency,** of 150 ohms will be:

$$E = I \times X_L$$

$$= .02 \times 150 = 3 \text{ volts.}$$

The voltage across the resistor is in phase with the current in the circuit, but the voltage across the coil is **leading** the current by 90°.

To find the oscillator voltage we will find the vector sum of those two voltages. Figure 11(B) shows the vector diagram for this circuit. Since the current is common to both the coil and the resistor, it will be used as the reference vector. The resistor voltage is in phase with this current and the vector is drawn in that manner. The coil voltage leads the current by 90° and this is indicated in the diagram. The resistor voltage vector E_R is two units long, and the coil vector E_L is three units long. When the resultant vector E_T is drawn and scaled, it is found to be 3.6 units long. Thus, we find that the oscillator voltage must be 3.6 volts to force a current of 20 ma through the circuit.

In Figure 10, the sum of the 5 ma and 10 ma currents cannot be 15 ma. unless the two currents are in phase with each other. When the two currents to be added are out of phase they do not reach their maximum values at the same time. When the 10 ma current through the 300 ohms resistor is at its maximum value, the coil current (lagging by 90 degrees) is zero. The oscillator will never have to supply the maximum current to both resistor and coil at the same time. The oscillator will not have to supply a full 15 milliamperes.

In Figure 11, since the resistor and coil voltages are out of phase, the oscillator will never have to supply a full 5 volts for the resistor and coil.

The vector addition is certainly easy to handle. The important point is to have a good understanding of the phase relationship between voltage and current in coils.

The Q of a Coil and Skin Effect

In addition to reactance, all coils will have some resistance. A coil will be used in an electronics circuit because its inertia effect (or reactance) is needed to produce a desired result. The resistance of the wire in the coil is an undesirable factor in almost all coil applications.

The letter Q (standing for **Quality**) is used to indicate the ratio of reactance to resistance. Stated as a formula it is:

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

Since the reactance varies with frequency, the Q of a coil will also depend on the frequency.

What is the Q of a 2 millihenry coil having a resistance of 6 ohms if the coil is operated at 1000 Hz?

$$X_L = 2\pi fL$$

$$X_L = 6.28 \times 10^3 \times 2 \times 10^{-3} = 12.56 \text{ ohms.}$$

$$Q = \frac{X_L}{R} = \frac{12.56}{6} = 2.09$$

What is the Q of this same coil when operated at 5000 Hz?

$$X_L = 2\pi fL$$

$$X_L = 6.28 \times 5 \times 10^3 \times 2 \times 10^{-3} = 62.8 \text{ ohms.}$$

$$Q = \frac{X_L}{R} = \frac{62.8}{6} = 10.5$$

It will be difficult to calculate the Q of this coil when operated at radio frequencies, say 500,000 Hz. We can calculate X_L just as before without any serious errors:

$$X_L = 2\pi fL$$

$$X_L = 6.28 \text{ fL} = 6.28 \times 5 \times 10^5 \text{ x } 2 \text{ x } 10^{-3}$$

$$= 62.8 \times 10^2 = 6280 \text{ ohms.}$$

It would seem that if this figure, 6280 ohms, were divided by 6, the answer would give the Q of this coil. Actually the Q would be much lower than this value. This is because the 6 ohms resistance is the d-c resistance of the coil. That is, the resistance of the wire in the coil when direct current is flowing through it, or when measured with an ohmmeter.

The resistance of this coil will effectively be much larger than 6 ohms when the coil is operated at radio frequencies. The wire in the coil does not change but the radio frequency currents tend to flow near the surface of the wire. The higher the frequency of the current, the more pronounced will be this tendency of current to flow on the surface of the wire. This phenomenon is called **skin effect.**

In Figure 12(A) and 12(B) we have shown an enlarged cross section of a piece of wire. The entire cross section of the wire is available for handling current in d-c or low-frequency a-c circuits. At high frequencies current flow will take place only at the shaded area near the surface of the wire. This is illustrated in Figure 12(B). This effectively reduces the area available for current flow and effectively increases the resistance. This effective resistance is called the a-c resistance of a coil. It may be many times larger than the d-c resistance.

Copper wires for high frequency currents are sometimes made up of many strands of fine wire. Each strand is insulated, and the individual wires are inter-laced so that each wire is sometimes on the outside of the conductor and sometimes on the inside. Such a conductor is called "Litz" wire. This wire provides less a-c resistance for the same amount of copper. Many high frequency coils are wound with this wire.

Some high frequency coils are made of copper tubing. The fact that the tubing is hollow will not matter since the high frequency current will flow only on the surface of the tubing anyway.

It will not hurt to repeat that **a high Q is desirable.** A high ratio of reactance to resistance means that the coil will act as almost a pure inductance with nearly a full 90 degrees phase angle between current and voltage.

In Figure 11 for example, suppose that the 100 ohms of resistance is actually the resistance of the wire in the coil. The phase angle between E_T and the current in this circuit is only 56 degrees. The phase angle can be increased to a full 90 degrees only by eliminating the resistance drop E_R. This is a goal you will never quite reach since it will be impossible to completely eliminate resistance in any practical coil, but we try to get as near to it as possible.

Summary

Coils are used in all of the various branches of the electronics field. You have already found them in radio receivers, and it has been mentioned that they are also used in radio transmitters. They find similar applications in television receivers and transmitters. However, their use is by no means limited to these areas of the field—they are in almost **all** electronics equipment. For example, you will find them in the following electronics equipment: missile guidance and control, industrial electronics (automation), computers, radar, sonar, oceanography, aircraft, appliance, security, military and others.

Obviously, therefore, the information about coils which has been presented in this Assignment is a **very important** step toward your complete understanding of electronics circuits. You are strongly advised to first **read** this Assignment several times, and then to **study each step** carefully, so that you will be able to gain a complete mastery of the material included. In particular, you should **work each example.** This approach to this material will give you a complete understanding of the subject.

One of the most interesting phenomena in electronics is the **tuning** process. This is produced by means of a combination of the inertia effect of coils, and the effect of capacitors. It is this process that makes it possible for us to "tune-in" a particular radio or TV station, or to choose a particular telemetry channel in missile work. We shall find out how this is accomplished after we have studied capacitors.

"How to Pronounce..."

(Note: the accent falls on the part shown in CAPITAL letters.)

accelerate	(akk - SELL - ur - ate)
induced	(in - DEWST)
inductive	(in - DUCK - tiv)
inertia	(in - URR - she - uh)
reactance	(ree - ACT - ans)
vectorially	(veck - TORE - e - all - ee)

Test Questions

Use a multiple-choice answer sheet for your answers to this assignment.

The questions on this test are of the multiple-choice type. In each case four answers will be given, one of which is the correct answer. To indicate your choice of the correct answer, **mark out** the letter opposite the question number on the answer sheet which corresponds to the correct answer. For example, if you feel that answer (A) is correct for Question No. 1, indicate your preference on the answer sheet as follows:

1. ~~(A)~~ (B) (C) (D)

Submit your answers to this assignment immediately after you finish them. This will give you the greatest possible benefit from our personal grading service.

1. What is the name of the unit of inductance?

   (A) The mho.
   (B) The farad.
   (C) The henry.
   (D) The ampere.

2. In what units is the **inductive reactance** of the coil measured?

   (A) Amperes.
   (B) Ohms.
   (C) Volts.
   (D) Lines of magnetic flux.

3. What is the formula for finding the inductive reactance of a coil?

   (A) $X_L = 2\pi f L$
   (B) $R = \frac{E}{I}$
   (C) $X_C = \frac{1}{2\pi f C}$
   (D) $X_L = \frac{2}{\pi f L}$

4. In a pure inductance, what is the phase relationship between the current and the voltage?

   (A) The current and the voltage are in phase.
   (B) The current lags the voltage by 90 degrees.
   (C) The current and the voltage are 180 degrees out of phase.
   (D) The current leads the voltage by 90 degrees.

5. If a certain coil has a reactance of 300 ohms at 1000 kHz.

   (A) Its reactance will remain the same if the frequency is changed to 2000 kHz.
   (B) Its reactance will increase if the frequency is changed to 2000 kHz.
   (C) Its reactance will decrease if the frequency is changed to 2000 kHz.
   (D) It will have 3000 ohms impedance at all frequencies.

6. What will be the reactance of a 3 henry coil at a frequency of 100 Hz?

(A) 300 ohms
(B) 100 ohms
(C) 1884 ohms
(D) 628 ohms

7. What is the reactance of a 5 milli-henry coil at 2000 kHz?

(A) 62,800 ohms
(B) 10,000 ohms
(C) 10 ohms
(D) Approximately 63 ohms

8. What happens if a conductor is "cut" by magnetic lines of force?

(A) A voltage is induced in the conductor.
(B) Nothing.
(C) The conductor becomes an insulator.
(D) The conductor will be damaged.

9. Skin effect:

(A) Increases the effective resistance of a coil as the frequency is increased.
(B) Decreases the effective resistance of a coil as the frequency is increased.
(C) Does not affect the resistance of a coil as the frequency is increased.
(D) Is another name for inductive reactance.

10. How much current will flow through a 2 micro-henry coil if 1 volt at 500 kilohertz is impressed across the coil?

(A) 500 milliamperes.
(B) 159 milliamperes.
(C) Approximately 1.6 amperes.
(D) 6.28 amperes.

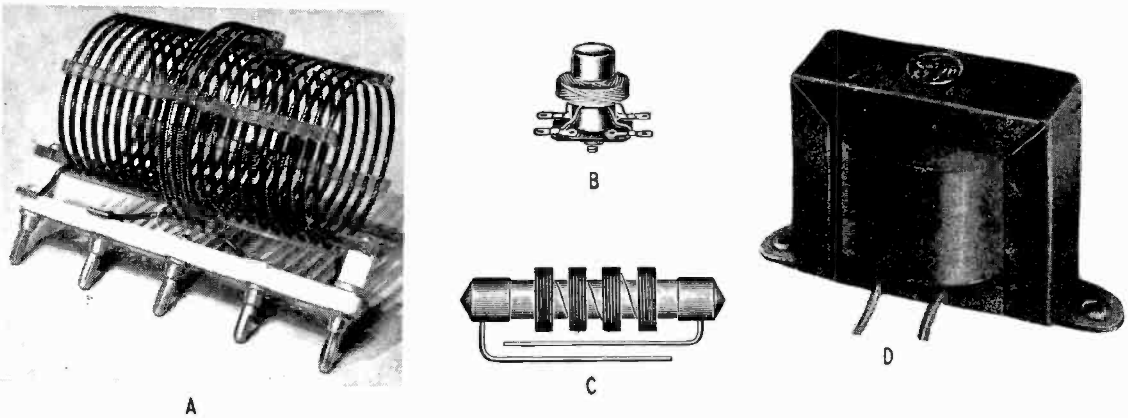


FIGURE 1

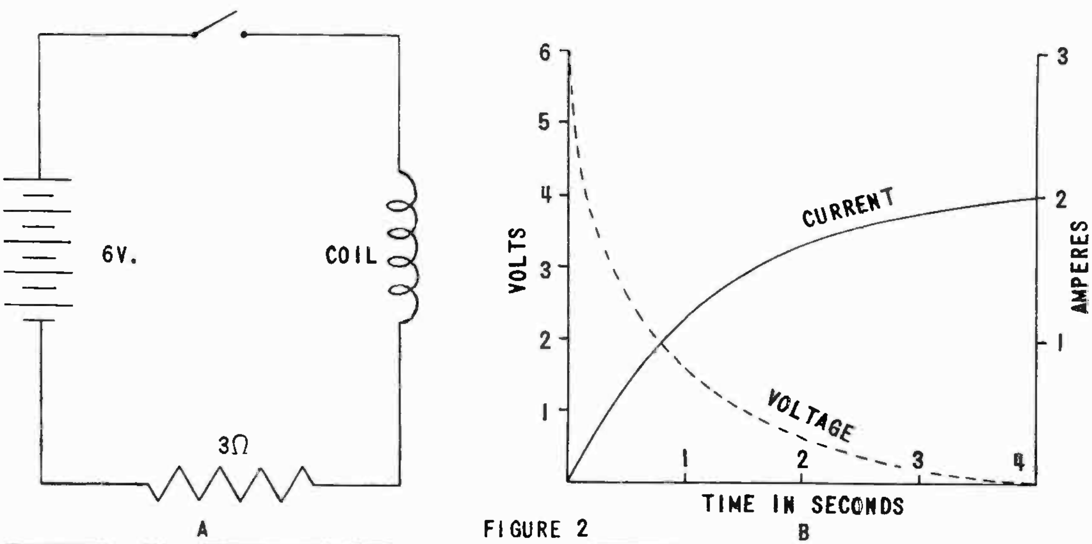


FIGURE 2

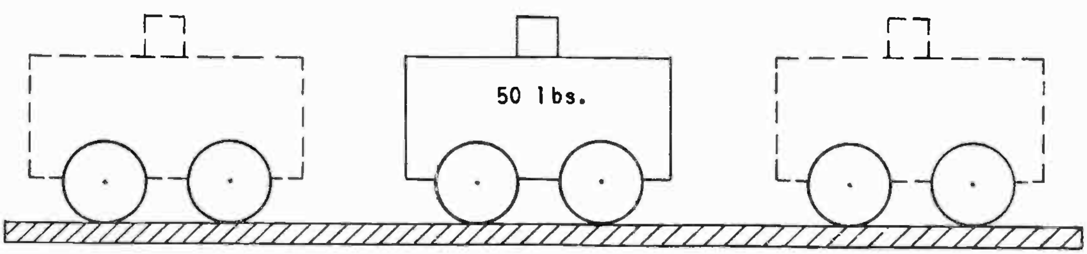


FIGURE 3

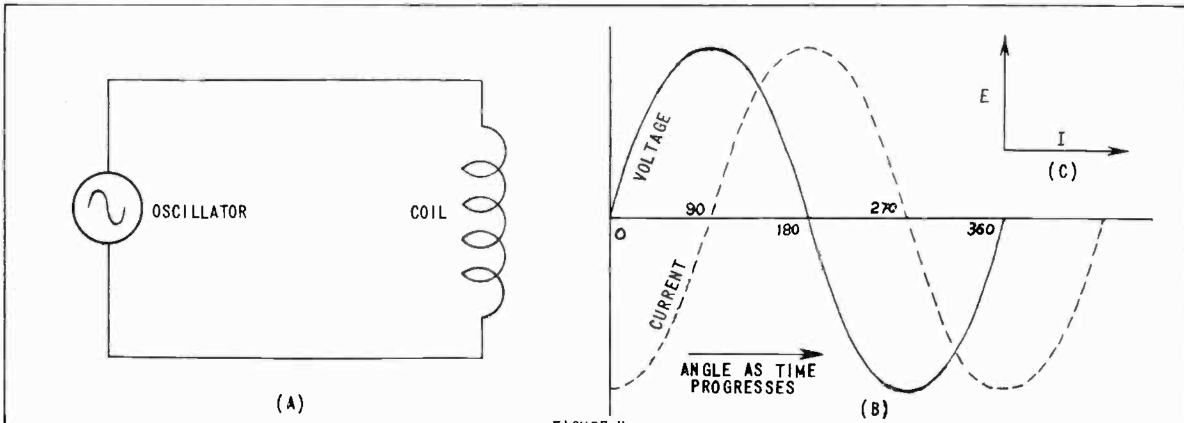


FIGURE 4

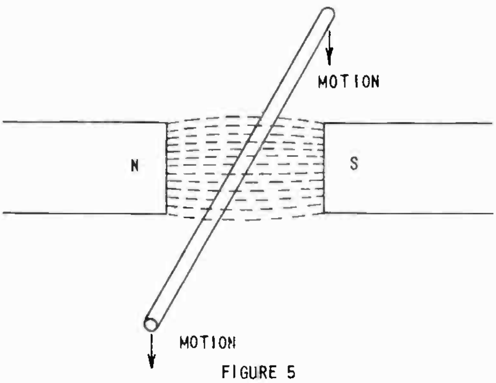


FIGURE 5

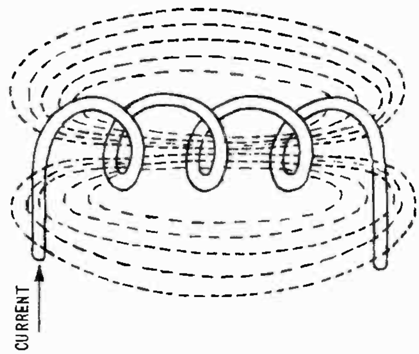


FIGURE 6

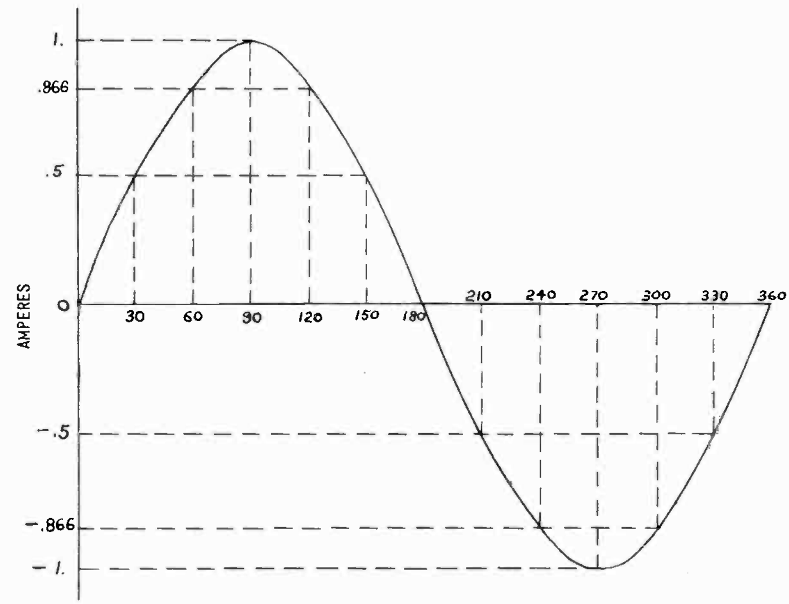
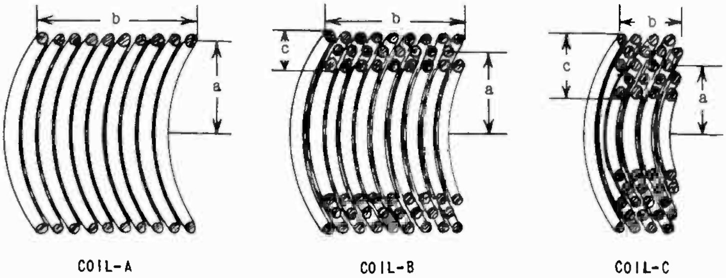


FIGURE 7



$L = \frac{a^2N^2}{9a + 10b}$ $\quad$ $L = \frac{.8a^2N^2}{6a + 9b + 10c}$ $\quad$ $L = \frac{a^2N^2}{8a + 11c}$

FIGURE 8

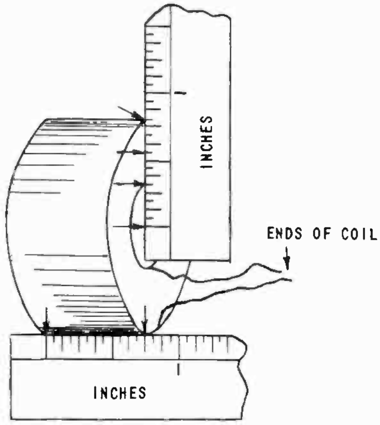


FIGURE 9

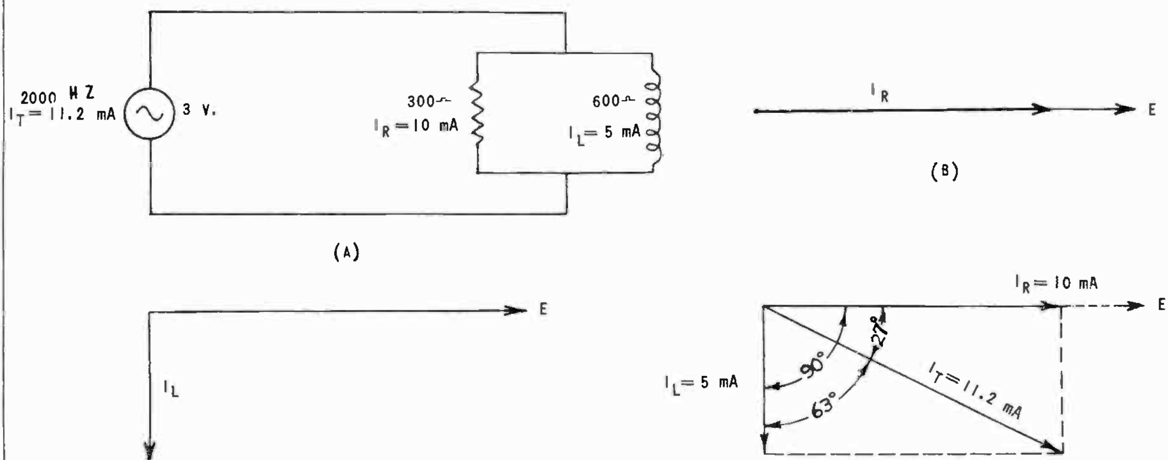


FIGURE 10

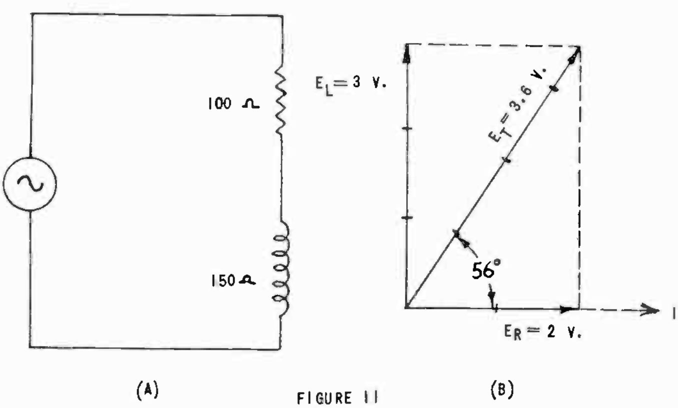


FIGURE 11

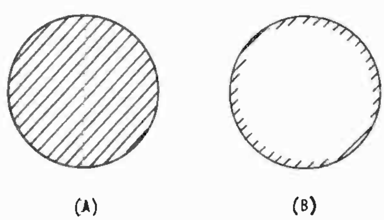


FIGURE 12