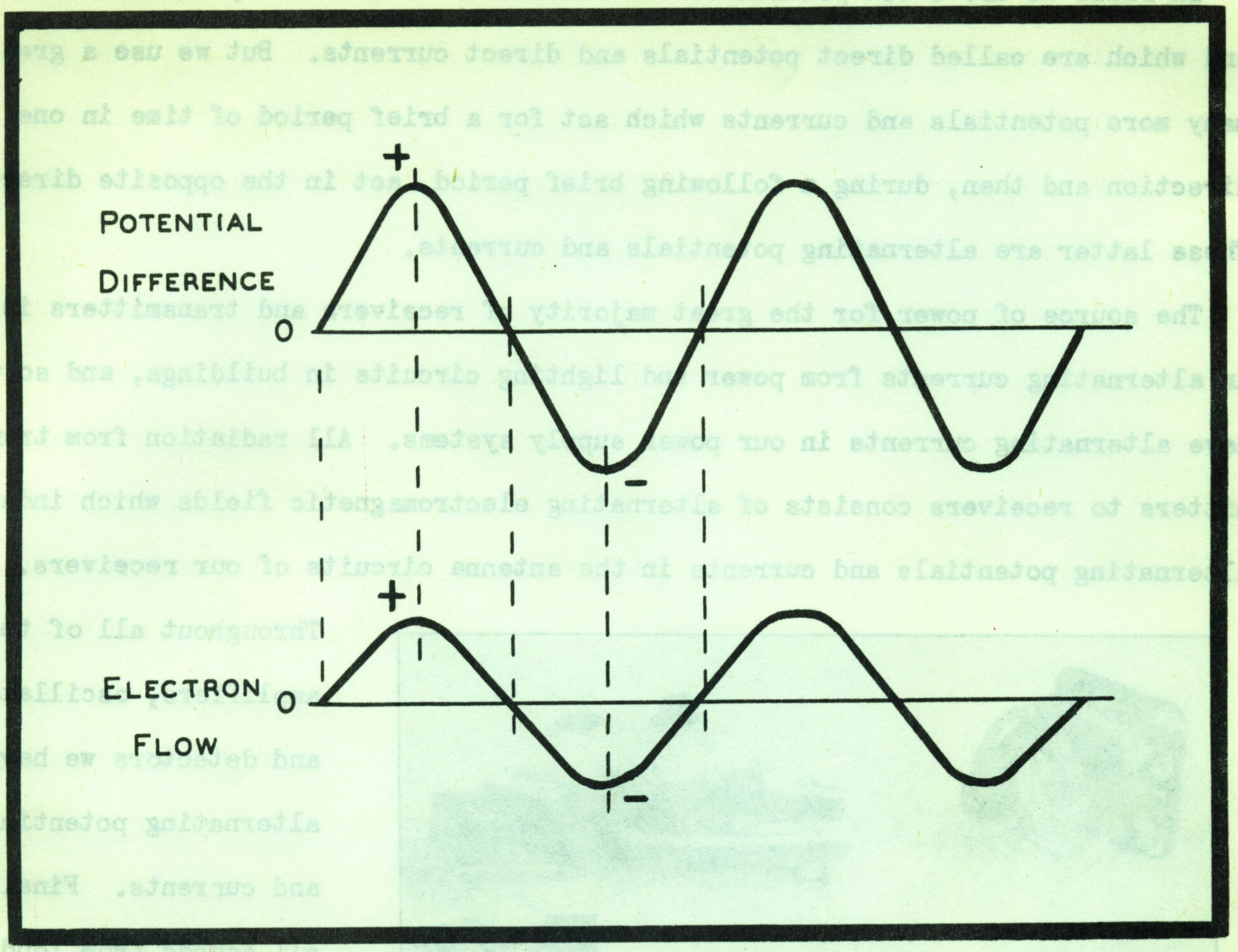

LESSON
8 R

ALTERNATING CURRENTS IN RADIO

RADIO-TELEVISION TRAINING SCHOOL, INC.
LOS ANGELES
ESTABLISHED 1922

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In radio we use a few potentials and currents which act always in one direction, and which are called direct potentials and direct currents. But we use a great many more potentials and currents which act for a brief period of time in one direction and then, during a following brief period, act in the opposite direction. These latter are alternating potentials and currents.

The source of power for the great majority of receivers and transmitters is in alternating currents from power and lighting circuits in buildings, and so we have alternating currents in our power supply systems. All radiation from transmitters to receivers consists of alternating electromagnetic fields which induce alternating potentials and currents in the antenna circuits of our receivers.

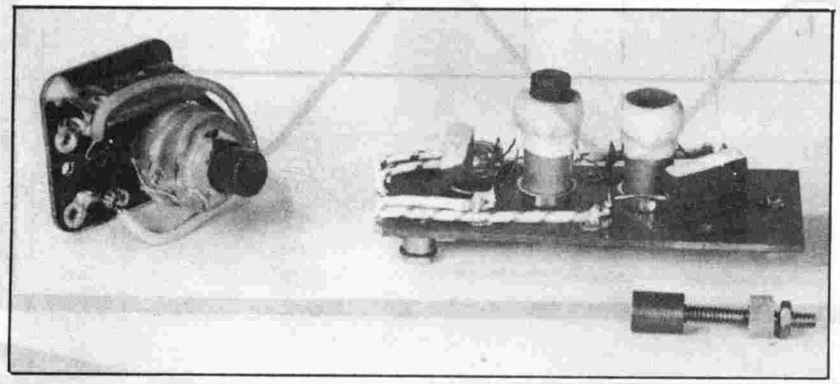

FIG.1.
In these i-f transformers, which have powdered iron cores, are circuits containing inductance, capacitance, and resistance.

Throughout all of the amplifiers, oscillators, and detectors we have alternating potentials and currents. Finally, all sounds from loud speakers result from alternating currents in the speaker circuits.

In receivers operated from alternating-current power and lighting lines there are only a few really important uses for direct potentials and currents, and where these are used they nearly always are combined with alternating potentials and currents which are carrying the signals. Such combination currents are found in plate circuits and also in control grid circuits of the tubes. In receivers operated from batteries there is additional use for direct current in heating the filament-cathodes of the tubes.

All of the foregoing makes it evident that we should become thoroughly acquainted with the behavior of alternating potentials and currents in resistors, capacitors and inductors. To begin with we must understand the meanings of certain words,

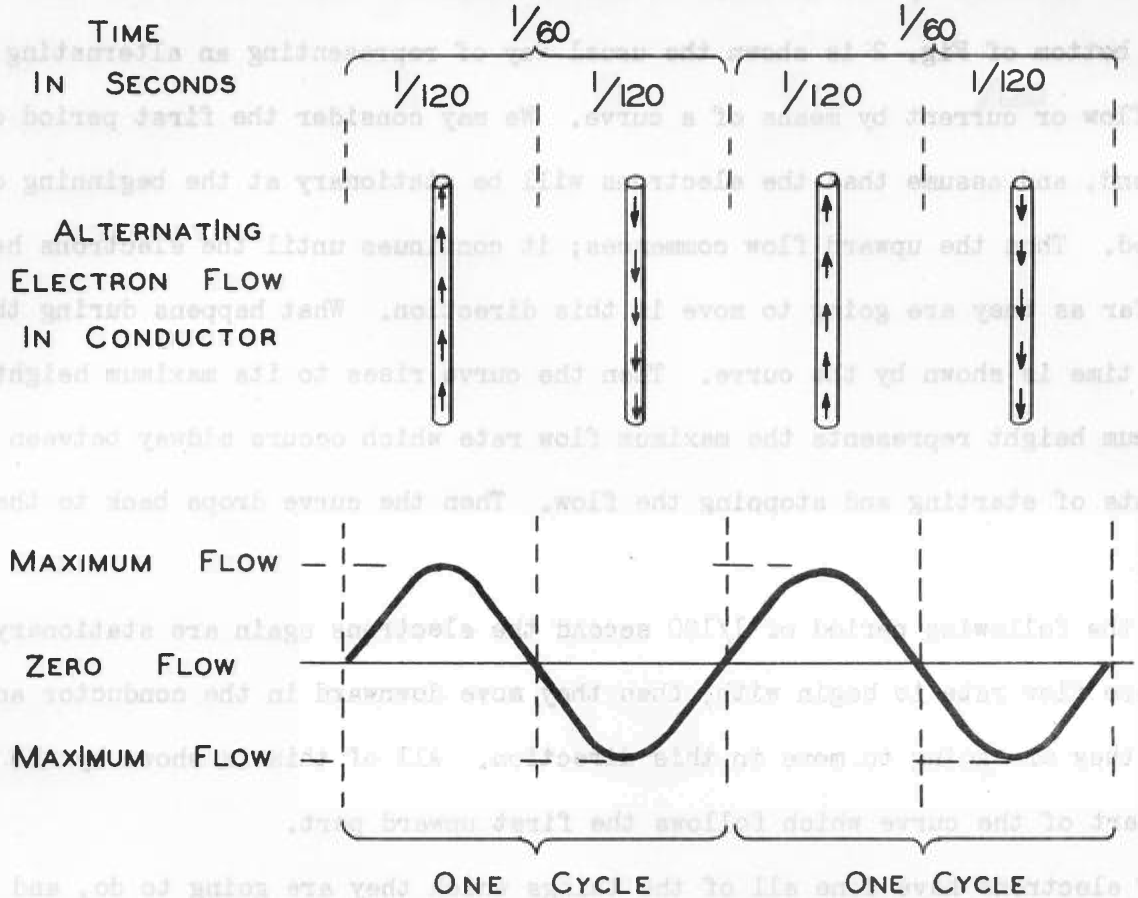

FIG.2
Electron flows during two cycles of alternating current.

such as frequency, cycle, amplitude, peak value, and effective value. There is nothing mysterious about any of these, and it will take only a few paragraphs to explain their meanings.

ALTERNATING POTENTIALS AND CURRENTS

At the top of Fig. 2 is represented a short piece of conductor in which there is alternating electron flow during four periods of time, each 1/120 second long. The electron flow is shown as being upward in the conductor during the first 1/120 second, downward during the following 1/120 second, then upward and downward again during the third and fourth periods. The flow might continue indefinitely to thus reverse its direction. The speed of electrons in conductors was discussed in an earlier lesson, and so we know that the electrons in our conductor may move only a very short distance up and down as the flow alternates.

At the bottom of Fig. 2 is shown the usual way of representing an alternating electron flow or current by means of a curve. We may consider the first period of 1/120 second, and assume that the electrons will be stationary at the beginning of this period. Then the upward flow commences; it continues until the electfons have moved as far as they are going to move in this direction. What happens during this period of time is shown by the curve. Then the curve rises to its maximum height. This maximum height represents the maximum flow rate which occurs midway between the instants of starting and stopping the flow. Then the curve drops back to the zero line.

During the following period of 1/120 second the electrons again are stationary or have zero flow rate to begin with, then they move downward in the conductor and as far as they are going to move in this direction. All of this is shown by the downward part of the curve which follows the first upward part.

Now the electrons have done all of the things which they are going to do, and they mefely repeat the performance indefinitely. There has been a flow commencing at zero, going to maximum in one direction, returning to zero, going to maximum in the opposite direction, and again returning to zefo-- ready to start over again. This series of events which repeats over and over is called one <u>cycle</u>. A following cycle, shown toward the right in Fig. 2, is just like the first one. Either half of a cycle may be called an alternation, although they are commonly called half-cycles.

The same general type of curve may be used to repfesent either an alternating electron flow or an alternating potential. The upper curve of Fig. 3 might show changes of alternating potential and the lower one changes of alternating electron flow in a conductor or circuit.

Usually we speak of the upward curves as positive alternations or positive half-cycles, and of the downward curves as negative alternations or half-cycles. Actually

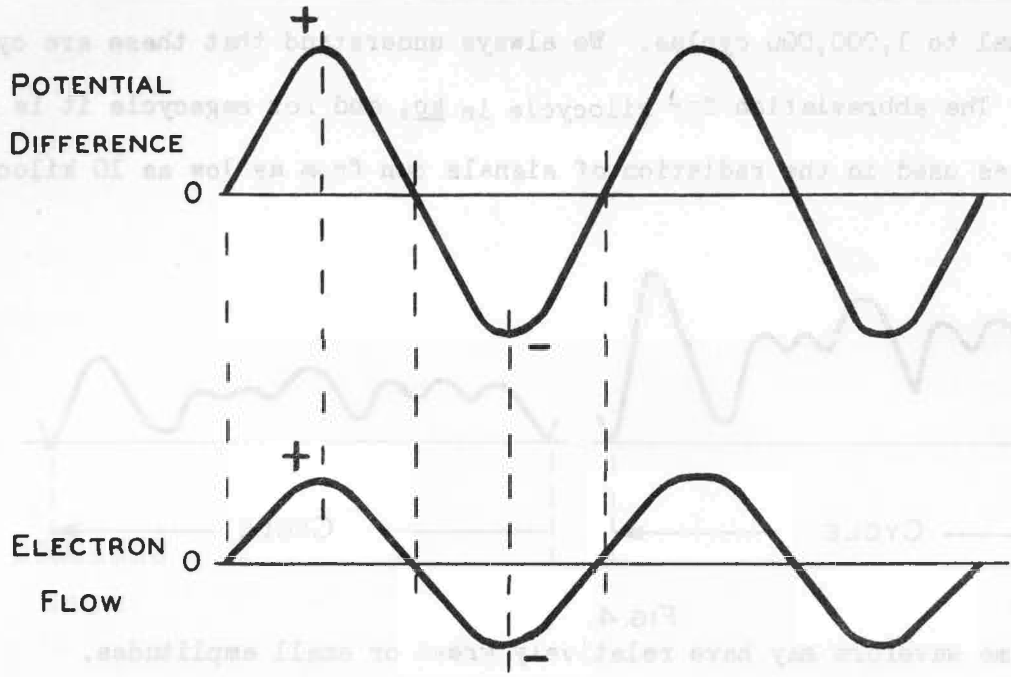

FIG.3.

Alternating potentials and currents are shown by the same kind of curve.

which of the directions of potential and flow is considered positive makes no difference, because whichever one is considered positive, the other direction must be considered as negative. Alternating potentials and electron flows continually reverse their polarities; they have "instantaneous" values in each polarity, but have no continual polarities in either direction.

Curves such as those of Fig. 3 may represent either actual electron flow or current flow. Actual potential differences in a conductor having only resistance are in the same directions as the resulting electron flows; both are positive or both are negative at any one instant. Conventional potential differences or voltages would correspond in polarity to conventional current directions, both being either positive or negative at any one instant.

The number of alternating cycles that are completed within a total time of one second is called the <u>frequency</u> of the potential or electron flow or current. In Fig. 2 each complete cycle takss 1/60 second. There will be 60 cycles in one full second. Therefore, we have here a frequency of 60 cycles per second. The "per second" part always is understood, and so we might speak of a 60-cycle frequency. The term "cycles per second" often is abbreviated as <u>cps</u> or as <u>c.p.s</u>.

The basic unit of frequency is the cycle. Frequencies may be measured also in kilocycles or in megacycles. One kilocycle is equal to 1,000 cycles. One megacycle is equal to 1,000,000 cycles. We always understand that these are cycles per second. The abbreviation for kilocycle is kc, and for megacycle it is mc.

Frequencies used in the radiation of signals run from as low as 10 kilocycles

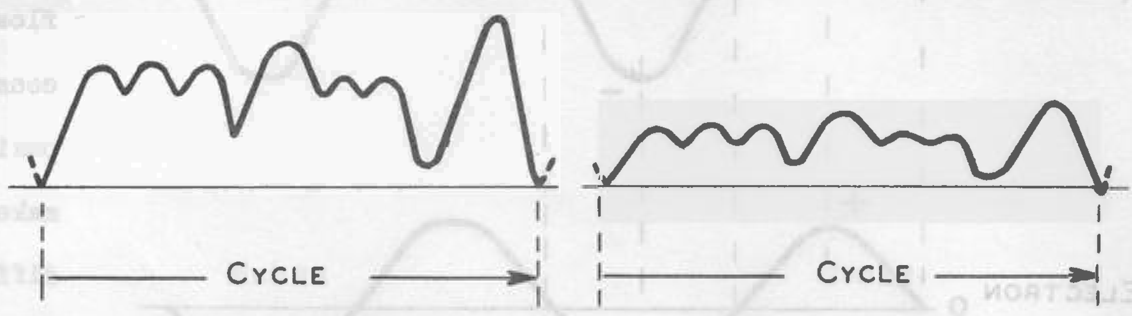

FIG. 4.

The same waveform may have relatively great or small amplitudes.

to as high as several thousands of megacycles, all depending on the kind or class of signals. All of these may be called radio frequencies. Frequencies which produce audible sounds, called audio frequencies, range from about 20 to 20,000 cycles per second. Power frequencies, used in commercial electric power and lighting systems, range from 25 to 60 cycles in most places, with the 60-cycle frequency most commonly used.

Actual alternating potentials and currents seldom vary in such uniform and regular manner as represented in Figs. 2 and 3, rather they may rise, fall and reverse somewhat irregularly. This is especially true of potentials and currents in the audio frequency range. One of the sounds which go to make up a word might result from an alternating current having the waveform shown at the left in Fig. 4. Such a sound wave has no one frequency. In the wave shown there may be frequencies all the way from 250 to more than 4,000 cycles per second, all combining into one wave.

At the right in Fig. 4 is shown exactly the same waveform as at the left, but the amplitude has been changed, having been reduced to half of the amplitude at the left. The amplitude of an alternating potential or current is its greatest departure from zero value, in either direction. For instance, if an alternating potential reaches its greatest value at 10 volts in either direction from zero, its amplitude is 10 volts. If a current reaches its greatest value at 20 milliamperes, the current has an amplitude of 20 milliamperes.

The waveform of an alternating potential or current refers to the intervals between rises and falls and reversals, and to the manner in which the values change from instant to instant. At the right in Fig. 4 we have just the same intervals between similar changes as we have at the left, so the two waveforms are alike, although the amplitude is great at the left and small at the right. In such irregular waves of potential or current, we consider one cycle to be the portion of the wave between points at which it has the same value and is changing in the same direction, or between points at which the waveform commences to repeat itself.

THE SINE WAVE

Even though the actual waveform is decidedly irregular, the wave might be separated into a number of different waves, each having a frequency different from the others, but each having the same waveform as all the others, Then all of the alternations in these separate waves (of potential or current) might exist together in a single circuit, and in that circuit they would produce the original complex wave.

The basic waveform is called a <u>sine wave</u>. The changes of potential follow the form of a sine wave when the electromotive force is induced in a straight conductor rotating at constant speed in a uniform magnetic field, as shown by Fig. 5. The uniform magnetic field is between the upper and lower poles of a magnet, with the lines of force vertical between the poles. The conductor is assumed to start its rotation at position <u>1</u>, and to rotate counter-clockwise as indicated by the arrows.

We may identify successive positions of the rotating conductor by the numbers, from <u>1</u> to <u>8</u> and back to <u>1</u>, but it is better to identify the position by the number of angular degrees of a circle through which the conductor has traveled from its starting point. As you know, every circle may be divided into 360 equal degrees, which here we call electrical degrees.

At position <u>1</u>, which corresponds to zero degrees, the conductor is moving vertically, and in the same direction as the lines of force. Therefore, the conductor is cutting no lines and no emf is induced in the conductor. This we show at 1 on the curve which starts from zero degrees on the horizontal line for zero potential or zero emf in this case. By the time the conductor reaches position 2, at 45 degrees from the start, it is cutting lines of force at an increasing rate per second; and when the conductor passes through position 3, at 90 degrees, it is cutting lines at the maximum possible rate because it is traveling straight through the lines. The increasing emf is indicated at 2 or at 45 degrees on the curve, and the maximum emf at 3 or at 90 degrees.

As the conductor continues its rotation, the rate of cutting decreases through position 4 at 135 degrees, and becomes zero at position 5, or at 180 degrees from the start. The decreasing emf is shown by the curve at the corresponding points on the curve. From position 5 back to position 1 there are increased cuttings, then the maximum rate of cutting (at 7 or 270 degrees), and a decrease back to posi-

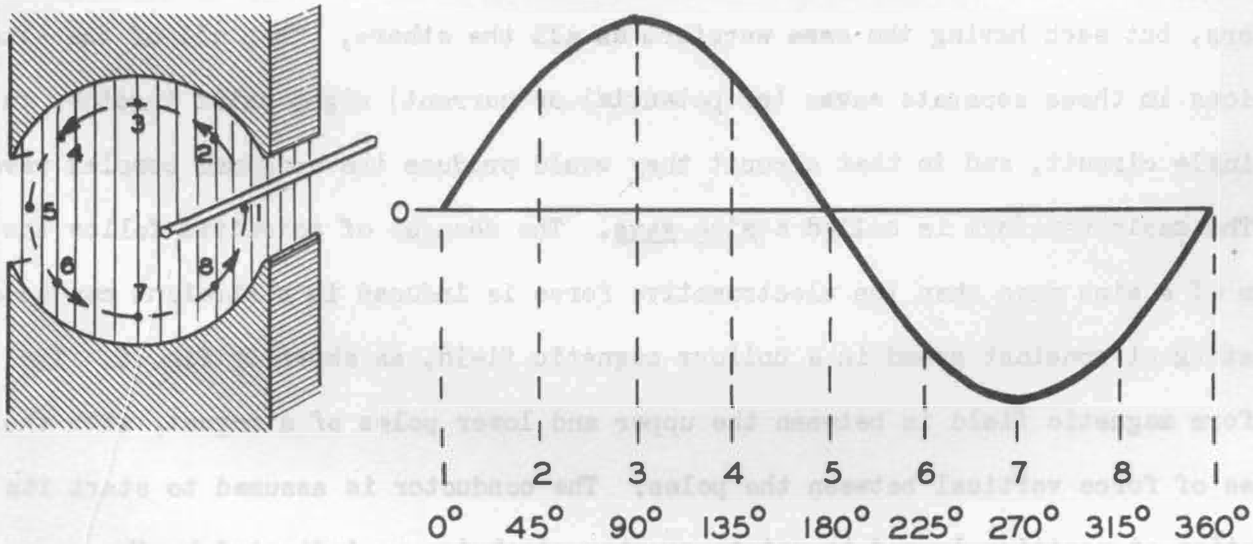

FIG. 5

How a potential having a sine-wave form may be induced.

tion 1, the starting point for the following revolution. Position 1 is at 360 degrees for the first rotation, and becomes also zero degrees for the next rotation.

The increase and decrease of emf follows a sine curve or a sine wave. We get this name from the fact that, at any instant, the fraction of the maximum emf is the same as the "sine" of the angle through which the conductor has progressed from its starting point where it travels in line with the field.

Fundamental rules and formulas relating to alternating potentials and currents are based on the assumption that the potential or current follows a sine wave. Because most actual currents have waveforms fairly close to a sine wave, or consist of combinations of sine waves, there usually is but little error, and the formulas and rules are greatly simplified.

Note that the curve of Fig. 5 shows one complete cycle. The various points in a cycle often are specified in accordance with the electrical degrees shown here. Note that a full cycle occupies 360 degrees, a half-cycle occupies 180 degrees, and a quarter-cycle occupies 90 degrees. We may specify differences in position by electrical degrees. For example, the difference between positions 2 and 4 is 90 degrees, between positions 5 and 6 it is 45 degrees, and so on.

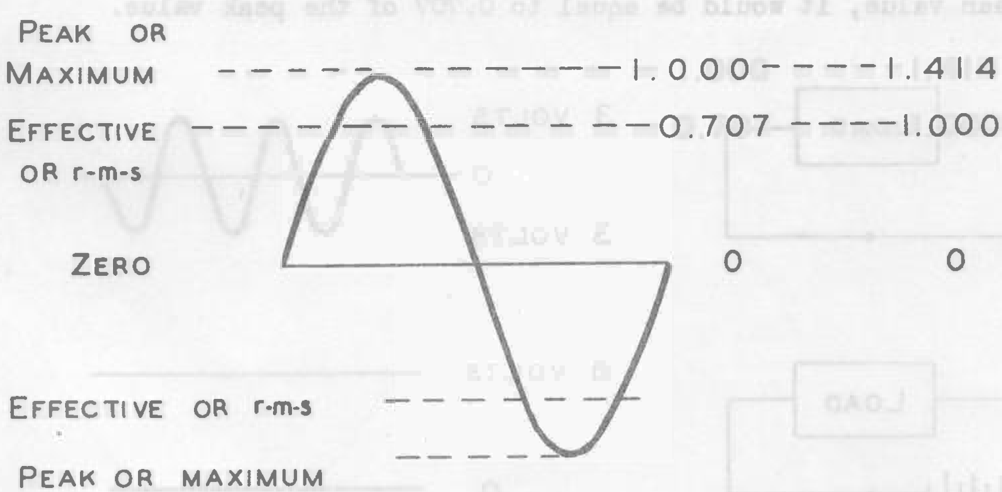

FIG. 6.
The "values" of alternating potentials and currents.

There are certain values of potential or current in a sine waveform which often are referred to. They are shown by Fig. 6. The greatest potential or current reached during a cycle is called either the peak or the maximum potential or current. A value equal to 707/1000 or to 0.707 of the maximum is called the effective value or the root-mean-square value (abbreviated r-m-s value). As shown by the numerical values at the upper right, when we consider the peak or maximum value as proportional to 1.000, then the effective or r-m-s value is proportional to 0.707. If we consider the effective or r-m-s value as proportional to 1.000, then the peak or maximum value is proportional to 1.414. If you know the peak value, in volts or milliamperes, multiply it by 0.707 or divide it by 1.414 to find the effective value. If you know the effective value, divide it by 0.707 or multiply it by 1.414 to find the peak value.

Here is an explanation of why we use the name "effective value". Supposing that you are using a sine-wave alternating current for producing heat, and you measure the maximum or peak value of that current as 1.000 ampere. Then supposing that you use a steady direct current to produce heat at the same rate. The steady direct current would have a value of 0.707 ampere. Then, compared with the direct current, the effective (heating) value of the alternating current is only 0.707 of its peak value. As to the name "root-mean-square", if we were to measure all of the sine-wave alternating values at hundreds of equal intervals in a cycle, were to take the mean (practically the average) value of all these instantaneous values, then find the square root of the mean value, it would be equal to 0.707 of the peak value.

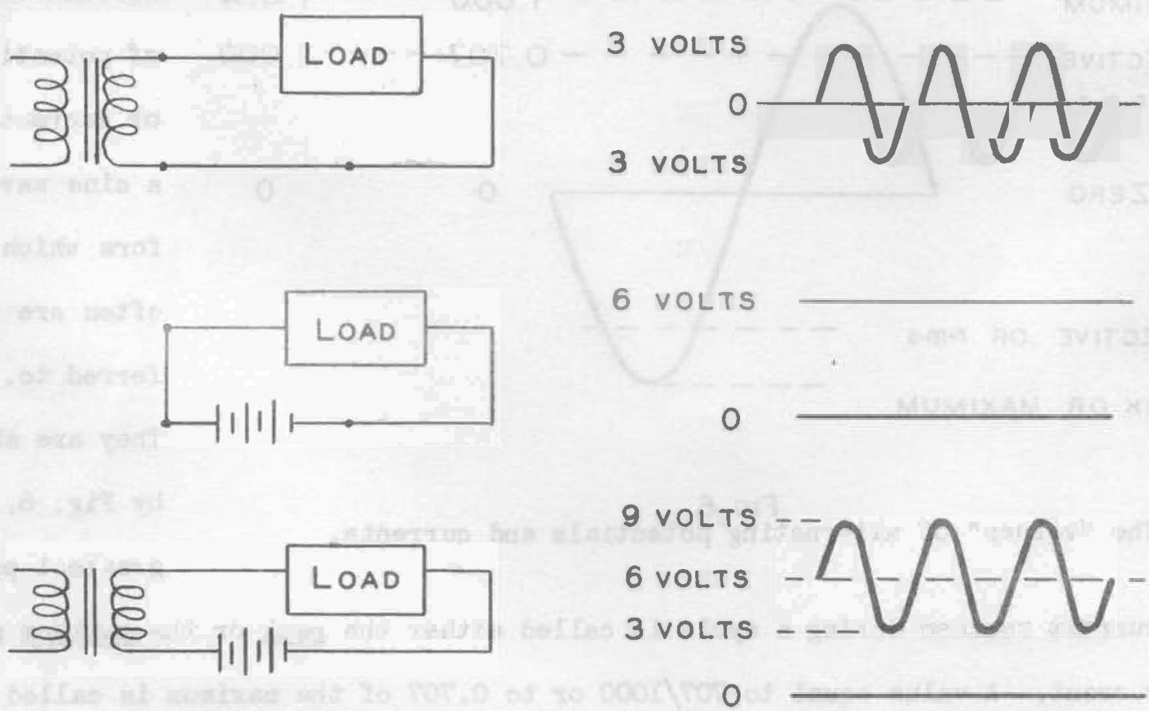

FIG.7.
How a combination potential may be produced.

Unless some other value is specifically mentioned, all alternating potential or current measurements are of effective or r-m-s values. If you say simply two amperes or six volts, you are understood to mean effective values of two amperes or six volts. If you wish to refer to peak values or to some other values, you have to specify what you are talking about.

COMBINATION POTENTIALS AND CURRENTS

At the top of Fig. 7 is represented a "load", which is any device or apparatus in which work is done by electron flow. The load is in series with the secondary winding of a transformer which is applying a 3-volt peak alternating potential difference to the load. This alternating potential may be represented as at the right.

In the center diagram we have taken out the transformer and have connected a battery in series with the load. All batteries furnish direct potentials. If this is a 6-volt battery, the potential difference applied to the load may be represented as at the right, where the potential line is 6 volts above the zero line.

In the lower diagram both the transformer and the battery are in series with the load. During "positive" half-cycles the direct and alternating potentials add together and we have miximum values of 9 volts. During "negative" half-cycles the direct and alternating potentials oppose, leaving minimum values of 3 volts. At the right is represented the combined potential difference, which has maximums of 9 volts, minimums of 3 volts, and an average value of 6 volts. Here we have a direct potential with an alternating component. The word component means the same as "part", so we have a direct potential with an alternating part. It is a direct potential, because it always acts in the one direction, although it varies.

In Fig. 8, at the left, is represented an alternating potential which has peak values of 6 volts in each polarity. At the center is represented a 3-volt direct potential. The two potentials are combined in the combination potential at the right. During positive half-cycles the direct and alternating potentials add to produce peaks of 9 volts. During negative half-cycles the direct potential opposes the alternating potential, but since the direct potential has the lesser value, the combined potential still goes to negative peaks which are equal to the difference between the alternating peaks and the direct potential, or to 3 volts. Here we have an alternating potential with a direct component. The potential is alternating, because it acts alternately positive and negative, although the positive alternations are much greater than the negative alternations.

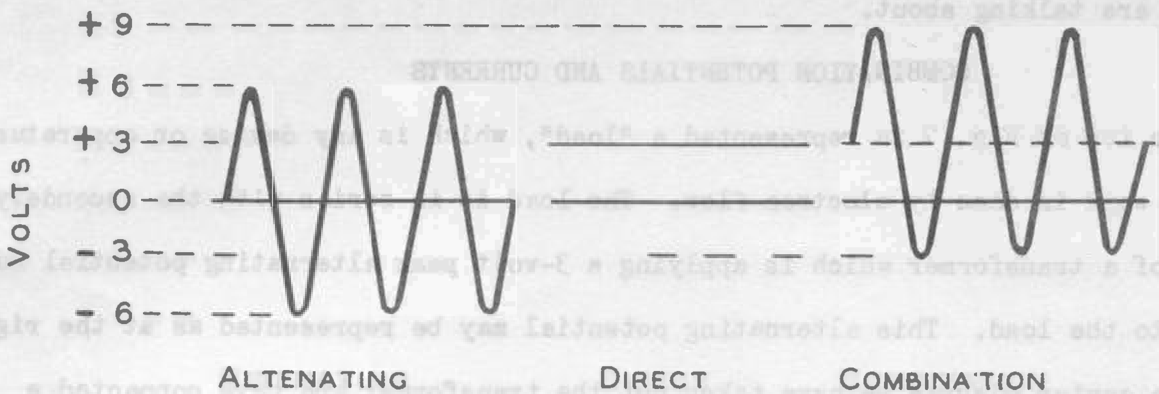

FIG.8.
An alternating potential with a direct component.

Instead of talking about potentials in Figs. 7 and 8 we might have talked about alternating and direct electron flows or currents. The combination currents would be developed, and would be shown just as are the combination potentials.

INDUCTIVE REACTANCE

While studying induction we learned that every change in the rate of electron flow or current causes in the coil or circuit carrying the change an electromotive force whose direction is such as to oppose the change. We learned that this counter-emf tries to keep electrons flowing when the rate of flow is decreasing, and that it tries to prevent the flow when the rate is increasing and decreasing, it becomes evident that the counter-emf of induction must oppose the entire flow of alternating current.

The opposition that is offered to flow of alternating currents by the counter-emf of induction is called <u>inductive reactance</u>. The name <u>reactance</u> is used, because the counter-emf acts against, or <u>re-acts</u> against, the flow. The word <u>inductive</u> refers to the fact that this reactance is due to induction. Counter-emf is induced in circuits or coils having the property called inductance, and so we usually think of inductive reactance as being due to inductance. The greater the inductance, in henrys or other units, which is possessed by a circuit or a coil, the greater will be the inductive reactance of that circuit or coil -- this because the greater the inductance, the stronger are the induced counter-emf's.

Inductance is not the only factor which affects the amount of inductive reactance. This kind of reactance is affected also by the frequency of the applied potential difference and of the current flowing in the circuit or coil. Inductive reactance is affected by frequency because frequency determines the rate of change of electron flow or current, and because counter-emf is proportional to this rate of change.

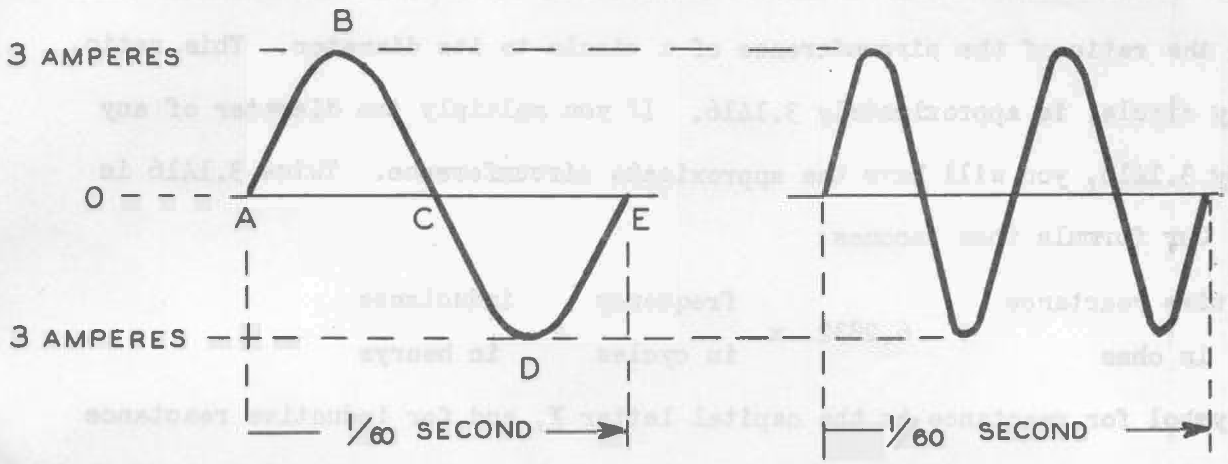

FIG.9.

Rate of change of electron flow increases with frequency.

The effect of frequency on inductive reactance may be explained with the help of Fig. 9. At the left we have one cycle taking a time of 1/60 second, which means a 60-cycle frequency. For illustration the peak value is taken as 3 amperes. From A to B in the cycle there is a change of 3 amperes in the rate of flow, because the flow is zero at A and becomes 3 amperes at B. There are similar 3-ampere changes from B to C, C to D, and D to E. Then in the whole cycle the rate of change is 12 amperes in 1/60 second. In 60 cycles, taking one second, the total change will be 720 amperes per second.

At the right we have two complete cycles within 1/60 second, which would mean 120 cycles in a whole second, and would mean a frequency of 120 cycles per second. Now we have twice as many 3-ampere changes in the same length of time as with the 60-cycle frequency, and so have twice the total rate of change of current because we have a total change of 1,440 amperes per second. Since the counter-emf is proportional to rate of change of current, we will have twice the counter-emf and twice the inductive reactance at 120 cycles as at 60 cycles. Inductive reactance always is directly proportional to frequency.

Inductive reactance, like all other kinds of opposition to electron flow or current, is measured in ohms. In arriving at a formula for the number of ohms of inductive reactance in a circuit or coil we will need inductance for one factor and frequency for another, because inductive reactance is directly proportional to both of these. In addition we need a factor based on the sine wave. This factor will be twice the ratio of the circumference of a circle to its diameter. This ratio, for every circle, is approximately 3.1416. If you multiply the diameter of any circle by 3.1416, you will have the approximate circumference. Twice 3.1416 is 6.2832. Our formula then becomes:

$$\text{Inductive reactance in ohms} = 6.2832 \times \text{frequency in cycles} \times \text{inductance in henrys}$$

The symbol for reactance is the capital letter <u>X</u>, and for inductive reactance the symbol is <u>X</u> with a subscript letter <u>L</u> (the symbol for inductance). The symbol for frequency is the small letter <u>f</u>. Then the formula may be written:

$$X_L = 6.2832 \times f \times L$$

A certain number of ohms of inductive reactance, were this the only opposition to current, would have just the same effect as an equal number of ohms of resistance in limiting the current with a certain applied potential difference. Of course, we are talking about alternating current and alternating potential difference.

We don't always deal with frequencies in cycles and with inductances in henrys, and may need some of the variations of the basic formula, as follows:

$$X_L \text{ ohms} = 6.2832 \times \text{kilocycles} \times \text{millihenrys}$$

$$X_L \text{ ohms} = \frac{\text{kilocycles} \times \text{microhenrys}}{159.155}$$

$$X_L \text{ ohms} = .0062832 \times \text{megacycles} \times \text{millihenrys}$$

$$X_L \text{ ohms} = 6.2832 \times \text{megacycles} \times \text{microhenrys}$$

These four formulas, also the one for inductive reactance in terms of cycles and henrys, are worth putting into your notebook for future reference.

We shall have much more to do with inductive reactance, but before studying it further, we may examine the kind of opposition offered by a capacitor to alternating electron flow or current. Before leaving the subject of inductive reactance for the time being, it might be mentioned that a coil used especially because of its inductive reactance or its ability to limit alternating current often is called a reactor. The same coil might be called either a reactor or an inductor; a reactor when used to limit the current, and an inductor when used to provide inductance.

CAPACITIVE REACTANCE

Although a capacitor allows alternating electron flow or current as the plates of the capacitor charge and discharge, the flow is not nearly so free as though the capacitor were replaced by a conductor. All capacitors limit the rate of electron flow or the current when the flow is alternating. The opposition offered by capacitors or capacitance to alternating flows is called capacitive reactance. This kind of reactance, like all oppositions to flow, is measured in ohms, The symbol for capacitive reactance is the capatal letter X for reactance and the subscript letter C for capacitance, thus: X_C.

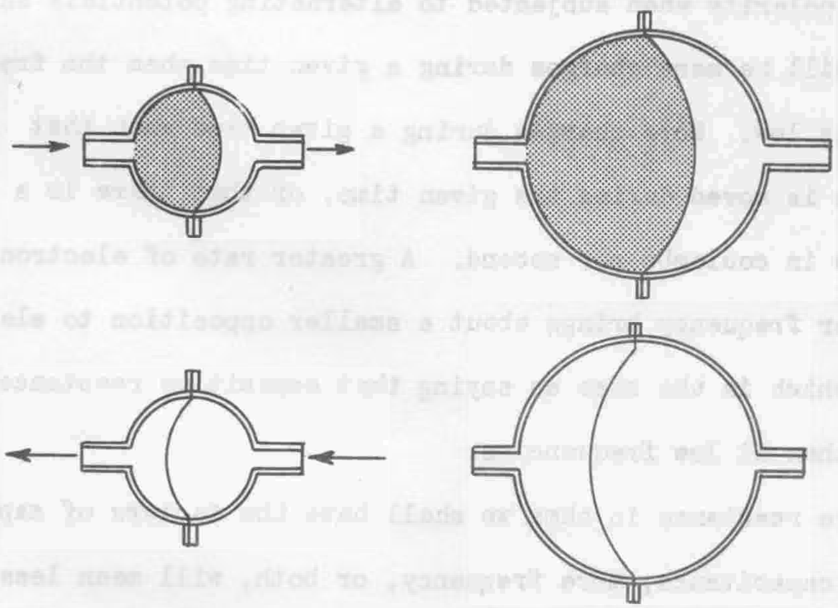

FIG.10.

Large air chambers allow greater air flow, just as large capacitance allows greater electron flow.

Let's think back to our comparison of a capacitor with a device consisting of two air chambers separated by a flexible diaphragm. Such chambers are shown again in Fig. 10. At the left we have small air chambers, corresponding to small capacitance in a capacitor, and at the right are large air chambers corresponding to large capacitance.

When there is the same difference between air pressures in opposite air chambers of small and large units, it is quite plain that a much greater quantity of air will pass into and out of the unit with large air chambers than into and out of the unit with small air chambers. When the same potential difference is applied to small and large capacitances, the large capacitance will have much greater charges, and greater quantities of electrons will flow into and out of it, than with the small capacitance.

When an alternating potential difference is applied to a capacitor, the plates are charged first in one polarity and then in the opposite polarity during each cycle. If the capacitance is large, the charges will be large, and large quantities of electrons will be moved during each cycle. With small capacitance relatively small quantities of electrons will be moved. The greater the quantity of electrons moved in any given time, or during one cycle, the less is the effective opposition of the capacitor to electron flow. This is the same as saying that a large capacitance has less capacitive reactance than a smaller capacitance.

Now let's look at Fig. 11 where are represented a relatively low frequency at the left and a higher frequency at the right. Each half-cycle means that a capacitor will be charged in one polarity when subjected to alternating potentials such as represented here. There will be more charges during a given time when the frequency is high than when it is low. More charges during a given time mean that a greater quantity of electrons is moved during the given time, or that there is a greater rate of electron flow in coulombs per second. A greater rate of electron flow must mean that the higher frequency brings about a smaller opposition to electron flow in the capacitor, which is the same as saying that capacitive reactance is less at high frequencies than at low frequencies.

In a formula for capacitive reactance in ohms we shall have the factors of capacitance and frequency. More capacitance, more frequency, or both, will mean less capacitive reactance. In the formula we must have also the factor which brings in the sine wave value; this factor being twice 3.1416, or 6.2832. Then our basic formula for capacitive reactance is:

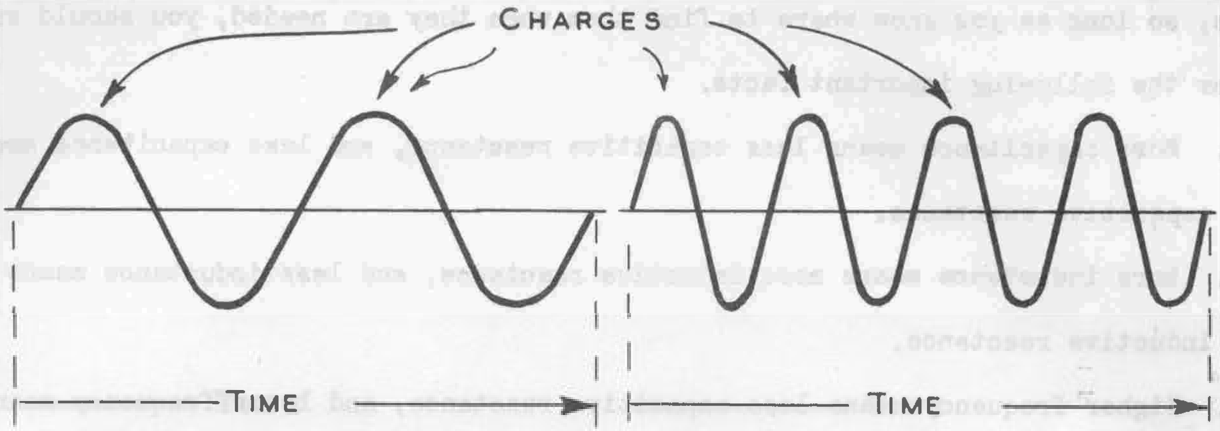

FIG. 1.

A capacitor is charged more often at high frequency than at low frequency, with the same applied potential difference.

$$\text{Capacitive reactance in ohms} = \frac{1}{6.2832 \times \text{frequency in cycles} \times \text{capacitance in farads}}$$

Whenever an <u>increase</u> in values of factors causes a <u>decrease</u> in the value being computed, the formula will show the number 1 divided by the factors which cause the decrease, and so here we have 1 divided by the factors whose increase causes a decrease of capacitive reactance.

Capacitances never will be so large as to be measured in farads, and oftentimes we will use frequencies measured in units other than cycles. Consequently, for practical formulas showing capacitive reactances we will use the following, all of which are derived from the basic formula.

$$X_C \text{ ohms} = \frac{159155}{\text{cycles} \times \text{microfarads}} \qquad X_C \text{ ohms} = \frac{159.155}{\text{kilocycles} \times \text{microfarads}}$$

$$X_C \text{ ohms} = \frac{159155000}{\text{kilocycles} \times \text{micro-microfarads}}$$

$$X_C \text{ ohms} = \frac{0.159155}{\text{megacycles} \times \text{microfarads}}$$

$$X_C \text{ ohms} = \frac{159155}{\text{megacycles} \times \text{micro-microfarads}}$$

These five formulas for capacitive reactance often are useful, and they should be kept handy in your notebook which gradually is being built up.

FACTS ABOUT REACTANCES

Although there is no need whatever for memorizing any of the formulas for reactance, so long as you know where to find them when they are needed, you should remember the following important facts.

1. More capacitance means less capacitive reactance, and less capacitance means more capacitive reactance.

2. More inductance means more inductive reactance, and less inductance means less inductive reactance.

3. Higher frequency means less capacitive reactance, and lower frequency means more capacitive reactance.

4. Higher frequency means more inductive reactance, and lower frequency means less inductive reactance.

5. More current will flow, with a given alternating potential difference, when
   a. Inductance is made smaller.
   b. Capacitance is made greater.
   c. Frequency is lowered in a circuit containing mostly inductance.
   d. Frequency is raised in a circuit containing mostly capacitance.

6. Less current will flow when changes are opposite to those mentioned above.

You will remember these facts if you read each of the six statements, and after reading each one, think out the answer to why that statement is true. If you can't think out the answers, go back and read this lesson over again up to this page, and write the answers as you come to them.

Fig. 12 shows changes of inductive reactance in an inductance (left) and of capacitive reactance in a capacitance (right) when the frequency changes. We have chosen the values of 159.155 microhenrys of inductance and 159.155 micro-microfarads of capacitance because these values make it easy to figure reactances with our formulas. The range of frequencies is from 400 to 1,600 kioocycles, which more than covers the standard broadcast range of radio frequencies.

The inductive reactance increases directly with frequency; it is twice as much at 800 kc as at 400 kc, and twice as much at 1,600 kc as at 800 kc. Capacitive reactance decreases as the frequency goes up, but it does not decrease at a constant

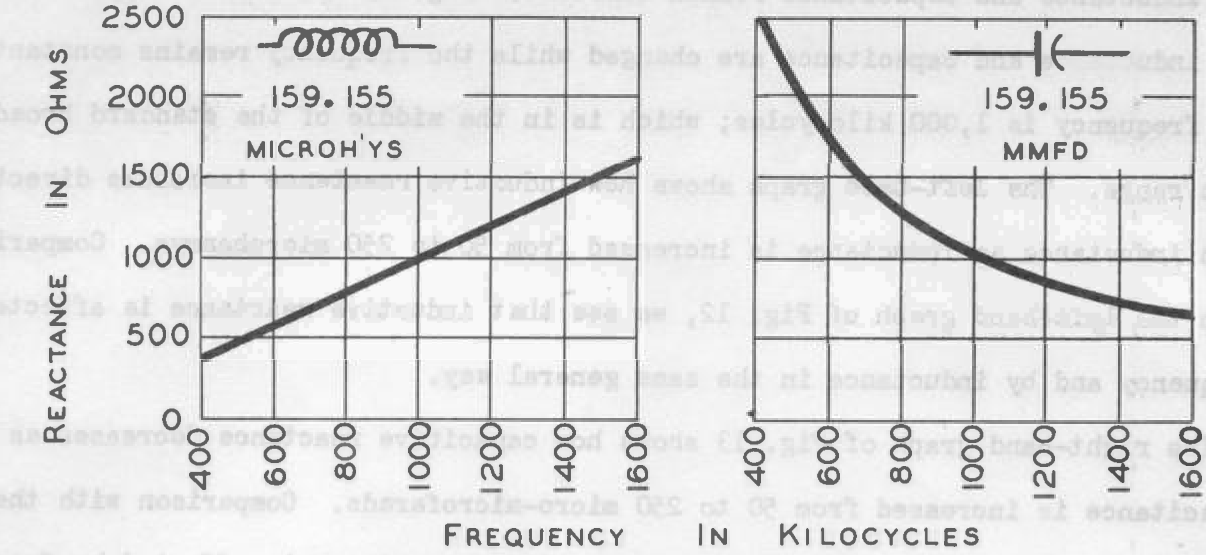

FIG.12.
How reactance changes in an inductance and in a capacitance when the frequency is varied.

rate with equal changes of frequency. There is much greater decrease of capacitive reactance between frequencies of 400 and 800 kc than between 800 and 1,200 kc, although there is a change of 400 kc in frequency in both cases.

The graphs of Fig. 12 show what happens when the frequency is changed while the

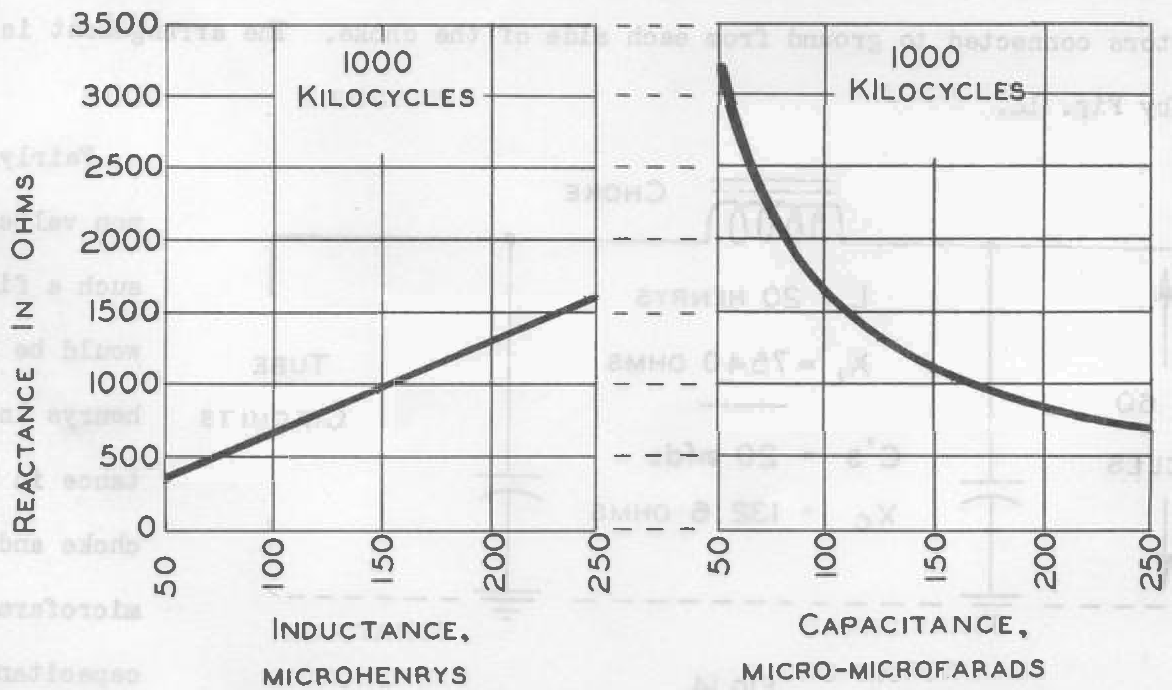

FIG.13.
How reactance changes when the frequency remains constant and the inductance is varied or the capacitance is varied.

the inductance and capacitance remain constant. Fig. 13 shows what happens when the inductance and capacitance are changed while the frequency remains constant. The frequency is 1,000 kilocycles, which is in the middle of the standard broadcast range. The left-hand graph shows how inductive reactance increases directly with inductance as inductance is increased from 50 to 250 microhenrys. Comparing with the left-hand graph of Fig. 12, we see that inductive reactance is affected by frequency and by inductance in the same general way.

The right-hand graph of Fig. 13 shows how capacitive reactance decreases as the capacitance is increased from 50 to 250 micro-microfarads. Comparison with the right-hand graph of Fig. 12 shows that capacitive reactance is affected by frequency and by capacitance in the same general way. You may note this in both graphs which apply to capacitance: doubling the frequency or doubling the capacitance halves the capacitive reactance, while halving the frequency or the capacitance doubles the capacitive reactance.

We have learned enough about reactances to understand, among many other things, why the filter system of a power supply is designed as it is. You will recall that we looked at some filter systems containing a choke coil, which is a reactor, with capacitors connected to ground from each side of the choke. The arrangement is shown by Fig. 14.

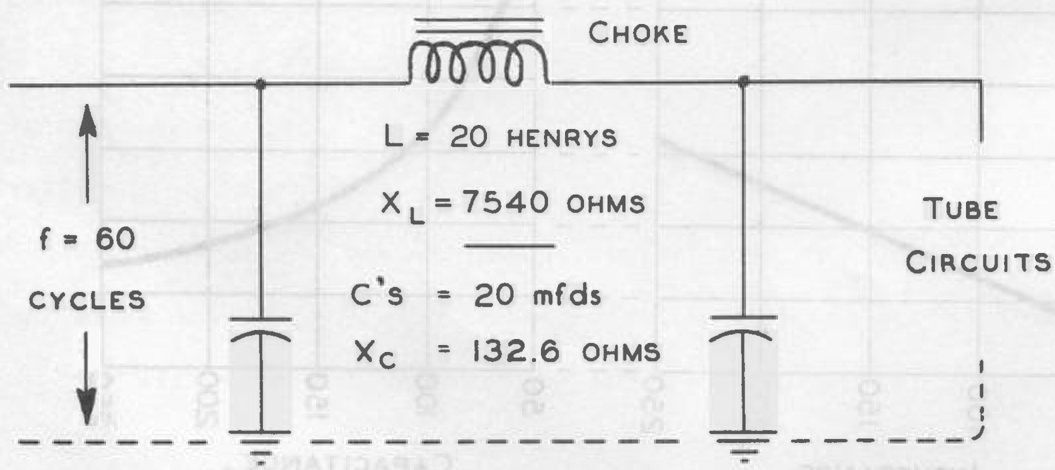

FIG.14.
Reactances in the inductance and the capacitances of a power-supply filter.

Fairly common values in such a filter would be 20 henrys inductance in the choke and 20 microfarads capacitance in each of the capacitors. If we have a rectifier which delivers to the filter a frequency of 60 cycles in the combination current, which is a direct current with an alternating component, we may use our formulas for reactance with these values. The capacitive reactance of the capacitors are about 132.6 ohms each, and the inductive reactance of the choke is about 7,540 ohms. Then the alternating component of the current, in trying to get through the choke, meets opposition of 7,540 ohms. But this component may go to ground and return to the rectifier circuit without going to the tube circuits by passing through only 132.6 ohms of capacitive reactance in the left-hand capacitor. The portion of the alternating component that does get through the choke then has another easy path to ground through the right-hand capacitor.

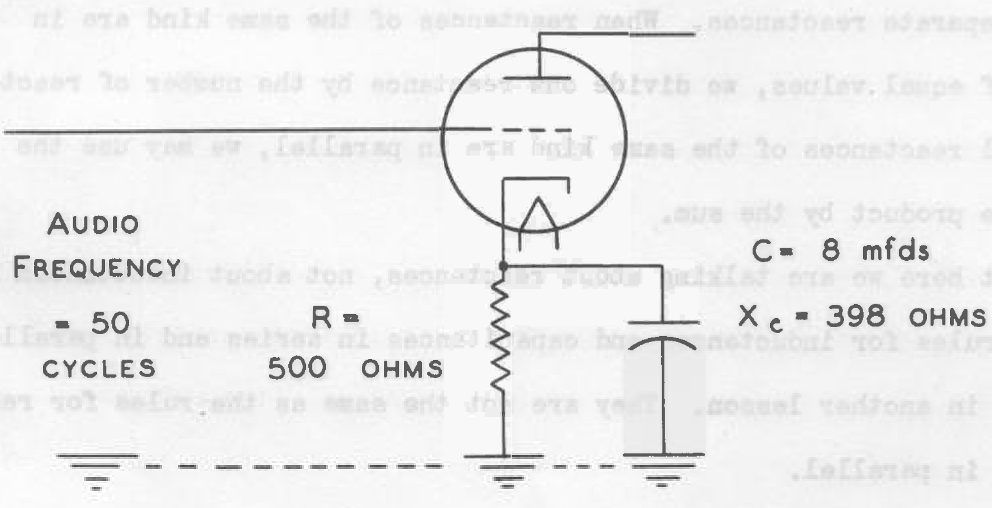

FIG.15.

Low reactance in a bypass capacitor for a biasing resistor.

Quite plainly the current that goes on through the tube circuits is going to be mostly steady direct current with very little alternating component.

In Fig. 15 is shown a 500-ohm "biasing resistor" in the cathode circuit of an amplifying tube. In parallel with the resistor is a "bypass" capacitor whose capacitance is 8 microfarads. The purpose of the bypass is to permit most of the alternating component of the cathode current to pass around the resistor without going through the resistor. We are assuming that the lowest audio frequency at which the bypass is to be effective is 50 cycles. One of our formulas for capacitive reactance will show that the capacitive reactance of the capacitor is about 398 ohms at 50 cycles. Consequently, more of the alternating component will go through the 398-ohm path than through the paralleled 500-ohm path, and our purpose will have been accomplished. Figs. 14 and 15 show only two out of scores of cases in which an understanding of reactances is a great help.

REACTANCES IN SERIES AND IN PARALLEL

Reactances are a form of opposition to alternating electron flow, just as resistance is a form of opposition to all kinds of electron flow. Both oppositions are measured in ohms. The rules for the total or combined reactance of either inductive or capacitive reactances in series and in parallel are exactly the same as the rules for resistances in series and in parallel, so long as all of the reactances are of the same kind, all inductive or all capacitive.

Any number of the same kind of reactances in series have a total reactance equal to the sum of the separate reactances. When reactances of the same kind are in parallel, and are of equal values, we divide one reactance by the number of reactances. When unequal reactances of the same kind are in parallel, we may use the rule of dividing the product by the sum.

Keep in mind that here we are talking about reactances, not about inductances and capacitances. The rules for inductances and capacitances in series and in parallel have been explained in another lesson. They are not the same as the rules for reactances in series and in parallel.

A-C CIRCUITS CONTAINING RESISTANCE

Now we have learned about three kinds of opposition to flow of alternating current. The three oppositions are (1) resistance, (2) inductive reactance, and (3) capacitive reactance. Every actual circuit contains all three oppositions. This is true because (1) every circuit consists of conductors, and all conductors have resistance, because (2) even a straight conductor possesses inductance, and so all conductors have inductive reactance, even though they are not wound into coils, and because (3) there is capacitance between every pair of conductors which are separated by insulation; all circuits consist of insulated conductors and, therefore, must contain capacitive reactances.

What happens when there are alternating potentials and currents in a circuit containing resistance and both kinds of reactances is not difficult to understand provided we don't try to understand too many things at one time. To avoid difficulty we shall examine (1) alternating-current circuits containing only resistance, meaning that we ignore the effects of inductance and capacitance, then (2) a-c circuits considered as containing only inductance, and then (3) a-c circuits considered as containing only capacitance. When we understand the behavior of these three kinds of circuits, it will be easy to combine them and to learn what actually occurs in real circuits.

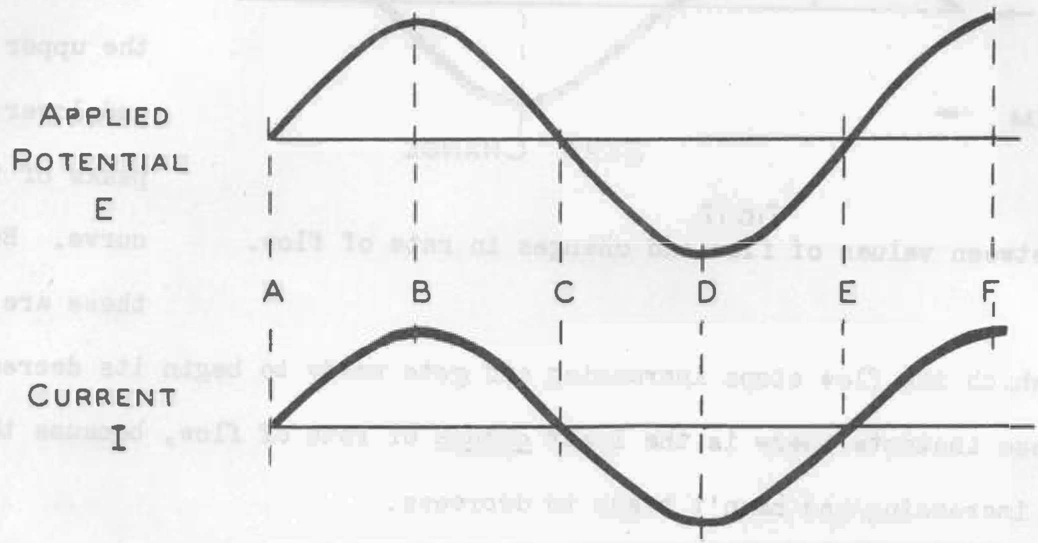

FIG.16.
Applied potential and current are in phase when the circuit contains only resistance.

At the top of Fig. 16 is represented a sine-wave alternating potential. At the bottom is represented the sine-wave current that will be produced by the potential in a circuit containing only resistance. Instants of time are represented by letters A, B, C, and so on. The current always is in the same direction or polarity as the potential, current and potential pass through their peak values at the same instants, and pass through their zero values at the same instants.

We say that the applied potential and the resulting current are in phase. The word phase, as used in electrical work, refers to time relations between potentials and currents, between two potentials, or between two currents. When the two are exactly in time with each other, as in Fig. 16, they are in phase.

A-C CIRCUITS CONTAINING INDUCTANCE

Now we shall examine the relations between applied potential and current, also the counter-emf, in a circuit assumed to have only inductance, with no resistance and no capacitance. Watch carefully the steps in the explanation, because we are about to prove one of those things which you will know is a fact even though it doesn't seem to make sense.

Now look at Fig. 17, which represents an alternating current. There is maximum current just as the flow reaches the values at the upper and lower peaks of the curve. But these are the instants at which the flow stops increasing and gets ready to begin its decrease. Therefore, at these instants there is the least change of rate of flow, because the flow has stopped increasing and hasn't begun to decrease.

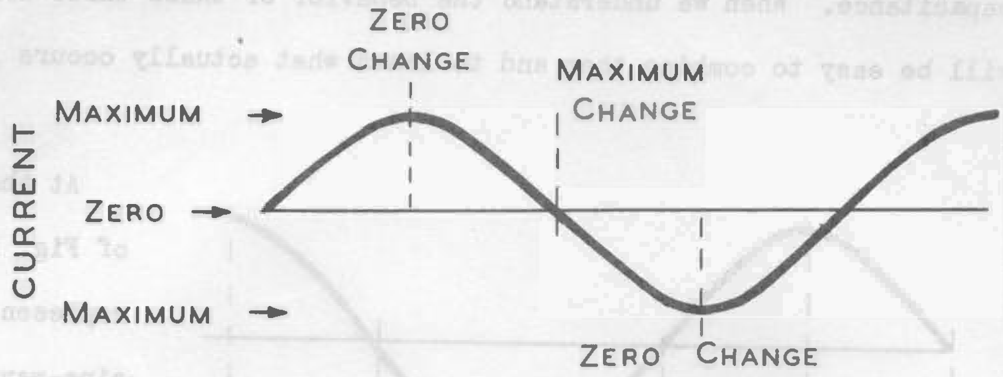

FIG.17.
Relations between values of flow and changes in rate of flow.

There is zero current or rate of flow at the instants in which the curve crosses the horizontal zero line. But at these instants there is the maximum change in rate of flow. There is maximum change because here the current reverses its direction, going from positive to negative or from negative to positive. If you were an electron going north and in the briefest instant of time started south, you certainly would undergo the greatest possible change in rate of motion at this instant.

Next let's consider the counter-emf induced by the alternating current. The counter-emf is represented by the lower curve of Fig. 18, where the current curve is at the top. Here are the reasons why the counter-emf curve must be drawn this way.

As we learned in an earlier lesson, the counter-emf always acts in such direction or polarity as to oppose the change of current that is taking place. When the current is increasing, the counter-emf must oppose the increase, and when the current is decreasing, the counter-emf must oppose the decrease. To oppose decreases of current, the counter-emf must be positive while the current is positive, but decreasing. This is the condition between instants B and C and F and G. And to oppose decreases, the counter-emf must also be negative while the current is negative, as between instants D and E. That is, to oppose the decrease of current the counter-emf must act in the direction that the current is flowing, just as when you try to keep someone from slowing down, you would push in the same direction that they are

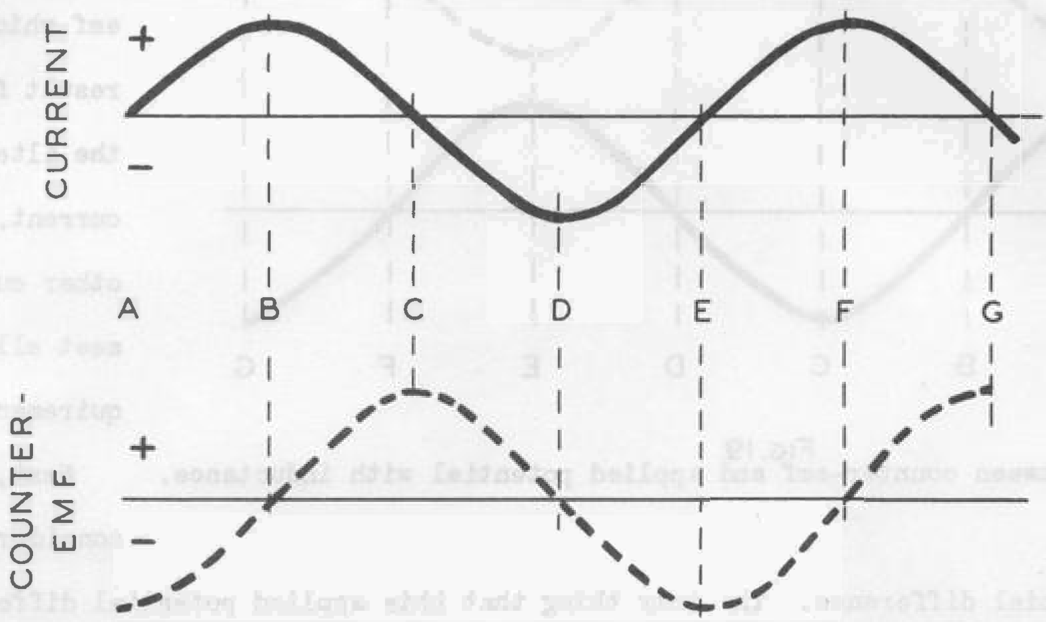

FIG.18.

The phase relations between current and counter-emf with inductance.

traveling.

To oppose increases of current, the counter-emf must act oppositely to the direction of the current, just as to keep someone from speeding up, you would push against them in the direction that they are traveling. The current is increasing between instants A and B, C and D, and E and F. During each of these intervals the counter-emf is negative when the current is positive, and the counter-emf is positive when the current is negative.

The counter-emf must be zero when there is zero change of current. There is zero change of current at the current peaks, B, D and F, so at these instants we have the counter-emf curve go through its horizontal zero line.

The counter-emf must be maximum when there is maximum rate of change of current. There is maximum change of current at instants A, C, E and G (as we learned from Fig. 17) and so we have the counter-emf curve go through its maximum value at these instants. Now we have plotted the curve for the counter-emf which must result from the alternating current. No other curve would meet all our requirements.

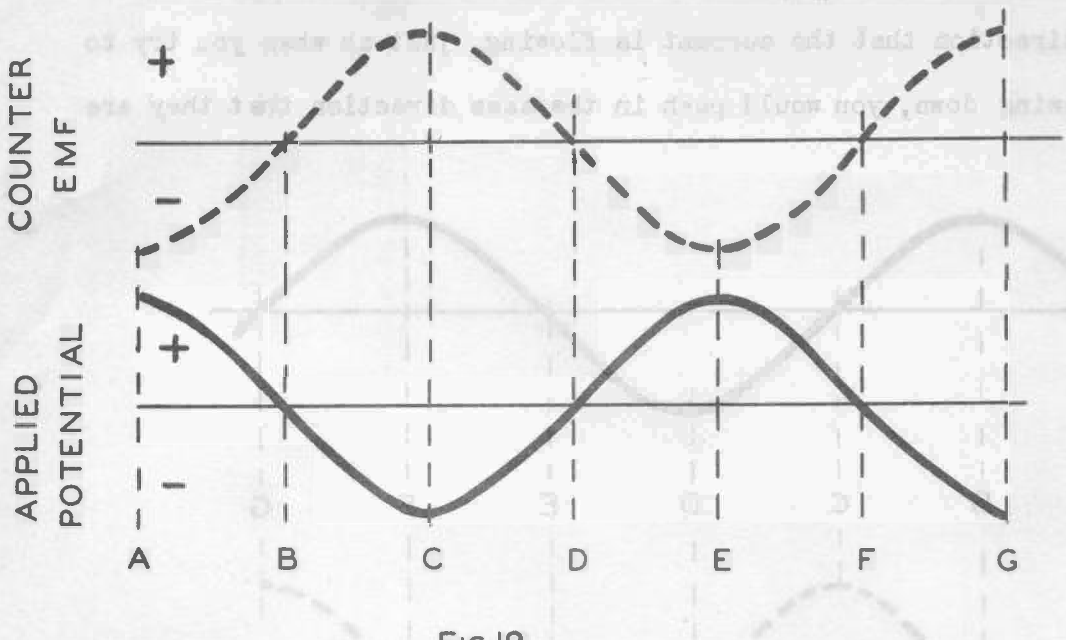

FIG.19.
Relations between counter-emf and applied potential with inductance.

Next, let's consider the applied potential difference. The only thing that this applied potential difference has to do is counteract the counter-emf. If these two forces were not of equal value (in volts) and in opposite directions or polarities at every instant of time, we would have an excess force in one direction. With no resistance (our assumed condition) this excess force would cause infinitely great current, because there would be nothing to oppose the current. There cannot be an infinitely great current. To always be equal in voltage and opposite in direction, the curve of applied potential must be related to the curve of counter-emf as in Fig. 19.

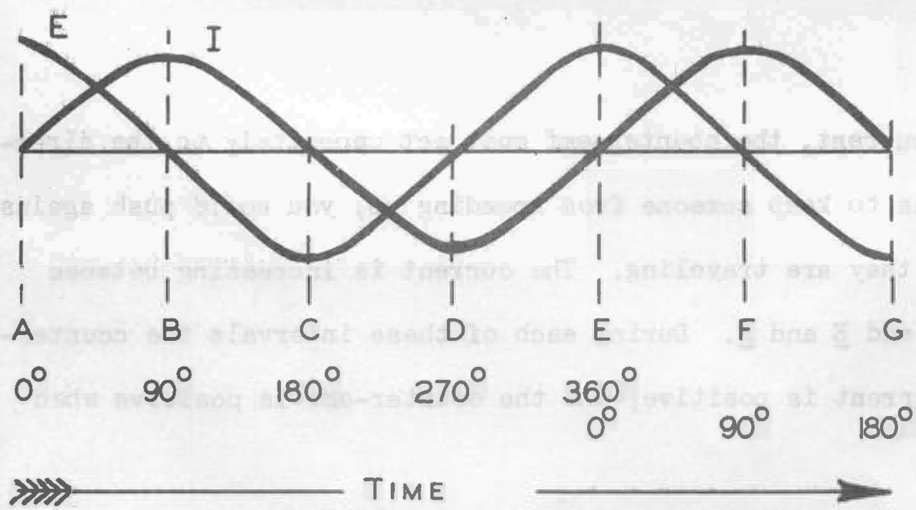

FIG. 20.
The applied potential, E, and the current, I, in a circuit containing only inductance.

For the final step we take the current curve from Figs. 16, 17 or 18, and place it on the same graph with the applied potential curve from Fig. 19. The result is shown by Fig. 20 where the curve for current is marked I and that for applied potential is marked E. Down below are marked the degrees in the first cycle of current, from 0° to 360°, and in part of the second cycle whose 0° point is the same as 360° in the first cycle.

Here is the all-important thing to remember. In a circuit containing only inductance, the alternating current lags the applied alternating potential by 90 degrees. When we say that the current lags the potential or voltage, we mean that the positive peaks of current occur later in time than the positive peaks of voltage, and that negative peaks of current occur later than negative peaks of voltage. Positive voltage peaks occur at A and E, at 0° in the cycles. Positive current peaks occur at B and F, at 90° in the cycles. Negative voltage peaks occur at 180° in the cycles, and negative current peaks follow at 270° in the cycles. Everything that has been explained in connection with Figs. 16 to 19 has been for the purpose of proving that the "phase relations" of voltage and current shown by Fig. 20 really do happen this way. Remember that the effect of inductance is to make the current "lag" the applied voltage.

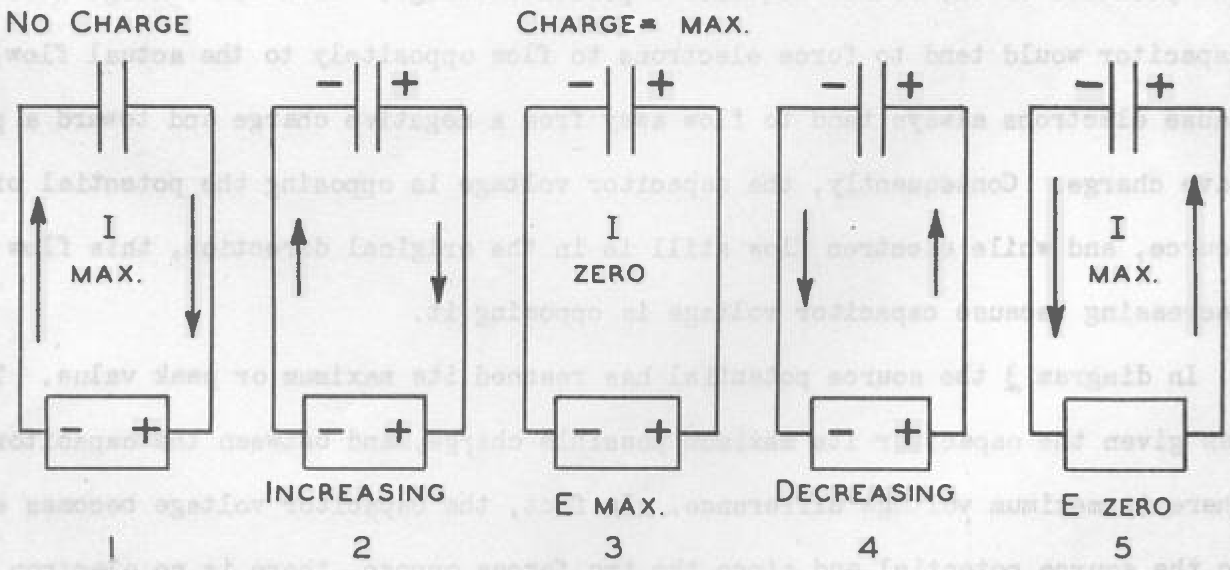

FIG. 21.
Charge and discharge of a capacitor during a half-cycle of applied alternating potential.

A-C CIRCUITS CONTAINING CAPACITANCE

Now we shall examine the behavior of a circuit which is assumed to contain only capacitance, with no inductance and no resistance. This circuit is represented in Fig. 21. At the top a capacitor is represented by its symbol. At the bottom is a source of alternating potential. Polarities of the capacitor charge and of the source potential are shown by positive and negative signs. Directions of electron flow are shown by arrows.

In diagram 1 the capacitor is assumed to have no charge, and with no charge it will have no voltage difference between its plates. The potential of the source is supposed to be starting from zero and commencing to increase in the polarities as marked. Since there is no capacitor voltage to oppose source potential, and since we assume that the circuit has no resistance, even the smallest imaginable rise of source potential will cause the maximum possible electron flow for charging the capacitor.

In diagram 2 the capacitor is being charged. The capacitor plate connected to the negative of the source acquires a negative charge, and the plate connected to the positive of the source acquires a positive charge. Then the voltage across the capacitor would tend to force electrons to flow oppositely to the actual flow, because electrons always tend to flow away from a negative charge and toward a positive charge. Consequently, the capacitor voltage is opposing the potential of the source, and while electron flow still is in the original direction, this flow is decreasing because capacitor voltage is opposing it.

In diagram 3 the source potential has reached its maximum or peak value. This has given the capacitor its maximum possible charge, and between the capacitor plates there is maximum voltage difference. In fact, the capacitor voltage becomes equal to the source potential and since the two forces oppose, there is no electron flow.

In diagram 4 the source potential is decreasing, after having passed through its peak value. This leaves the capacitor voltage greater than the source potential, and electron flow reverses in direction because now it is being caused by capacitor potential.

In diagram 5 the source potential has dropped back to zero. There is still some voltage from the capacitor, and because this capacitor voltage is opposed by neither source potential or circuit resistance, there is maximum possible electron flow in the direction corresponding to capacitor voltage.

In the diagrams of Fig. 20 we have followed the source potential through a half-cycle; from zero potential through peak potential and back to zero, with the polarity in one direction. During the following half-cycle the source potential will again go from zero through its peak and back to zero, with the only difference that all the directions or polarities are reversed.

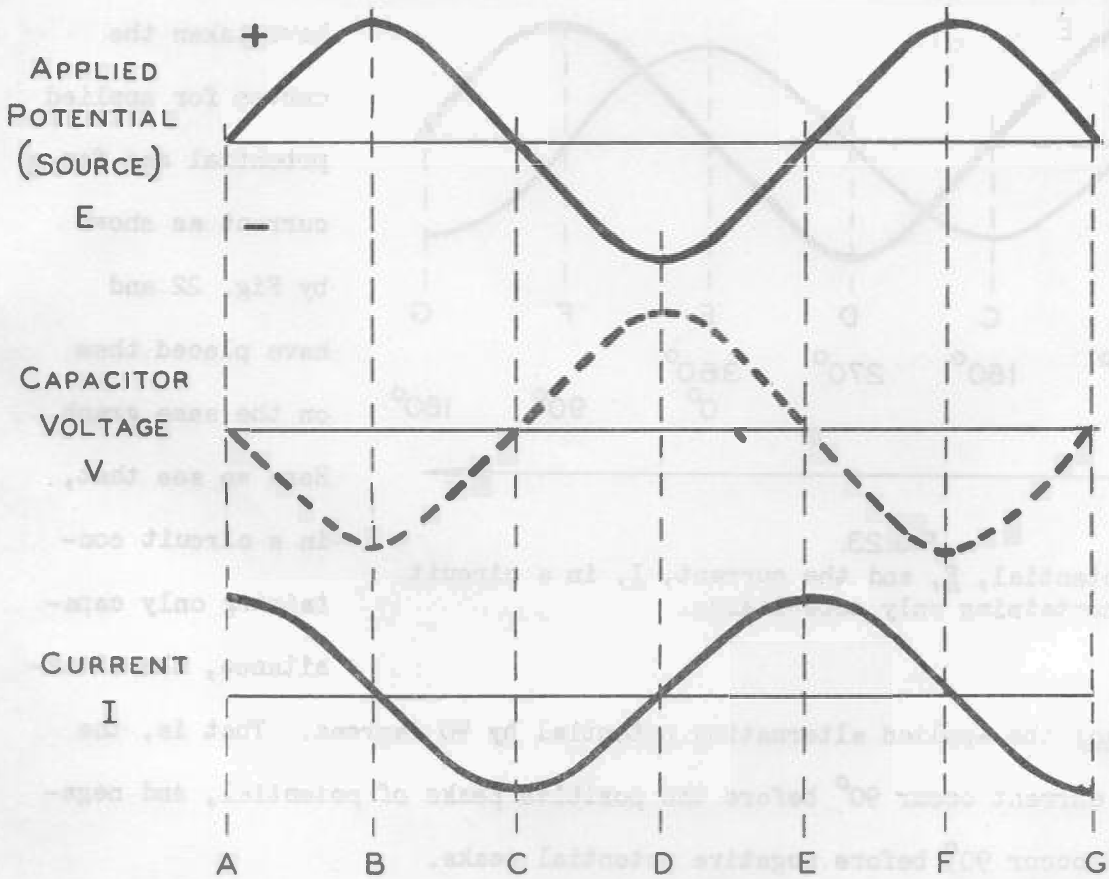

FIG. 22.
Applied potential, capacitor voltage, and current in a circuit containing only capacitance.

The two half-cycles, making one complete cycle, may be shown with curves as in Fig. 22. The complete cycle of applied potential extends from instant A to instant E, with a following half-cycle shown from E to G. Instant A corresponds to diagram 1 of Fig. 21, with applied potential starting from zero, no capacitor voltage, and maximum current in the same polarity as the applied potential. Diagram 2 corresponds to the time between instants A and B, with rising applied potential and capacitor voltage in opposite polarities, and with decreasing current. Diagram 3 corresponds to instant B, with maximum and opposite applied potential and capacitor voltage, and with zero current. Diagram 4 corresponds to the interval between instants B and C, with decreasing and opposite applied potential and capacitor voltage, and with a reversed current which is increasing in value. Diagram 5 corresponds to instant C, with zero applied potential, with capacitor voltage just reaching zero, and with maximum current in the reversed direction or polarity.

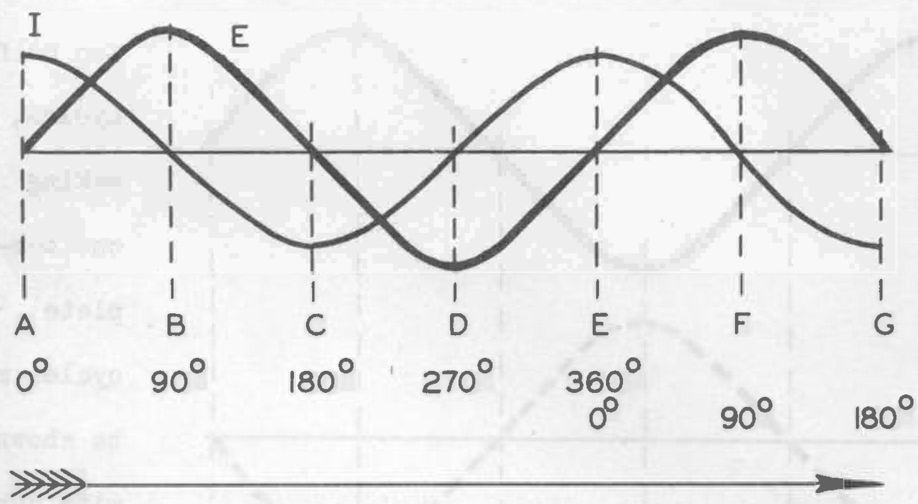

FIG.23.
The applied potential, E, and the current, I, in a circuit containing only capacitance.

In Fig. 23 we have taken the curves for applied potential and for current as shown by Fig. 22 and have placed them on the same graph. Here we see that, in a circuit containing only capacitance, the alternating current leads the applied alternating potential by 90 degrees. That is, the positive peaks of current occur 90° before the positive peaks of potential, and negative current peaks occur 90° before negative potential peaks.

Compare Fig. 23 with Fig. 20. Inductance makes the current lag the applied potential (Fig. 20), and capacitance makes the current lead the applied potential. Then look back at Fig. 16. Resistance causes neither lag nor lead of current.

When we have inductance, we must have inductive reactance; and when we have capacitance, we must have capacitive reactance. Now we may state the effects of the three kinds of opposition in alternating-current circuits.

1. Resistance tends to prevent both lag and lead of current, it tends to keep the current and applied potential "in phase".

2. Inductive reactance tends to make the current lag the applied potential.

3. Capacitive reactance tends to make the current lead the applied potential.

IMPEDANCE

Several times it has been mentioned that every circuit must have resistance in addition to whatever inductive reactance or capacitive reactance may be present. In a circuit containing inductance, capacitance, or both, the opposition to current cannot be due only to inductive reactance, capacitive reactance, or to both, but must be due to the combination of reactance and resistance. This combined opposition is called <u>impedance</u>. Impedance, like every kind of opposition to current, is measured in ohms. The symbol for impedance is the capital letter <u>Z</u>.

If we know the resistance in ohms and the reactance in ohms when the two are in series, it is not difficult to compute the impedance in ohms, although the computation involves some arithmetic. The impedance is not equal to the sum of the resistance and reactance, nor is it equal to the square root of the sum of the resistance and reactance, rather it is equal to the square root of the sum of the squares of the resistance and the reactance. As a formula we would write:

$$\text{Impedance in ohms} = \sqrt{\text{resistance}^2_{\text{in ohms}} + \text{reactance}^2_{\text{in ohms}}}$$

This formula applies when the resistance and the reactance are in series. Whether the reactance is inductive or capacitive makes no difference in the impedance, provided the amount of the other kind of reactance in the circuit is negligible. If the reactance is inductive, the current will lag the potential; and if it is capacitive, the current will lead the potential; but the impedance or opposition to current is the same in either case.

If the resistance and reactance are in parallel, we have a different formula. First, we find the product of the resistance and reactance, both in numbers of ohms. Then we divide that product by the square root of the sum of the squares of the resistance and reactance. That is, we divide the product by the quantity found with the preceding formula for series impedance. The formula for parallel impedance would be written like this:

$$\text{Parallel impedance in ohms} = \frac{\text{resistance in ohms} \times \text{reactance in ohms}}{\sqrt{\text{resistance in ohms}^2 + \text{reactance in ohms}^2}}$$

We may learn about the behavior of reactance and resistance in series and in parallel much easier by looking at a couple of curves or graphs than by studying the formulas. For the curve of Fig. 24 we assume a resistance and a reactance in series. We begin, at the left-hand end of the bottom horizontal scale, with zero reactance (X) and 200 ohms of resistance (R). The impedance here is composed wholly of resistance and so it is the same as the resistance, or is 200 ohms as shown by the curve and the left-hand vertical scale for impedance. Then we steadily increase the reactance as we decrease the resistance, keeping their sum at 200 ohms. As shown by the curve, the impedance decreases quite steadily until the reactance and resistance become equal, at 100 ohms each. Thereafter, the impedance goes up again and finally reaches 200 ohms when we have 200 ohms of reactance and zero resistance at the right-hand side of the graph.

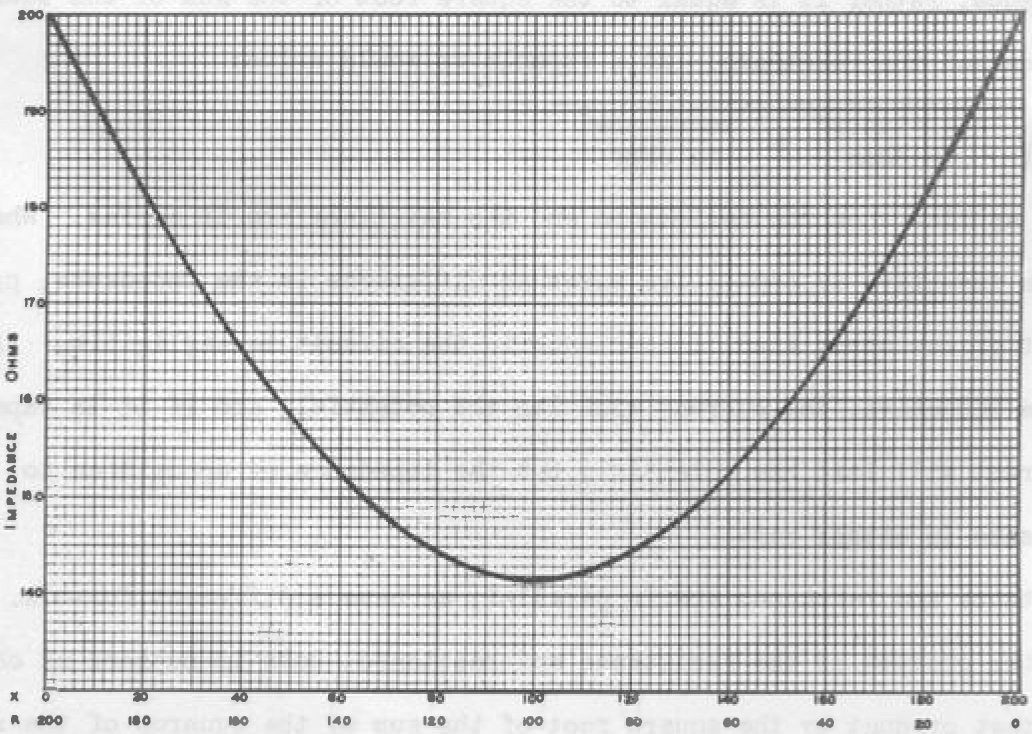

FIG.24.

How impedance changes when varying the values of reactanee and resistance in series.

What do we learn from Fig. 24? We learn, for one thing, that the series impedance always is less than the sum of the resistance and reactance. We learn that the impedance becomes of minimum value when the resistance and reactance are equal. Possibly the most important thing that we learn is this: when there is a lot of resistance in comparison with the reactance, the impedance is about the same as the resistance; and if there is a lot of reactance and not much resistance, the impedance is about the same as the reactance. These facts are shown near the ends of the curve, where you may compare the impedance with the sums of the resistance and reactance.

Fig. 25 shows changes of impedance when the reactance and the resistance are connected in parallel with each other. Again we keep the sum of the two values at 200 ohms, starting with no reactance and 200 ohms of resistance, and ending with 200 ohms

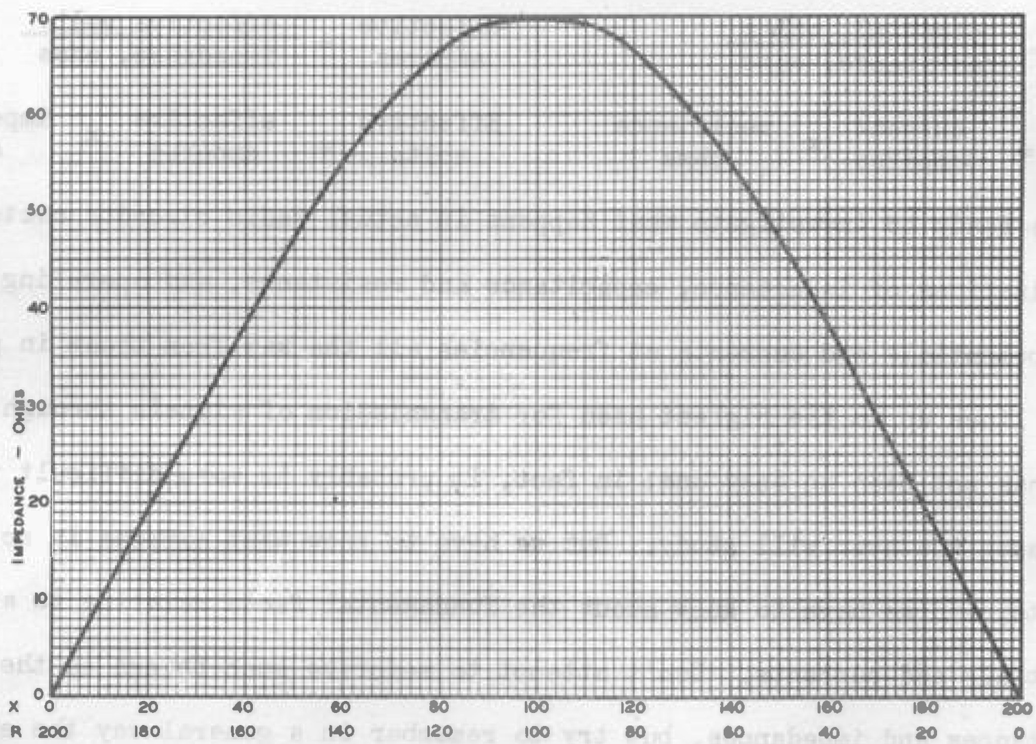

FIG.25.
How impedance changes when varying reactance and resistance in parallel.

of reactance and no resistance. Of course, with either branch of the parallel combination having zero opposition, the impedance would be zero, as shown by the ends of the curve. Then, as we increase the reactance and decrease the resistance from the left-hand side of the graph, or as we increase the resistance and decrease the reactance when working backward from the right-hand side, the impedance increases until reaching its maximum value with resistance and reactance of equal value. Even then the impedance is much less than the sum of the resistance and reactance.

When we know the impedance in an alternating-current circuit, we may use it in making computations with values of potential difference and of current, just as resistance is used with these values in a direct-current circuit. The one precaution to observe is that of using only effective or r-m-s values of current and of potential difference, not the peak or maximum values of either. All three of our Ohm's law formulas for direct current may be rewritten for alternating current like this.

Direct Current

$$\text{Resistance ohms} = \frac{\text{potential, volts}}{\text{current, amperes}}$$

$$\text{Current amperes} = \frac{\text{potential, volts}}{\text{resistance, ohms}}$$

$$\text{Potential volts} = \text{current amperes} \times \text{resistance ohms}$$

Alternating Current

$$\text{Impedance ohms} = \frac{\text{effective volts}}{\text{effective amperes}}$$

$$\text{Effective amperes} = \frac{\text{effective volts}}{\text{impedance, ohms}}$$

$$\text{Effective volts} = \text{effective amperes} \times \text{impedance ohms}$$

Now we are ready to investigate what happens in actual radio circuits containing various combinations of inductance, capacitance and resistance, and operating with alternating potentials and currents at frequencies all the way from those in power and lighting lines up to the highest used for transmission of signals through space. This lesson has not been an easy one; in fact, it probably is more difficult than any other lesson you ever will study. But we have to know what happens in actual radio circuits, and we have to know about the fundamental facts relating to alternating potentials and currents. Don't attempt to memorize such things as the formulas for reactances and impedances, but try to remember in a general way the effects of inductance, capacitance and frequency. It will be easy to come back, later on, and look up the points whose importance will become evident only as we continue with our practical work in following lessons.

Examination Questions on following page