HOW IRON-CORE COILS AND TRANSFORMERS OPERATE IN RADIO CIRCUITS

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STUDY SCHEDULE NO. 11

For each study step, read the assigned pages first at your usual speed. Reread slowly one or more times. Finish with one quick reading to fix the important facts firmly in your mind, then answer the Lesson Questions for that step. Study each other step in this same way.

☐ **1. Magnetic Circuits . . . . Pages 1-8**

Magnetic circuits can be directly compared to electric circuits; this makes their study easy and interesting. Many of the facts presented here are review, but study them carefully so that you can fully understand how iron cores affect the operation of magnetic devices in which they are used. Answer Lesson Questions 1, 2, 3, 4 and 5.

☐ **2. Iron-Core Chokes . . . . Pages 9-11**

Here you learn how air gaps in the core prevent saturation and make it possible to use a choke coil in circuits containing large values of d.c.

☐ **3. Iron-Core Transformer Fundamentals . . . . Pages 11-17**

A transformer transfers POWER from one circuit to another. This is a very important fact—it explains why the currents and voltages have the definite relationship you will find described. Be sure to study carefully the practical section on the power transformer. Answer Lesson Question 6.

☐ **4. Interstage Audio Transformers . . . . Pages 18-20**

This audio transformer is used for voltage amplification, as well as a coupling device between stages. However, as you will see, fidelity requirements are such that a transformer gain of 3-to-1 is considered good. Answer Lesson Question 7.

☐ **5. Impedance Matching Transformers . . . . Pages 21-25**

Transformers handling appreciable amounts of power must be designed for efficiency. Hence, they are designed to match impedances so that a maximum power transfer is possible. In receivers, the output transformer used to match the speaker to the power output tube is the best example. Answer Lesson Question 8.

☐ **6. Special Transformers—Identifying Types . . . . Pages 26-28**

After a short section introducing unique transformers, there is a very practical section on identifying transformers and choke coils. Answer Lesson Questions 9 and 10.

☐ **7. Mail your Answers for this Lesson to N.R.I. for Grading.**

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

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HOW IRON-CORE COILS AND TRANSFORMERS OPERATE IN RADIO CIRCUITS

Magnetic Circuits

AT the low frequencies handled in power supplies and in audio amplifiers, coils and transformers must have high inductances to offer the necessary reactance values. The only practical way of getting such high inductance values is to use cores of magnetic materials, such as iron or alloy steel. (These cores are all commonly known as "iron cores.")

However, the use of an iron core causes inductance devices to have special characteristics that have much to do with the operation of stages in which they are used. For example, the iron cores of audio transformers limit the frequency response or fidelity of audio amplifiers; the iron cores of power transformers prevent them from transferring power with equal efficiency when operated from power lines of different frequencies. It is, therefore, necessary for us to understand the characteristics of these parts so that we may understand the radio stages in which they are used.

► In this lesson, we shall first review a few of the fundamentals about inductances that you learned in earlier lessons. Then, we will consider the general characteristics of magnetic circuits in an iron core. Finally, we will discuss choke coils, power transformers, and audio transformers in detail. In so doing, we will prepare the way for your study of low-frequency stages and power supplies.

MAGNETIC CIRCUIT FACTS

Magnetic circuits have certain things in common with electric circuits, as you learned in an earlier lesson. A simple electric circuit is shown in Fig. *1A:* it consists of a source of electromotive force, and a resistance *R* which opposes the flow of current through the electric circuit. Voltage *E* and resistance *R* together determine the amount of current that will flow. A magnetic circuit likewise has a source, which produces magnetic

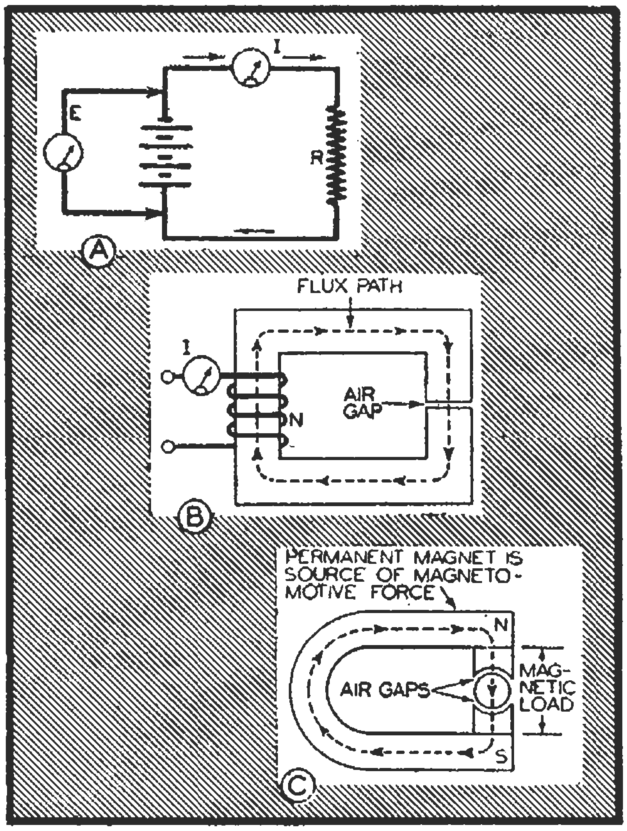


FIG. 1. A comparison between electrical and magnetic circuits proves their actions to be quite similar.

flux, and also has an opposition to the flux. The source of flux is called the *magnetomotive force* (abbreviated m.m.f.), while the *opposition effect* of the magnetic circuit is called its *reluctance.*

One example of a magnetic circuit is shown in Fig. *1B*. Here the electric current *I*, flowing through a coil of *N* turns, creates the magnetomotive force that produces the magnetic flux; the iron core in series with the air gap forms the magnetic circuit that offers a certain opposition or reluctance to this magnetic flux. Actually, the greatest part of the reluctance occurs in the air gap, for iron offers little opposition to magnetic flux. Thus, the iron acts as a "conductor" for the magnetic lines, just as the connecting wires in Fig. *1A* act as electrical conductors.

Another example of a magnetic circuit is given in Fig. *1C*. The magnetomotive force is produced here by a permanent magnet, and the controlling reluctance in the magnetic circuit is that offered by the two air gaps associated with the cylindrical iron core. Incidentally, this magnetic circuit is typical of those found in direct-current meters.

Thus, you can see that electromotive force (voltage) in an electric circuit is comparable to magnetomotive force in a magnetic circuit, resistance is comparable to reluctance, and current is comparable to magnetic flux.

The same general circuit rules are followed also: increasing the magnetomotive force increases the magnetic flux; decreasing the magnetomotive force decreases the flux. Increasing the *reluctance* of the magnetic circuit by changing some part of its path decreases the magnetic flux; decreasing the reluctance of a magnetic circuit permits the flux to increase.

How is Magnetic Flux Measured? The amount of magnetic flux in a magnetic circuit cannot be measured in the direct fashion we use to measure current in electric circuits. Instruments have been devised that will measure flux, but they are not simple to use; further, a great many measurements usually must be made to discover the total flux flowing, since a single measurement shows only the amount in a small cross-section of the circuit. Fortunately, you need not worry about flux measurements in practical radio work; that is something we can leave to the research scientist. However, the *units* in which flux and the two other magnetic quantities—magnetomotive force and reluctance—are measured are of interest to us, for we shall meet them constantly in discussions of magnetic circuits. Let's take a few moments to see what these units are.

Units of Force. You know that an increase either of the number of turns in a coil or of the current through the coil will increase the flux-producing ability (magnetomotive force) of the coil. This magnetomotive force therefore can be expressed in terms of *ampere-turns*.

The *ampere-turn* is the practical unit of magnetomotive force for coils, as it provides a direct means of measuring the magnetomotive force. However, this unit cannot be applied to permanent magnets. For this reason, scientists use the *Gilbert,* a unit of magnetomotive force that applies directly to permanent magnets as well as to coils. To change ampere-turns to gilberts, simply multiply the number of ampere-turns by 1.26; to change gilberts to ampere-turns, multiply the m.m.f. in gilberts by 0.80.

► The magnetomotive force is the

total force acting *throughout* the magnetic circuit. To express the force developed over a portion of the length of the path, a term giving the *magnetomotive force per unit length* is also used. This may be given as gilberts per centimeter. This unit of measurement is called the *magnetic force,* or *magnetizing force,* to distinguish it from the *magnetomotive force.*

Units of Flux. The magnetic line of force (used to represent flux) is a unit originally conceived by the great scientist Faraday, and it is retained to this day because of its convenience. The technical name for a magnetic line of force is the *maxwell.* A larger unit, the *kilomaxwell,* is equal to 1000 lines of force or to one *kiloline.*

► *Flux density* indicates how many lines of flux pass through a given unit of area. Flux density therefore can be expressed in terms of lines per square inch, maxwells per square inch, kilolines per square inch or kilomaxwells per square inch. If the unit of area is one square centimeter (metric units) another unit is used; a flux density of one line per square centimeter is known as a *gauss.* A kilogauss is equal to 1000 gausses or 1000 lines of flux per square centimeter.

Units of Reluctance. Now we can define the magnetic opposition to the existence of flux in a magnetic circuit. If a circuit has a magnetomotive force of one gilbert and this sets up a flux of one maxwell (one line of force), then scientists say that the magnetic circuit has a reluctance of one *oersted.*

Let us see what controls the reluctance of a magnetic path. Turning back once more to electric circuits for comparison, you will remember that the resistance of the circuit can be increased either by increasing the length of wire path, by decreasing the cross-sectional area of the wire path, or by making the current flow through wire that has a high resistivity, such as nichrome wire. Similarly, in a magnetic circuit, the reluctance of the path for flux is increased *by increasing the length of the path, by decreasing the cross-sectional area of the path, or by using materials for the path that have higher reluctivity* (higher reluctance per unit volume). Under normal operating conditions, air has much more reluctivity than iron or steel. Different types of iron vary greatly in reluctivity; cast iron is very high and wrought iron is low.

► The comparison to electrical circuits is so close that Kirchhoff's laws for magnetic circuits are much like those for electrical circuits. These laws are:

1. All the flux flowing to a point in a magnetic circuit equals all the flux flowing away from that point.

2. The sum of the reluctance drops in a magnetic circuit must equal the sum of the magnetomotive forces acting in that circuit.

Permeance of Magnetic Circuits. In electrical circuits, we express the ability of the circuit to conduct current as its conductance. This rating is expressed in mhos, and is obtained by dividing the number *one* by the circuit resistance in ohms. Similarly, the ability of a magnetic circuit to allow magnetic lines to exist is called its *permeance.* The number *one* divided by the reluctance in oersteds gives the permeance.

MAGNETIC SATURATION

You know that doubling the source voltage will double the current in an *electric* circuit that contains only resistance. However, you will recall that saturation occurs in a tube, which prevents the current from being exactly proportional to the voltage when a tube is used. Similarly, it is not always true that doubling the magnetomotive force in a magnetic circuit will double the magnetic flux. Except for air and certain non-magnetic metals, the reluctance of a magnetic path varies with the magnetomotive force acting upon it.

The two curves in Fig. *2* illustrate the difference in action of electric and magnetic circuits. Fig. *2A* shows the relation between the voltage applied to a resistor and the current that flows through it. As you would expect, the resultant graph is a straight line.

Fig. *2B* is the curve for a magnetic circuit containing iron. This curve shows the relation between the magnetomotive force (m.m.f.) applied to a reluctance and the magnetic flux that flows through it. (The magnetomotive force, the reluctance, and the flux correspond, respectively, to the

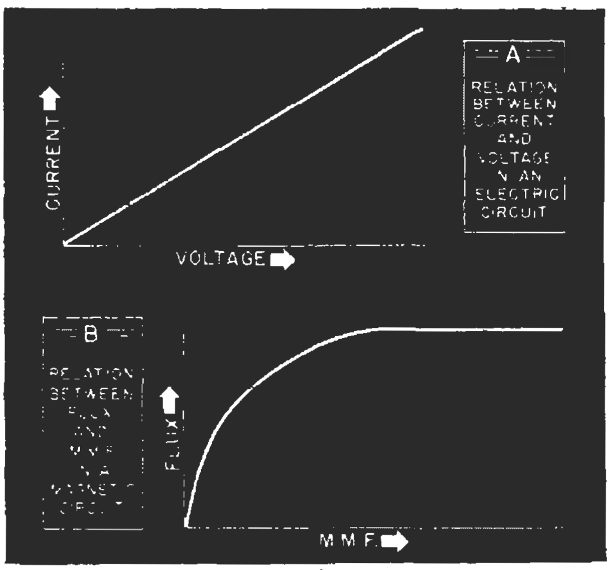


FIG. 2. These curves show how a magnetic circuit differs from a single resistive circuit in that saturation occurs in the magnetic circuit.

voltage, the resistance, and the current in the electric circuit.) Notice—the graph is not a straight line. Instead, it is a curve that gradually becomes horizontal as the magnetomotive force is increased. In other words, in an iron-core circuit, increases in m.m.f. beyond the point of greatest curvature do not produce proportionate increases in flux—in fact, when the horizontal part of the curve is reached, the magnetomotive force can be increased greatly without producing more than a small increase in flux.

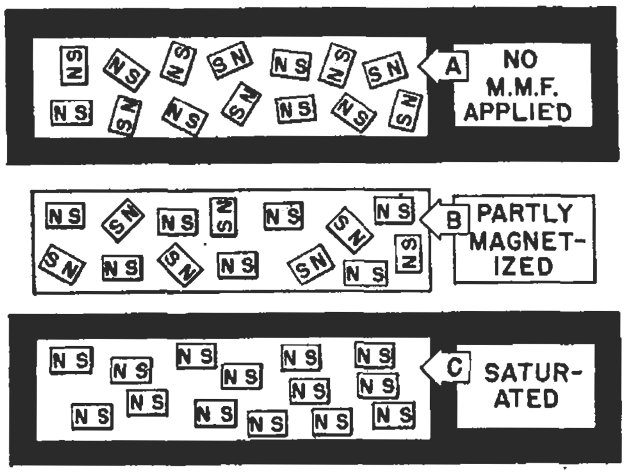


FIG. 3. How the tiny magnets line up in a magnetic material and add their forces to the total applied.

This condition, in which an increase of the magnetomotive force in a circuit produces little change in the flux, is called "saturation," and is similar to the saturation action that occurs in tubes. (You will recall that an increase of the filament temperature beyond a certain point does not increase the emission.) Magnetic saturation occurs only in magnetic circuits that contain *magnetic* materials, such as iron or steel; an air-core coil cannot be saturated.

► Scientists explain the phenomenon of magnetic saturation in a very simple way. They say that iron, or any other magnetic material, is made up of millions of tiny individual magnets, which ordinarily are arranged in a random fashion throughout the material as shown in Fig. *3A*. When a magnetomotive force is applied to the circuit containing this magnetic material, some of these little atomic magnets line up parallel to the magnetic lines of force (Fig. *3B*), with their North poles all pointing in the same direction. The flux in the circuit then consists of the flux caused by the applied m.m.f., plus the much greater flux caused by the individual magnets; the total circuit flux, therefore, increases tremendously over what it would be in an air-core coil for the same amount of magnetomotive force. If we keep increasing the amount of m.m.f. applied to the circuit, more and more of the individual magnets line up, and the flux continues to increase rapidly. Soon, however, all the individual magnets are lined up (Fig. *3C*); they have then added as much to the total flux in the circuit as they can. Then, any further increase in the applied m.m.f. adds to the total flux merely the relatively small amount that an equivalent increase in m.m.f. would add in air. The curve of flux plotted against m.m.f. then becomes almost flat, and we say that saturation has been reached.

► The m.m.f. that must be applied to cause saturation depends on the size, material, and construction of the core. Very often, when we are using an iron-core choke or transformer, we do not want saturation to occur when a normal amount of current flows through the coil. For this reason, transformers and choke coils are often made with air gaps in their cores. An air gap increases the reluctance of the core, so a relatively large current must flow through the coil to cause saturation. (We will say more about air gaps later in this lesson.) Large cores also help prevent saturation, for the larger the core, the more flux it can carry before saturation occurs.

B-H CURVES

Engineers use graphs—known as "B-H curves"—much like those in Fig. *4* to show the magnetic characteristics of various materials. These curves are not exactly the same as the curve in Fig. *2B*, because the units are different. Flux density—that is, the number of *flux lines per square centimeter* of the material—is plotted along the vertical scale, and magnetizing force (*m.m.f. per unit length*) is plotted along the horizontal scale. Flux density is assigned the symbol *B* while *magnetizing force* is given the symbol *H*.

In these curves, *B* and *H* are used

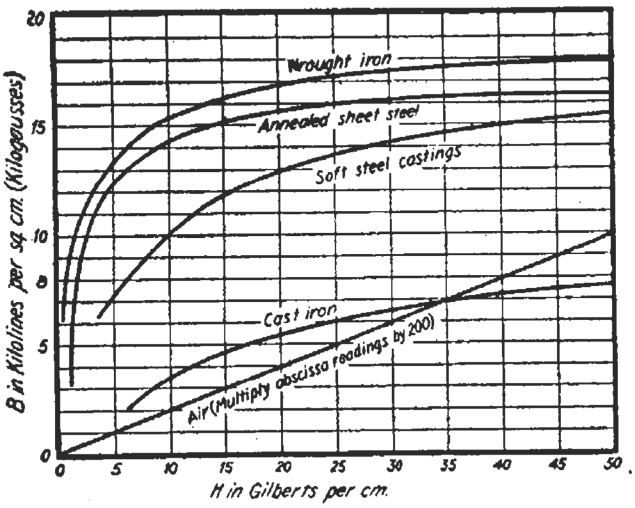


FIG. 4. B-H curves are useful to engineers because they show how various materials differ in their characteristics.

instead of flux and m.m.f. so that the information can be made to apply to cores of any size and also so that the curves will apply only to a particular material (not to an entire magnetic circuit, which may contain an air gap or other materials). These curves make it possible to find the characteristics of the material itself in such a way that the information can be applied to *any* core using that material, whereas the curve shown in Fig. 2 would apply only to a *particular* core or magnetic circuit. (*B* and *H* are also commonly expressed in English units—flux per square inch and m.m.f.

per inch—as well as in the metric (centimeter) units that are used in Fig. 4.).

Notice that for air the abscissa (horizontal or *H* scale) readings must be multiplied by 200. Thus, to get a *B* reading of 5, there must be 5000 *H* units (25 × 200) for air; this is because air is so much poorer a magnetic conducting material than either iron or steel. The curve for air applies also to non-magnetic materials like brass, copper, wood, bakelite, and fiber. Furthermore, this graph shows that flux density increases uniformly with the magnetic force only for air and non-magnetic materials; all magnetic materials become saturated when subjected to large magnetizing forces.

► Very likely you will never use *B-H* curves in your work, as they are intended primarily for the designer of iron-core devices. They are shown here to familiarize you with them, for you will frequently find them mentioned in technical articles.

IRON CORE LOSSES

So far, we have discussed what might be called "d.c. magnetic circuits"—circuits in which the magnetizing force is supplied by a direct current of steady value flowing through a coil. In radio, however, we are concerned principally with the effects of alternating current flow through coils. As you may suspect, the behavior of coils is considerably more complicated when a.c. is passed through them.

For example, there are certain magnetic losses that every iron-core device has to some extent when a.c. is passed through it—*hysteresis* (pronounced *hiss-ter-E-sis*) *losses, eddy current losses, and flux leakage losses.* (This last loss occurs also in d.c.-operated devices, but is much more important, as you will see, when the device is a.c.-operated.) All of them reduce the efficiency or effectiveness of the device in which they occur, and all can be minimized (but not eliminated altogether) by proper design. As a knowledge of what causes these losses will help you to select low-loss devices for circuits that require their use, let's take a moment to see why these losses occur.

Hysteresis Losses. If we send a current through a coil that has an unmagnetized iron core, then reduce the current to zero, the core of the coil will remain magnetized to a certain extent. (This, in fact, is the way permanent magnets are made.) The core is then said to have "residual magnetism." If we want the core to be completely unmagnetized, we have to do more than reduce the coil current to zero—we must send a small current through the coil in the reverse direction. In other words, we must use up electrical energy to eliminate the residual magnetism of the core.

The reason the core has residual magnetism is that the tiny magnets of which it is composed, once they have been lined up by the magnetic field of the coil current, exert forces on one another that tend to make them stay lined up. Thus, when we reduce the current through the coil to zero, some of these magnets remain lined up and cause some flux to continue to pass through the core. We have to send flux through the core in the reverse direction to turn the magnets from their lined-up positions, thus restoring the core to its original unmagnetized condition.

The property of iron (or other magnetic materials) of retaining magnetism after the magnetizing force is removed is called *hysteresis.* The electrical energy that must be used to bring the iron back to its original non-magnetic state represents the *hysteresis loss.*

► Any iron-core device fed with a.c. power will waste part of the power in this manner. As you know, the a.c. current in the coil causes the flux to act first in one direction, then in the other. A certain amount of power is converted into heat in restoring the core to its non-magnetic condition each half cycle, so that the next half cycle of flux change may follow.

We cannot eliminate hysteresis loss altogether, but proper choice of materials will minimize it. For example, hard steel retains its magnetism, which is why it is used for permanent magnets. It is, then, a poor material for a transformer or choke core, as a great deal of power would have to be wasted in overcoming hysteresis. On the other hand, soft iron and annealed silicon steel retain very little of their magnetism, so cores made from these materials would have far less hysteresis loss. These are the materials that are generally used in transformer cores.

Eddy Current Losses. From your fundamental study of inductances, you know that when a varying current flows through a coil, a varying flux is produced in the coil. This flux variation will induce a voltage in any metallic conductor with which it can link, and the direction in which this induced voltage will act (force a current to flow) is at right angles to the direction of the flux lines.

Now, let's consider the core commonly used in chokes and transformers. For the moment, let's consider the core to be solid, as shown in Fig. *5A*. When the flux follows the indicated paths, the iron in the core acts as if it were made up of a great number of parallel rings at right angles to the flux path (that is, *across* the core—see the drawing). The varying flux in the core induces a voltage in each ring; this voltage sends through the ring a current that is known as an *eddy current.*

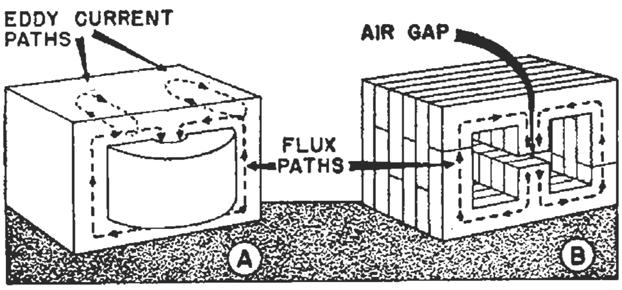


FIG. 5. Notice the large eddy current paths in the solid core. These are reduced in the laminated core.

This eddy current produces two effects. First, it sets up a flux in the opposite direction to the original magnetic flux and thus reduces the amount of change in the total flux through the core. As a result, the inductance of the iron core coil is lowered.

Even more important—you know that iron has considerable electrical resistance. Therefore, the eddy current flowing in each ring produces a power loss (I^2R). This power loss is more important than the loss in inductance, because it, together with the hysteresis loss, wastes power that otherwise could be put to useful work.

► Eddy current losses can be reduced considerably in low-frequency iron-core devices by constructing the core from thin sheets called *laminations*, as shown in Fig. *5B*. (Here the coil is not shown, but it would be in the same position as in Fig. *5A*.) These sheets are annealed (softened) in such a way that their surfaces are coated with an iron-oxide scale that is a fairly good insulator. Often the surfaces of the laminations are varnished in addition, to give even better insulation. Insulated in this way, each thin lamination acts like a separate core, and the eddy current rings that form can be no wider than a single lamination. The rings thus become much smaller than in a solid core; less flux can pass through each ring (there is less flux linkage) and therefore less voltage is induced in each ring to cause a power loss.

► Both eddy current and hysteresis losses increase greatly with frequency; this is the reason why even laminated iron cores are of no value for radio frequency purposes. At these frequencies, the only magnetic cores that may be used are made of finely powdered iron or steel mixed with a clay or plastic binder. The iron or steel particles are so separated that losses are kept low, yet there is enough of this material in the flux path to reduce the reluctance to the point where the inductance is fairly high.

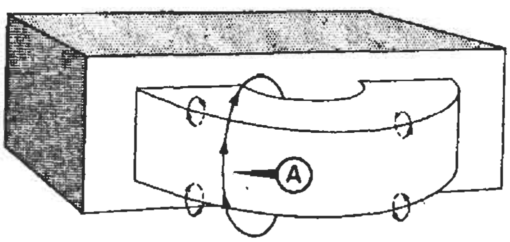


FIG. 6. Leakage lines of force usually fail to link with the entire winding.

Flux Leakage Losses. Since iron is a much better magnetic conductor than air, most of the flux produced by a coil will flow through the iron core rather than through the surrounding air. However, as indicated in Fig. *6*, a certain amount of the flux always takes the high-reluctance air path. (You may compare this to the action of electrical current through a circuit made up of a high and a low resistance in parallel. Most current will flow through the low resistance, but some will go through the high resistance.) Furthermore, as the core approaches saturation, more flux takes these air leakage paths, for the reluctance of a saturated core goes up very rapidly and soon approaches that of the air path.

Where the flux path through the air links the entire coil winding (or windings, when there are more than one) as shown by line *A* in Fig. *6*, complete flux linkage occurs just as if the flux had passed through the core. However, the other air paths in Fig. *6* do not completely link the coil (or coils). The flux that passes through these paths is called "leakage flux," because it "leaks" out of the desired path. Any leakage from the primary winding of a transformer causes less energy to be transferred to the secondary, because *primary leakage flux* does not link with the secondary, so it cannot induce a voltage into the secondary.

This leakage flux is undesirable, both because it reduces efficiency and because it can create interference by inducing voltages in nearby circuits. Design engineers minimize it by designing the iron core to operate well below saturation. Often, also, the coil and core are covered with a soft steel casing so leakage flux will flow through this casing and back to the iron core instead of wandering off through the air.

Iron-Core Chokes

As you know, the reactance of a coil depends upon both its inductance and the frequency of the applied voltage. If the frequency is low, the inductance of the coil must be high for it to have a fairly high reactance. When we want a high-reactance choke coil in a low-frequency amplifier or a power supply, we must use an iron-core choke, because this is the only kind of choke that can give us the necessary high inductance and still be reasonable in size.

But, while the use of an iron core in a choke solves the problem of getting high reactance at low frequencies, it introduces other problems. In particular, it introduces the problem of saturation—a very real difficulty, because in most practical choke coil applications, d.c. as well as a.c. flows through the choke coil. The d.c. value is frequently high enough to cause saturation or near-saturation of the choke core.

You learned earlier in this lesson that iron-core choke coils very often have an air gap in the core. Now, such a gap increases the reluctance (decreases the flux) in the core considerably, since air has a very much higher reluctance than magnetic materials. Perhaps it seems strange to you that chokes should be built with iron cores to increase the flux through them, only to have the flux reduced by the addition of the air gap, but there is a good reason.

► As you know, the inductance of a coil depends upon the amount of *change* of flux within the coil, rather than upon the total flux present. (Voltages are induced only by variations in flux.) If the flux change for a given change in current is high, the inductance is high; if the flux change is low, the inductance is low.

► We can use the solid-line curve in Fig. 7 to show what may happen when a mixture of d.c. and a.c. flows through a coil that has no air gap.

Let us first assume that a small amount of d.c. flows, and produces the amount of core flux indicated by point *1* on the curve. Then, let us presume that enough a.c. flows to cause a variation in the flux from point *A* to point *B* on the curve.

Let us now draw a horizontal line from point *A* toward point *C*, and draw a vertical line from point *B* to meet it, as shown in Fig. 7. The length of the horizontal line *A-C* is a measure of the amount of a.c. current change, while the vertical line *B-C* represents the amount of change in the core flux produced by this current change. The longer the vertical line (*B-C*) for a particular line length *A-C*, the greater the amount of flux change for the particular current variation, and hence the greater the inductance.

► Now let's suppose that the d.c. cur-

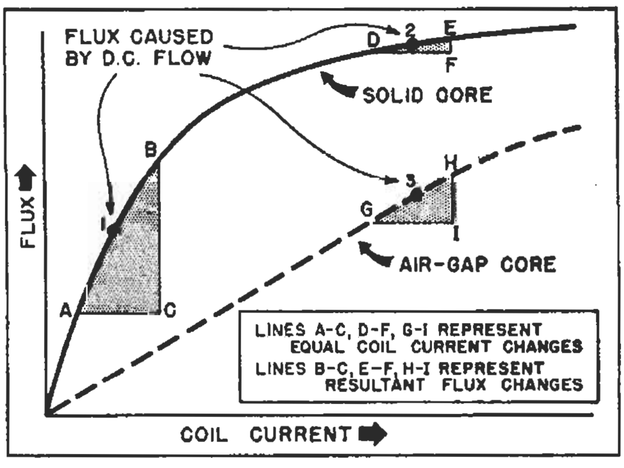


FIG. 7. An air gap reduces the inductance somewhat, but, as a compensation, a magnetic circuit containing an air gap undergoes less change in inductance with d.c. variations; also, a higher current can be applied before saturation occurs. The dotted curve applies to the air-gap core.

rent flow is much greater than that for point *1*, so that it produces the coil flux represented by point *2*, up in the saturation region of the curve. Let's suppose we have the same amount of a.c. The a.c. will now vary the core flux from point *D* to point *E* on the curve. That is, if we draw horizontal and vertical lines as before, we find that the line *D-F* is the same length as the line *A-C*, so it represents the same amount of a.c. variation. However, when we compare the length of the line *E-F* with the line *B-C*, we find that the *E-F* line is very much shorter. You remember that this vertical line represents the amount of flux change caused by the a.c. Therefore, the increased d.c. flow has, by almost saturating the core, reduced the amount of core flux *change* that the a.c. can cause. And, since the inductance of the coil depends on the amount of flux change that the a.c. causes, the inductance of the coil has decreased.

► Naturally, we would prefer to operate at point *1*, where the coil has its greatest inductance. Unfortunately, the d.c. current in most radio circuits either changes considerably from time to time or is much too large to permit operation at the desired point. Either condition is bad: the first will give us an inductance that varies over a wide range; the second, an inductance that is too low. Therefore, we introduce an air gap into the core to minimize saturation effects, even though we thereby sacrifice some inductance.

► The air gap, as we said, reduces the amount of flux in the core for a given amount of current. This changes the shape of the current-flux curve. For example, an air gap introduced into the core for which the solid-line curve of Fig. *7* is drawn may produce the current-flux curve shown as a *dotted line* in Fig. *7*. Notice—this curve is much more nearly linear (straight) than the solid-line curve that represents the current-flux relationship in a solid core. This means that we will approach the ideal condition far more closely when we operate along the dotted curve, for equal changes in coil current will produce approximately equal changes in flux as long as the d.c. does not cause operation beyond the straight portion of the curve. Since this curve has a longer straight portion, a much higher value of d.c. is permitted.

Let's use these curves to compare the inductance of the air-gap coil with that of the solid-core coil. Say we send through the air-gap coil the same amount of d.c. that caused operation at point *2* on the solid curve. As you see from Fig. *7*, this amount of d.c. produces operation at point *3* on the dotted (air-gap) curve. If we use the same size a.c. current variation (*G-I*) that we used for operation on the solid curve, we produce a flux variation *H-I*. This flux variation is considerably greater than the flux variation *E-F* produced by the same current variation at point *2* on the solid curve. Therefore, our air-gap coil has a greater inductance than the solid-core coil has when this amount of d.c. flows through it.

However, the flux change *B-C* produced in the solid-core coil when operated at point *1* is considerably larger than the flux change produced in the air-gap coil by an equal current change. The air-gap coil, then, has less inductance than the solid-core coil when the latter is operated at point *1*. In other words, a solid-core choke may have more or less inductance than a similar choke using an air-gap core, depending upon the amount of d.c. sent through the coil. On the other hand, the air-gap choke will have a fairly constant inductance even with wide variations in the d.c. going through it.

It is quite important that the air gap remain exactly as designed. The space cut into the laminations may be very small. To prevent changes in air-gap spacing, it usually is filled with some non-magnetic material, such as copper or brass strips, cardboard, or paper.

► Even with an air gap, it is possible to saturate the core and reduce the inductance of the coil if we allow enough d.c. to flow through it. For this reason, a normal d.c. flow (often called the *polarizing current*) is specified for chokes by the manufacturer. This flow cannot be exceeded much if the rated inductance of the choke is to be secured. Incidentally, if the d.c. flow is *less* than the specified value, the inductance will be *greater* than its rated value. When speaking of the inductance of an iron-core coil, always remember that this value is obtained only at a specified current value.

► Since a choke coil is always operated on a.c. or on pulsating d.c. (a combination of a.c. and d.c.), it has all the iron-core losses we have previously discussed. It must be designed to keep hysteresis and eddy current losses low, because it wastes power otherwise. This power produces considerable heat, which may eventually damage the insulation on the coil wire and ruin the choke.

Swinging Choke. While most choke coils are designed with an air gap of sufficient size to avoid saturation within their normal operating current ranges, there is a special type that deliberately uses saturation to *obtain* a change in inductance. Since the inductance varies or "swings" with changes in d.c. flow, it is called a *swinging choke*.

We won't go into details of the operation of this choke here, as you will find it fully described in later lessons on power supplies. Briefly, it is used as a kind of voltage regulator in power supplies, it changes in inductance (and therefore in reactance) when the current drawn from the power supply varies, and this changed reactance acts to keep the output voltage of the power supply fairly constant.

This choke is made with a very small, carefully chosen air gap, and is designed for a particular *range* of current values.

Iron-Core Transformer Fundamentals

The ability of a varying magnetic field to induce a voltage in any conductor with which it links makes it possible to transfer power from one circuit to another without direct wire connections. Furthermore, by arranging the linkage properly, we can get a step-up or step-down of voltage and can match impedances.

► Suppose we have a coil so placed that the varying magnetic field produced by another coil links with it. A voltage is induced in the first coil, the amount depending on the flux linkage. This, in turn, depends on the amount of varying flux and on the number of turns of wire on the first coil. (For convenience, the winding connected to the *source* is called the primary, while the other winding, inductively linked to the **primary**, is called the *secondary*.)

The amount of flux is determined by the design of the primary winding and the primary current. Assuming a fixed current and a particular primary design, the flux *linkage* in the secondary depends on the number of turns of the secondary winding and on the coupling. (With an iron core, the coupling usually is close to unity, so we can assume perfect coupling for now). The more turns, the greater the flux linkage and the greater the voltage induced in the secondary. We can make the secondary voltage higher or lower than the primary voltage by choosing the proper number of turns for the secondary winding. There is, in fact, a very simple relationship between these two voltages:

The ratio of primary to secondary voltage is the same as the ratio of the turns on these windings.

► Let us take as an example a transformer, having no losses, with 100 turns of wire in its primary. The secondary of this transformer has 300 turns of wire on it. The ratio of turns on the primary to the turns on the secondary is 1-to-3 (100-to-300), so for every volt applied to the primary there will be three volts from the secondary. Thus, the voltage supplied by the secondary will be three times that fed into the primary. If we apply 10 volts to the primary, the secondary will supply 30 volts. If the primary voltage is 110 volts, the secondary voltage will be 330 volts. This is known as a "step-up" transformer, because the transformer steps up, or increases, the voltage.

(In a practical transformer, there would be many more than 100 turns on the primary and 300 turns on the secondary. However, the *ratio* of the turns may be 1 to 3. The actual number of primary turns depends on the intended use. In selecting the number of turns, the primary voltage and frequency, the type of circuit, the size of the core, and the secondary voltage and current requirements must all be considered.)

► This action can be reversed by using fewer turns on the secondary than on the primary. If our transformer has 10 turns on the secondary and 100 turns on the primary, the ratio of primary turns to secondary turns is 10-to-1 (100-to-10). The secondary, having fewer turns than the primary, will have a lower voltage; in fact, the secondary output voltage will be one-tenth the voltage applied to the primary. Therefore, if we apply 10 volts to the primary we will get 1 volt from the secondary, while 110 volts fed into the primary will give an 11-volt output from the secondary. Such a transformer is known as a "step-down" transformer, because it steps down, or reduces, the applied voltage.

Thus, a transformer can deliver a higher or a lower voltage from a source to another circuit.

► Here is a practical hint about turns ratios. It is common practice to give the ratio with the larger number first, then to state whether it is a step-up or a step-down ratio. For example, a transformer rated as a 5-to-1 *step-up* type delivers 5 times the primary voltage from the secondary, while a 5-to-1 *step-down* transformer delivers 1/5 the primary voltage from its secondary.

POWER TRANSFER

The relationship between primary voltage and secondary voltage is only one of the things you need to know to understand transformer action. We will now show that the relationship between primary and secondary *cur-*

rents is equally as important.

A transformer must always be considered as a *power* transferring device. Hence, the current flow in the primary winding depends on the power taken by the load. We'll use the circuit in Fig. 8 as an example. Here we have a 5-to-1 step-up transformer, which raises the 10-volt source value to 50 volts across R. Let us suppose R has a value of 25 ohms. The secondary current I_S will be 2 amperes ($I_S = E_S \div R$), and the power dissipated will be 100 watts ($P = I_S \times E_S = 2 \times 50$).

To supply the load, the transformer primary must draw enough current to take 100 watts from the 10-volt source. Hence, the primary current I_P must be 10 amperes ($I_P = P \div E_P = 100 \div 10$).

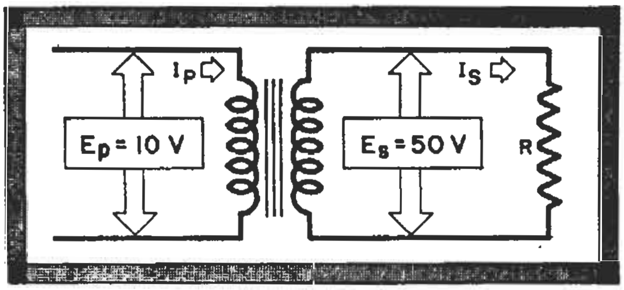


FIG. 8. A step-up transformer.

Compare the primary voltage and current with the secondary voltage and current. The *voltage* is stepped-up from 10 volts to 50 volts, a step-up ratio of 5-to-1. On the other hand, the *current* is stepped-down from 10 amps. to 2 amps., which is a step-*down* ratio of 1-to-5.

► Similarly, when we have a step-down transformer, the secondary voltage is less than that of the primary, but the secondary current is greater. For example, suppose we apply 110 volts to the primary of a 10-to-1 step-down transformer; the secondary delivers 11 volts ($110 \div 10$). Say the secondary power demand is 550 watts; the secondary current will be:

$I_S = P \div E_S = 550 \div 11 = 50$ amperes.

Then, the primary current will be:

$I_P = P \div E_P = 550 \div 110 = 5$ amperes.

Thus, the voltage goes down from 110 to 11 volts (10-to-1) while the current comes up from 5 to 50 amperes (1-to-10).

► These facts are true because a transformer must transfer *power* from one circuit to another, and *it takes from the source the amount of power required by the load.*

The *name* of the transformer (step-up or step-down) comes from what happens to the *voltage*—not to the current. Thus: if the *secondary voltage is higher than the primary voltage*, the transformer is a *step-up* type; if the *secondary voltage is lower than the primary voltage*, the transformer is a *step-down* type. The CURRENT relationships are opposite; that is, in the step-up transformer, the secondary current is less than the primary current, whereas in a step-down transformer, the secondary current is greater than the primary current. As a summary:

If the voltage is stepped up, the current is stepped down; if the voltage is stepped down, the current is stepped up; and the product of the current and the voltage (current multiplied by the voltage) **is the same for both the primary and the secondary.**

Losses. Of course, we don't actually get a 100% transfer of power. You should keep in mind that there are losses in all transformers caused by eddy currents and hysteresis in the core, which waste power in heat. Also, there are losses in the coils caused by the flow of current through the resistance of the windings. You may see this loss referred to as I^2R loss or "copper" loss. This also takes the form of heat, and varies as the load is varied: the greater the load, the greater the power loss.

► These losses explain why 100% transfer of power from the primary to the secondary cannot be obtained. Actually, the primary source must furnish more power than is taken by the secondary load, because it must supply a total power equal to the load demand plus the losses. As a result, the ratio of primary to secondary currents will not be *exactly* in the ratio of the turns. However, in practice, you can assume the ratios to be nearly correct, as power transfers of 95% to 97% are obtainable in iron-core devices.

Although a 3% to 5% loss seems small, it does limit the amount of power we can transfer through the transformer. The power dissipated in heat increases greatly as the load is increased, so that eventually a point is reached at which the transformer becomes overheated and subject to breakdown. Power transformers are rated according to power-handling ability as well as to voltages and currents delivered. The larger the wire used for the windings (to reduce resistance) and the larger the iron core (to reduce hysteresis and eddy current losses), the more power a transformer can handle before breakdown occurs. This is why transformers having high power ratings are so large and heavy. The weight of a transformer is a good indication of its power-handling ability.

POWER TRANSFORMERS

The power transformer in a radio receiver is an excellent example of both step-up and step-down transformer actions.

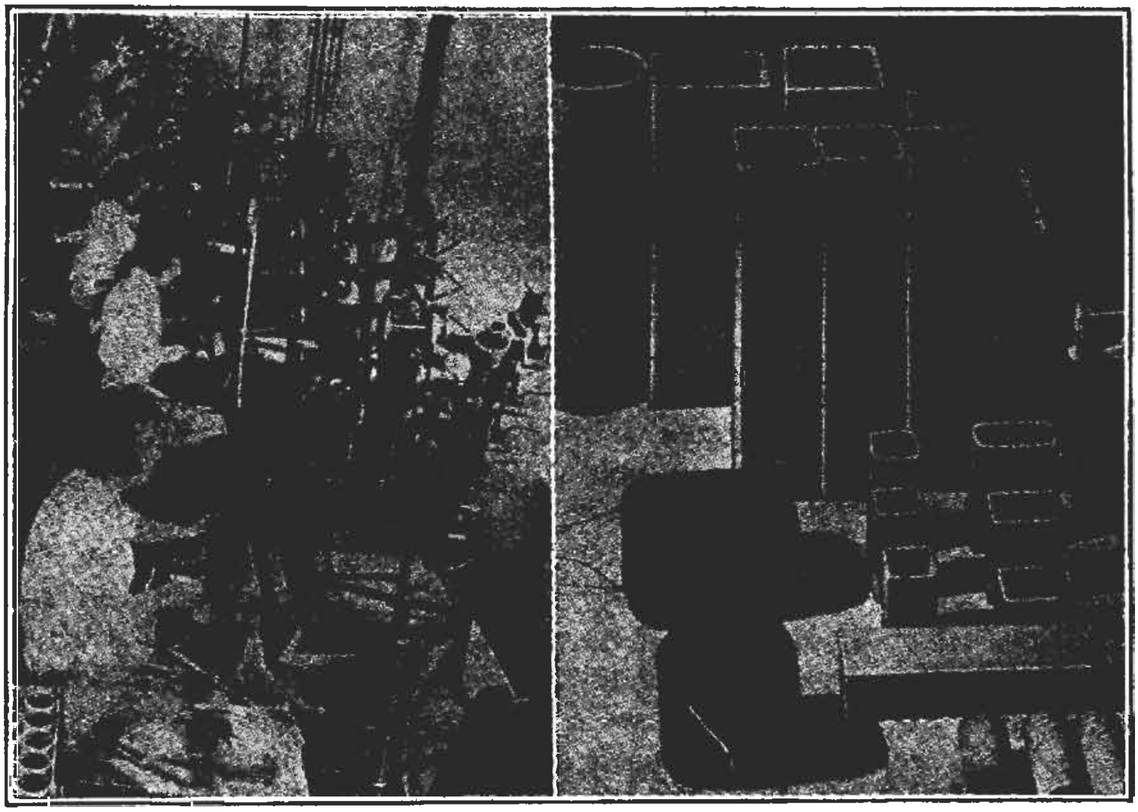
Homes in this country usually are wired so that power outlets deliver 110 to 115 volts a.c. It is highly desirable to obtain all voltages required for a radio receiver from this power line; this means that we must have low a.c. voltages for the filaments and heaters of the tubes, and high a.c. voltages that can be converted into high d.c. voltages for the various tube electrodes. The line voltage value must be stepped-down (decreased) in one case and stepped-up (increased) in the other case. A single power transformer is used for this purpose.

While we won't go into the design of a power transformer, it is interesting to know that the engineer considers many factors. Cost, weight, and efficiency are of particular importance. He must choose first a suitable core material, and then must choose a core size that will give him the required characteristics in a minimum of space and weight. There must be a compromise between core characteristics and the number of primary turns. For example, when a transformer is not loaded (nothing is connected to its secondary winding) the flux changes in the core must induce a back e.m.f. in the primary nearly equal to the applied voltage. Otherwise, the primary current (which depends on the difference between the applied voltage and the back e.m.f.) would be excessive. For a given flux density in the core, a given core area, and power line frequency, the back e.m.f. will depend on the turns on the primary.

Therefore, the designer must make a compromise. If he increases the core size, the number of turns in the primary can be made less, but the cost of the transformer, its size, and its weight all increase. Increasing the turns reduces the required core size, but there is a minimum core size too —if the core is too small, saturation may occur before the required flux density is produced.

After selecting a core, the designer computes the number of primary turns that will allow only enough primary current to flow to keep the flux density in the core at the desired value when no load is on the secondary. He then divides this number of turns by the applied line voltage to find the *turns-per-volt ratio* of the primary. For example, he may find that he has wound 575 turns in his primary winding for a line voltage of 115 volts. Dividing 575 by 115, he finds that he has five turns on the primary for each volt applied to the primary winding.

After finding this ratio for the primary, the number of turns required on the secondary winding to secure a certain voltage can be determined by multiplying this desired voltage by the turns-per-volt ratio of the primary. For example, if the primary has a ratio of 10 turns-per-volt, and 500 volts is desired from the secondary winding, the secondary winding will require 500 times 10, or 5000 turns. The turns-per-volt ratio of a power transformer varies considerably with the design of the transformer, since, as we have indicated, it depends on the size of the core, the core ma-



Courtesy Universal Winding Co.

At the left—this view shows the automatic coil-winding machinery used in the manufacture of chokes and transformers. Six or more coils are wound on a single spiral-wrapped paper form like one of those shown at the right; when winding is completed and the operator has anchored the lead wires, the machine automatically cuts the coils apart. Operators perform only the starting and finishing operations; the machines do the rest, placing layers of insulating paper between each layer of a winding and stopping automatically when the correct number of turns has been wound. Samples of finished coils produced by machines like these can be seen in the foreground in the right-hand photo. The iron core is stacked inside the coil (or coils) to complete the unit. Then, the choke or transformer may be dipped in a moisture-excluding sealing compound and may be enclosed in an iron shield can.

terial, the power line frequency, and the desired flux density.

Turns Ratio. Although designers of power transformers think in terms of turns-per-volt, you will undoubtedly follow the practice of other transformer users and think of power transformers only in terms of what they can deliver. In other words, you are interested solely in the voltages that may be obtained from each secondary and in the respective current ratings of the secondary windings.

As you know, the output voltage is dependent upon the turns ratio—how many times more turns there are on one winding than on another. The turns ratio times the primary voltage will give you the secondary voltage (provided, of course, you know whether you have a step-up or step-down transformer action in that particular winding). Remember, there will be a different turns ratio for each secondary delivering a different voltage.

► Should it ever prove necessary, you can measure the turns ratio of a power transformer by connecting it to an a.c. source of known value and measuring the voltage across each winding. The larger voltage divided by the smaller voltage gives you the turns ratio. The winding giving the higher voltage will have the more turns of wire.

► *A word of caution*—before you connect a power transformer to a voltage source, be sure that the windings will handle that voltage safely, and be sure the frequency of the power source is correct for the power transformer. Otherwise, the current flow may be excessive and the transformer may heat up so much it will be seriously damaged. (You can connect a winding to a source producing a voltage *lower* than its rated value, but never to a voltage source that is considerably higher than its rated voltage.)

Therefore, the first thing you always want to know about a transformer is its primary voltage rating and the frequency for which it is intended. The operating voltages for a power transformer are given by the manufacturer. Most American power transformers are designed for use on 110-115 volt a.c. power lines, though some are designed for 220-230 volt power lines. (You are most apt to find these latter in sets intended for export to foreign countries, where these power line voltages are more common.) Occasionally, too, you may find a transformer especially designed for some unusual power line voltage.

Transformers are usually designed for 25- or 60-cycle operation. Design compromises allow 25-cycle power transformers to operate on 25- and 40-cycle power lines, while 60-cycle transformers will operate on 50- and 60-cycle power lines. However, a 60-cycle transformer will overheat if it is connected to a 25-cycle power line, whereas a 25-cycle power transformer will tend to be overly efficient, giving higher-than-rated output voltages, if connected to a 60-cycle power line.

Never connect a power transformer to a *D.C.* source. On d.c., only the primary *resistance* limits current flow so the current flow is excessive. The transformer is certain to be damaged or destroyed.

► After making sure the transformer will work properly on the available power line, you will next want to know the voltage and current ratings of the various secondaries. When we take up power supplies, you will learn that a number of different secondary *voltages* are required. The values needed depend principally on the operating voltages required by the tubes used in the receiver and on the manner in which the tubes are connected (series or parallel connections between filaments).

Each secondary winding will have its own *current* rating, which is the *maximum* current that can be taken from the winding for long periods of time without overheating the transformer. Of course, less current than this can be drawn if desired. Thus, if a filament winding is rated at 2.5 amperes, it can deliver safely any current value up to 2.5 amperes. The current rating needed depends on the number and types of tubes to be supplied.

It is unnecessary to calculate the power handled by a transformer in a receiver as long as you make sure its individual windings have the proper voltage and current ratings. Remember, though, that when a power transformer has several secondary windings, the primary winding supplies the power required for all of them, plus the power wasted in the eddy current, hysteresis, and I^2R (or copper) losses of the transformer itself.

REQUIREMENTS OF AUDIO-FREQUENCY TRANSFORMERS

A power transformer is designed to work at one frequency—that of the power line for which it is intended. A transformer designed to handle audio frequencies must handle a *band* of frequencies instead of a single frequency, and it is supposed to operate over this band without discrimination—that is, it should deliver a voltage proportional to the turns ratio, regardless of frequency, within its designed range. As you will soon see, these requirements are far more difficult to meet than those imposed on power transformers.

Audio Frequencies. The a.c. voltages handled by audio stages correspond to sound waves, and so have the same frequencies as ordinary sound waves. However, although sound frequencies range from 30 cycles per second to about 20,000 cycles per second, good *voice* reproduction requires only frequencies from about 300 to 3000 cycles, and good musical reproduction requires only frequencies from about 60 to 8000 cycles. Thus, an audio transformer does not have to handle the entire range of sound frequencies. In fact, in ordinary receivers it has to handle only frequencies from about 100 cycles to near 5000 cycles, for cost limitations prevent such receivers from having a wider range. However, even this limited range creates a good many problems. We'll take these up in just a moment, but, before we do, let's see what are the two main types of audio transformers.

► Audio transformers are classified according to whether they are used to give voltage gain or to match impedances. The types designed for voltage gain are called interstage transformers, as they are generally used between two vacuum tube stages. Those intended to handle audio power are usually called impedance-matching transformers. In radio receivers, the most common use for such an audio transformer is to connect the power amplifier tube to the loudspeaker. (It is common practice to call this transformer the output transformer.)

Now, let's take up each type in detail and see what problems they will give you in servicing a receiver.

Interstage Audio Transformers

Interstage transformers are normally designed to have a step-up ratio between the primary and secondary windings, so that there will be a gain in signal voltage. These transformers are connected between the source and some voltage-operated circuit that does not require power, so the secondary current flow is negligible. A typical "load" would be a grid circuit, where only voltage is needed for operation. In effect, then, the secondary winding feeds into an open circuit (or, as radio men say, is not "loaded").

To provide a signal voltage step-up, the interstage transformer should have the highest possible turns ratio. However, the requirements imposed by the wide audio frequency band limits the amount of the turns ratio. Some, at a sacrifice of fidelity, go as high as 5-to-1, but most stay down around 2-to-1 or 3-to-1. Compare this with power transformers, which in high voltage work can easily have a 30-to-1 step-up ratio! Let's see what factors set these limits.

PRIMARY INDUCTANCE

A typical interstage transformer connection is shown in Fig. *9*. Since no power is transferred, the transformer, by itself, could give us a primary to secondary voltage step-up that would be almost constant over a rather wide band of frequencies. However, there are several factors that limit the frequency response of the whole circuit.

One of these is the fact that the a.c. plate voltage (μe_g) of tube VT_1 divides between the a.c. plate resistance r_p of the tube and the reactance of the primary of the transformer. The plate resistance is almost constant at audio frequencies, but the primary winding, since it is an inductance, has a reactance that increases with frequency. Therefore, the proportion of the a.c. plate voltage that appears across the primary depends on the frequency; more appears across it at high frequencies, less at low frequencies. The only way we can keep this from causing serious distortion is to make the reactance of the primary fairly high with respect to the a.c. resistance of the tube at all frequencies for which the system is designed. Then we will always have a reasonable proportion of the signal voltage appearing across the primary. There will be less at low frequencies than at high frequencies, but there will be a fair amount at all frequencies in the design range.

This means that we must have a high-inductance primary—one with many turns. The higher the plate resistance of the tube, the more inductance we need in the primary to make its reactance comparable to the plate resistance. As a practical matter, since the amount of inductance we can have in the primary is limited, we have to use a tube that has a low plate resistance; otherwise, the primary inductance would have to be

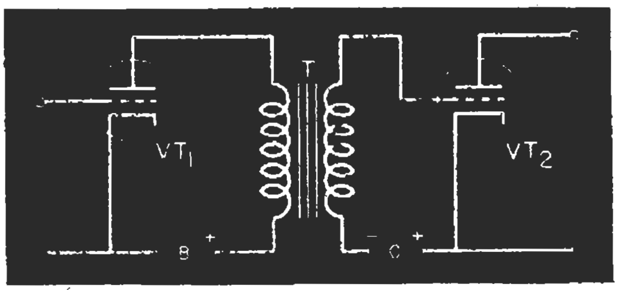


FIG. 9. Typical connections for an interstage transformer.

impossibly large. Generally speaking, only triodes have sufficiently low plate resistances; transformers are used rarely with other tubes.

► The inductance of the primary can be made high by using a large iron core or by using many turns of wire on the primary. However, the use of a large core increases the cost, weight, and size of the transformer greatly. All these factors must be considered in radio equipment, so the necessary high inductance is usually obtained by using a large number of primary turns. There are limits here, too, when voltage gain is desired. If the primary has many turns, a high step-up turns ratio would mean thousands of secondary turns, requiring a great amount of wire and a large core. Thus, a transformer designed to have a good low-frequency response and a high turns ratio at the same time would have to be very large and expensive.

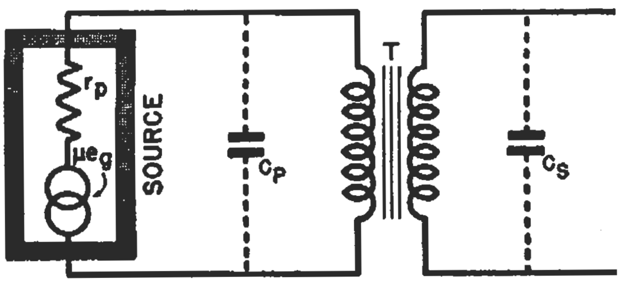


FIG. 10. Notice how the primary distributed capacity C_P acts as a voltage divider with r_P.

DISTRIBUTED CAPACITY

At times, it may seem worth the price to get a transformer with a high turns ratio. But the very fact that there are a large number of turns introduces another factor that limits the frequency range such a transformer can handle.

As you know, a capacity exists between any two conductors that are separated by an insulator. A very tiny capacity exists between the turns of wire on a transformer winding, and a somewhat larger capacity exists between layers of wire when they are wound like thread on a spool. These capacities add up; the more turns and the more layers, the greater the capacity. This winding capacity is called *distributed capacity,* from the manner in which it is distributed throughout the transformer.

The distributed capacities can be lumped together and represented by a single capacity across each transformer winding, as shown in Fig. *10*. In addition, C_P and C_S can be used to represent any stray capacities between the circuit wires, as well as internal tube capacities.

As you can see from Fig. *10,* the primary capacity C_p forms a voltage divider with the plate resistance r_p. The reactance of a capacity goes down as the frequency goes up. Therefore, as higher audio frequencies are fed into the circuit, more and more of the source voltage will be dropped in the plate resistance of the tube instead of appearing across the primary of the transformer *T*. In fact, at very high frequencies, C_P can actually act as a short-circuit across the primary.

► Careful design can remove some of the undesirable effects of C_P. For example, this capacity and the inductance of the primary winding can be so arranged that they form a parallel resonant circuit that has a very high impedance at its resonant frequency. If this is done, practically all the a.c. voltage μe_g that is at or near the resonant frequency will appear across the primary instead of being dropped in the tube resistance. However, at frequencies above this resonant point, the circuit will cut off sharply.

But even the best design cannot eliminate distributed capacity altogether; and, unfortunately, it is always true that attempts to increase the inductance by winding on more turns will increase the distributed capacity also. In other words, we can increase the gain of a transformer only by decreasing its fidelity (its ability to transfer all frequencies equally well). Again, we must compromise. We can have a transformer that has high gain and low fidelity, or low gain and high fidelity, or medium gain and medium fidelity, but we can very seldom get both high gain and high fidelity.

SATURATION

When a transformer primary is connected into the plate circuit of a vacuum tube, we introduce the problem of saturation. The d.c. plate current of the tube must flow through this primary; if this current is too large, it will produce core saturation and reduce the primary inductance greatly. For this reason, the amount of permissible d.c. current flow is specified for each transformer, and the air gap of the core is fixed for this value.

SUMMARY

Obviously, an interstage transformer is carefully designed. You can appreciate why the high-fidelity types are bulky and very expensive—they have to be wound in special ways to control the distributed capacity and get the proper inductance. Even with special design, it is impractical to have a high turns ratio and have a high fidelity response at the same time, because there are limits to the amount of correction that is economical. Therefore, all high-fidelity interstage transformers will have a *low* step-up turns ratio; usually it will be less than 3-to-1.

Today, high-gain tubes are available, and the increased gain from these tubes has made the voltage amplification of the interstage transformer unnecessary. This fact, plus the shortcomings of interstage transformers, have together practically eliminated this style of transformer from the average receiver. Other coupling methods offering higher fidelity are used instead. However, interstage transformers still are used where gain is important; where some special circuit action is desired; and where weight and cost are not vital factors.

► In your work, you will have occasion to replace these transformers as they become defective. Do not put in just *any* replacement; you must choose a transformer having characteristics similar to the original. Fortunately, transformers are standardized to a great extent so it is possible to get a duplicate or an acceptable substitute from the listings of supply catalogs. In these, you will find transformers listed according to the model number of the sets or other equipment in which they can be used; thus, it is easy to select the proper replacement.

Impedance-Matching A. F. Transformers

The entire object of amplification in a radio is to get enough signal power to operate the output device—whether it be a loudspeaker, a relay, a recorder, or something else. As the power needed is relatively small (1 to 20 watts in the average radio), a single power output stage is all that is needed, provided we can amplify the signal voltage enough to operate this output stage. For this reason, voltage amplifiers are used ahead of the output stage to deliver to it the required grid voltage. (The output *stage* may use two tubes, as you will learn later, but only one *stage* of power amplification is common today.)

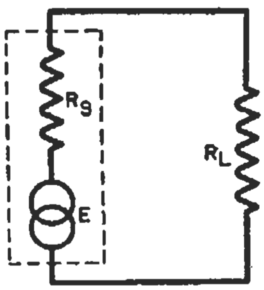


FIG. 11. This basic circuit is used to prove the necessity for impedance matching when the maximum power output is wanted.

► In the power stage, a reasonable efficiency must be obtained so that the output actually delivered will be sufficiently large without requiring too much B-supply power. We can get the greatest transfer of power to the load when the load impedance equals the tube a.c. plate resistance, but it rarely happens that the actual load (the loudspeaker in a receiver) comes anywhere near the tube plate resistance value. However, we can use an impedance-matching transformer to make the two values *appear* alike so that the maximum power output can be obtained.

► Before we learn how this is done, let's review the need for impedance matching by considering a few examples.

Suppose we have the circuit shown in Fig. *11*, where the source resistance is R_S and the load is R_L. Let's assume that E is 12 volts and R_S is 2 ohms, then let us vary R_L.

Case 1. First, let's make R_L equal 1 ohm. Then:

$$I = \frac{E}{R_S + R_L} = \frac{12}{2+1} = \frac{12}{3} = 4 \text{ amps.}$$

The voltage across R_L is then:

$$E_{RL} = I \times R_L = 4 \times 1 = 4 \text{ volts.}$$

Now, the power developed in R_L is:

$$P_{RL} = I \times E_{RL} = 4 \times 4 = 16 \text{ watts.}$$

Thus, when R_L is 1 ohm, 16 watts will be delivered to it under the assumed conditions.

Case 2. Let us now make R_L equal 2 ohms and go through the same procedure to find the power output.

$$I = \frac{E}{R_S + R_L} = \frac{12}{2+2} = \frac{12}{4} = 3 \text{ amps.}$$

$$E_{RL} = I \times R_L = 3 \times 2 = 6 \text{ volts.}$$

$$P_{RL} = I \times E_{RL} = 3 \times 6 = 18 \text{ watts.}$$

This is more power than that of Case 1.

Case 3. Let us now make R_L equal 3 ohms and find the power output.

$$I = \frac{E}{R_S + R_L} = \frac{12}{2+3} = \frac{12}{5} = 2.4 \text{ amps.}$$

$$E_{RL} = I \times R_L = 2.4 \times 3 = 7.2 \text{ volts.}$$

$$P_{RL} = I \times E_{RL} = 2.4 \times 7.2 = 17.28 \text{ watts.}$$

► We can now compare the three conditions: Case 1 has R_L *less than* R_S; Case 2 has R_L *equal to* R_S; and Case 3 has R_L *greater than* R_S. The circuit current drops as R_L is increased, while the voltage across R_L rises as R_L is increased, as we would expect. Notice the *power,* however. It is *greatest* when R_L equals R_S, and is less than this *maximum* if R_L is made *either larger or smaller*. Thus, we get a rule: **The maximum power output is obtained when the source and load impedances are matched or equal.**

As a further example of the need for matching, suppose we have a circuit like that shown in Fig. *12A*, with a load connected directly into the plate circuit of a tube. When this circuit is drawn in the equivalent form

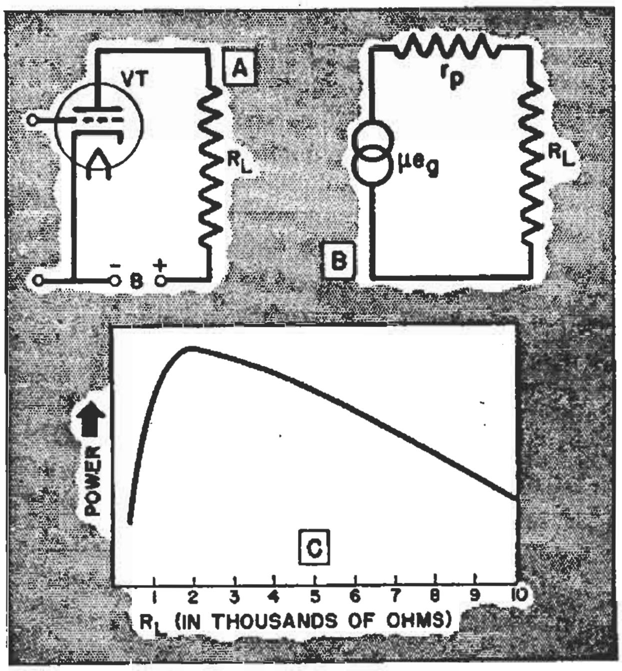


FIG. 12. When the load equals the 2000-ohm plate resistance, maximum power output is obtained.

shown in Fig. *12B*, R_L represents the load resistance, the generator μe_g represents the a.c. plate signal voltage, and r_p represents the plate resistance of the tube. Let us suppose r_p equals 2000 ohms and that R_L is variable, and let's see how the power absorbed by R_L varies as its resistance is increased from, say, 500 ohms to 10,000 ohms.

The curve in Fig. *12C* shows the power developed across the load under these conditions. Notice again that the maximum power is developed when the load resistance and the plate resistance of the tube are equal (or *matched*). If they are not exactly equal, considerable power still will be developed across the load—but if they are far different, particularly if the load resistance is much less than the plate resistance, then the power developed across the load will be reduced greatly.

► This at once introduces a problem, as the load is rarely equal to the source value in radio circuits. For example, suppose we have the following problem: A triode output tube having a plate impedance of 6400 ohms is to supply power to a 4-ohm speaker voice coil. Obviously, from what you've just learned, these impedances are so poorly matched that very little power will be developed across the speaker coil. We can, however, apply maximum power to the speaker if we couple it to the tube through an impedance-matching transformer.

To see why a transformer can match (that is, equalize) impedances, let us go back to the previously explained power transfer effect of a transformer. Let us suppose the 4-ohm voice coil has 1 ampere of current flowing through it. Its voltage will then be 4 volts and the power it absorbs will be 4 watts. The primary of the impedance-matching transformer must take this power from the source.

Turning now to the tube, we can assume that its a.c. plate voltage will be high. In fact, taking a typical example, the a.c. grid voltage e_g may well be as much as 30 volts, so if the tube μ is 6, there could be as much as 180 volts (30×6) in the plate circuit. Clearly, we need a step-down transformer, as the load only requires 4 volts.

Let's assume we have a step-down transformer with a ratio of 40 to 1.

(A step-down transformer can have a far larger turns ratio than a step-up type as it requires *fewer* secondary turns—not more.) As you know, the ratio of primary to secondary voltage depends on the turns ratio, so, with a 40-to-1 transformer and a requirement of 4 volts across the secondary, the primary voltage must be at least 4 × 40, or 160 volts. Under this condition, the load is absorbing 4 watts (at least) from the source. We can now find the primary current ($I_p = P \div E$). This gives us $4 \div 160$, or .025 ampere.

► Now, knowing the voltage across the primary and the current that must pass, we can find the primary impedance. From Ohm's Law, $Z = E_P \div I_P = 160 \div .025 = 6400$ ohms. At the beginning, we assumed a tube impedance of 6400 ohms, so the tube and the effective primary value are matched or equal. Thus, when the connections are as shown in Fig. *13*, the tube "sees" the 4-ohm loudspeaker through a 40-to-1 transformer as a load of 6400 ohms, so it delivers the maximum power to the transformer for transfer to the speaker.

► Of course, we assumed the proper transformer in our example. If we use some other turns ratio or a different load value, we will have a different primary matching value. Thus, if we use a 30-to-1 transformer with a 4-ohm voice coil, we would have a primary impedance of 3600 ohms, while a 6-ohm voice coil with the 40-to-1 transformer would offer an impedance of 9600 ohms to the tube. Thus, regardless of the tube's plate impedance or the load impedance, they can be matched if a transformer of the correct turns ratio is selected.

► In your service work, you won't have to figure the turns ratio needed to match a tube to a load, as the manufacturers list transformers for the tubes and speakers (or other loads) with which they will work properly. You can find the proper replacement transformer just by looking up the right tube and load. However, if you are interested in figures, the footnote * below gives the method of calculating the turns ratio.

Radio men often call the effective impedance of a primary when a load is connected to the secondary the "reflected impedance" of the load. Thus, in our example, the 4-ohm load caused the primary of a 40-to-1 transformer to have an effective impedance of

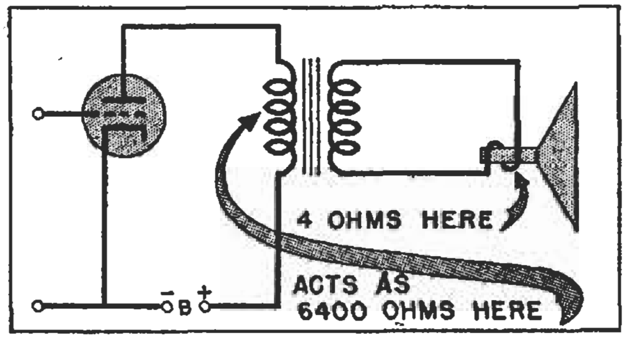


FIG. 13. The impedance-matching transformer causes the load to act in its primary circuit as the required impedance value.

6400 ohms. This 6400-ohm figure is called the "reflected impedance" of

* Dividing the source impedance by the load impedance gives a number that is the same as that found by multiplying the turns ratio by itself. That is, $N \times N$, or $N^2 = Z_A \div Z_L$. From this, the turns ratio is equal to the square root of the result of dividing the source impedance by the load impedance. Expressed as a formula:

$$N = \sqrt{\frac{Z_A}{Z_L}} \quad \text{where}$$

Z_A is the source impedance (connected to the primary), Z_L is the load impedance (connected to the secondary), and N is the ratio of primary-to-secondary turns.
Using the figures of our example, we have:

$$\sqrt{\frac{6400}{4}} = \sqrt{1600} = 40, \text{ so}$$

the 40-to-1 ratio is the proper one for this particular tube and speaker.

the 4-ohm load. It is equal to the load impedance multiplied by the square of the turns ratio.

► As you will learn in another lesson, an exact match of power tube to load will not give the greatest *undistorted* power output. In fact, the maximum *undistorted* power is obtained when a triode tube feeds into a load *twice* its plate impedance, while with a pentode, a value near one-seventh its impedance is the best value. Transformer lists take these facts into consideration; when you select a replacement from a list, it will give maximum undistorted power for the particular tube and load for which it is intended.

FIDELITY FACTORS

The fidelity, or frequency response, of a stage containing an impedance-matching transformer is affected by three factors with which the transformer itself is directly concerned. These are *the design of the primary, flux leakage,* and *distributed capacity.*

PRIMARY INDUCTANCE

High primary inductance is just as important in an impedance-matching transformer as it is in an interstage transformer. This will be easier to understand by referring to Fig. *14,*

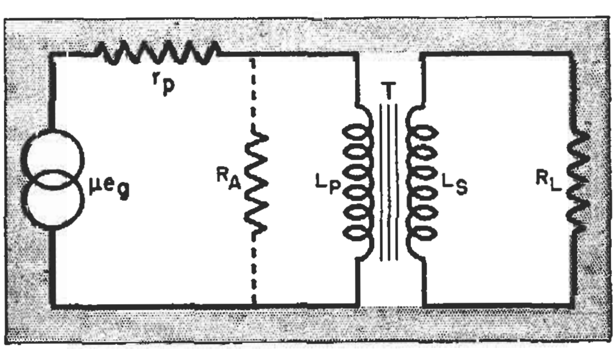


FIG. 14. The load "reflects" in the primary circuit as R_A. The primary winding must have a high reactance at the desired frequencies so that it will not reduce the effective load value.

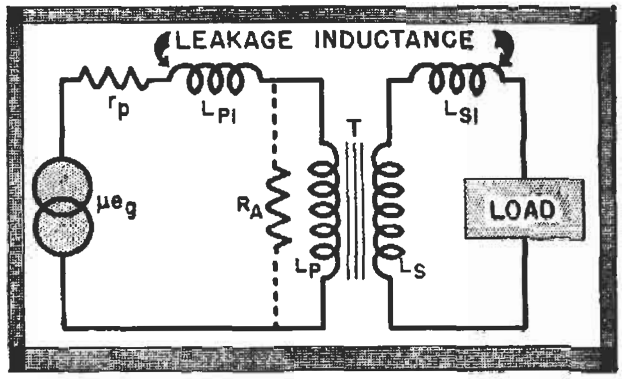


FIG. 15. The turns not used to actually transfer power are represented here as leakage inductances.

which is the equivalent circuit for Fig. *13.* In effect, the transformer "reflects" the value of R_L into the plate circuit as R_A—a value which is equal to R_L times the square of the turns ratio of the transformer.

As you will notice, R_A is effectively in parallel with L_P. When the primary reactance is very high compared to R_A, the parallel combination effectively has the value of R_A, so the tube feeds into the impedance for which the circuit is designed. We then say that the reactance of L_P has "disappeared," because it has no effect on the circuit.

However, as you know, inductive reactance goes down when frequency is decreased. Therefore, at low frequencies, it is quite possible for the reactance of L_P to be a rather low value compared with R_A. When this happens, the effective load is reduced; then the tube a.c. resistance and the load are no longer well matched, and more of the signal energy is lost in r_p.

To prevent this from happening, the primary inductance must be designed to have a reactance that is five to ten times the tube a.c. plate resistance. Then, when the secondary of the transformer is properly loaded, the primary reactance "disappears" even at low frequencies and is replaced by the reflected load R_A.

LEAKAGE INDUCTANCE

The fact that power is transferred in an impedance-matching transformer means that a high primary current flows (compared to that in interstage transformers), and, in turn, this means a higher flux density in the core. This condition tends to produce core saturation, which increases the leakage flux. We have already described leakage flux as the flux taking an air path that fails to link with all (or a part) of a winding. The turns that produce this leakage flux are really not a part of the transformer, for they do not assist the transformer action. We can therefore consider each transformer winding to be made up of two parts, as shown in Fig. *15*. One section of each winding represents the turns actually engaged in producing flux linkage (L_P and L_S), and the other represents the inductance producing the leakage flux (L_{P1} and L_{S1}). The latter are called leakage inductances, and are considered to be in the positions shown in Fig. *15*.

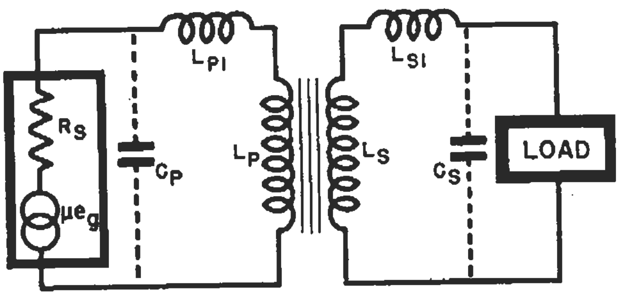


FIG. 16. The distributed capacity C_P can be made to resonate with the primary, which improves the high-frequency response up to the resonant frequency. However, above this point, there is a sharp drop in response.

The reactance of L_{P1} naturally reduces the amount of signal voltage that will be developed across R_A. Furthermore, since the reactance of L_{P1} increases with frequency, the voltage across R_A will decrease as the frequency is increased. In the secondary circuit, the reactance of L_{S1} reduces the voltage applied to the load.

The effects of these two leakage inductances, then, are to reduce the useful signal voltage in the circuit and

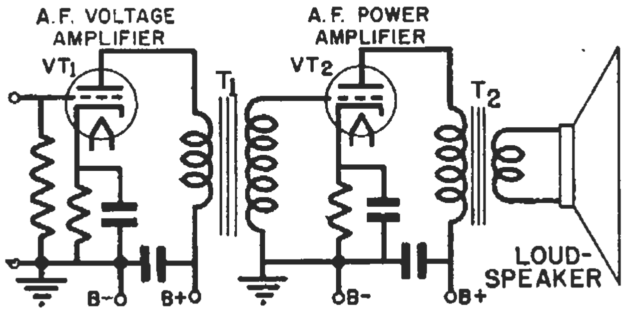


FIG. 17. Both an interstage and an impedance-matching transformer are shown in use here.

also to create distortion (since high-frequency voltages are reduced more than low-frequency voltages).

DISTRIBUTED CAPACITY

An impedance-matching transformer has distributed capacity, just like an interstage transformer. As shown by Fig. *16*, the distributed primary capacity C_P forms a parallel resonant circuit with the primary and its leakage inductance. Similarly, the distributed secondary capacity forms a series resonant circuit with the secondary and its leakage inductance. However, in a step-down transformer with a high turns ratio (which is what most impedance - matching transformers are), secondary leakage inductance and secondary distributed capacity are so small that they can be ignored.

► Sometimes both interstage and impedance-matching transformers are used in the same apparatus. For example, in Fig. *17* transformer T_1 steps up voltage while T_2 matches the loudspeaker voice coil to the plate resistance of VT_2.

Special Transformers—Identifying Types

There are one or two special types of transformers which are of interest. We will introduce them briefly here—their uses will be covered in another lesson.

CENTER-TAPPED TRANSFORMERS

Fig. *18A* shows the polarity that may exist, at a given instant, across the secondary of an ordinary audio transformer.. This polarity will be reversed on alternate half cycles. As there is but one output voltage, technicians say that this is a *single phase* output.

In Fig. *18B,* a center tap has been added to the secondary. The addition of the center tap does not change the voltage induced in the secondary by the primary, but does give us another point from which to measure. Thus, by measuring from this center tap to either of the original secondary terminals, we will get half the total secondary voltage. And notice—when point *A* is negative with respect to point *C,* point *B* will be positive with respect to point *C.* The next instant, the polarities will reverse, but they will remain *opposite* to each other at all times. Thus, if we use the center-tap *C* as a reference point, we can get both a positive and a negative voltage—that is, *two* voltages 180° out of phase with each other—from the transformer *at the same instant of time.*

You will see this principle used many times in radio work. It is used in power supplies to obtain full-wave rectification and in audio amplifiers to drive a push-pull stage (a type of amplifier) from a single tube stage. We will say more about these transformers when we study these stages.

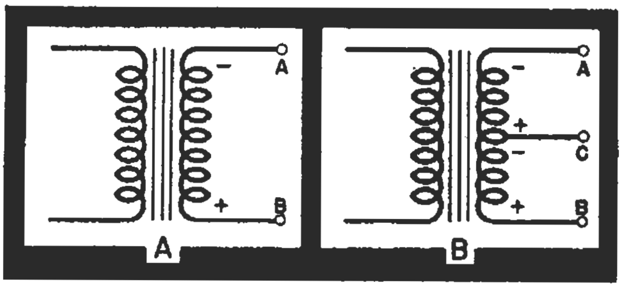


FIG. 18. Many transformers have a center tap on the secondary as at B. This provides a two-phase output that is necessary for the operation of certain radio stages.

AUTO-TRANSFORMERS

The schematic diagram of a special type of transformer known as an *auto transformer* is shown in Fig. *19.* (*Auto* means "self," the name coming from the fact that a single winding is used as a transformer.) You will notice there is a tap on the winding: primary voltage is applied between this tap and one end of the winding, and secondary voltage is taken off between the two ends of the winding. The number of turns in the entire winding divided by the number of turns connected across the input, or primary, terminals gives the voltage step-up ratio of this transformer. An auto-transformer also may be used as a step-down transformer by connecting the source voltage to the ends of the winding and taking the output from the tap on the coil and one end of the winding.

While an auto transformer has certain advantages (principally low cost) to recommend it, there are many circuits in which it cannot be used because of the common connection between the source and the load.

IDENTIFYING IRON-CORE CHOKES AND TRANSFORMERS IN RADIO RECEIVERS

Power Transformers. When the receiver is an a.c. type using a power transformer, you generally can assume that the largest iron-core device is the power transformer, for it must handle all the filament power and the electrode power required by the tubes in the receiver. (However, remember that there are many receivers, principally a.c.-d.c. sets, that do not use a power transformer.)

When you must be sure of your identification, remember that a power transformer has a great many terminals or leads. You will find wires running from it to the filament terminals of each tube socket. You will find two wires running from the power transformer to the plates of the rectifier tube (assuming it is a full-wave rectifier tube). Two more wires will run directly to the line cord, one connecting through the on-off power switch of the receiver.

Power transformers have a primary winding and several secondaries—a high-voltage secondary winding, and one or more filament supply secondary windings. The low-voltage filament supply secondaries will have the *lowest* resistance because they handle high currents. The primary winding will also be low in resistance, but not as low as the filament secondaries, because it has many more turns of wire than they do.

The *high-voltage* secondary winding of a radio receiver power transformer can always be identified with an ohmmeter, for it will have *the highest resistance* of all windings on the core. This winding usually will have a center-tap terminal located between the two outer terminals of the winding; naturally the resistance between this mid-tap and an outer terminal will be *about* half that between the two outer terminals. (While the tap

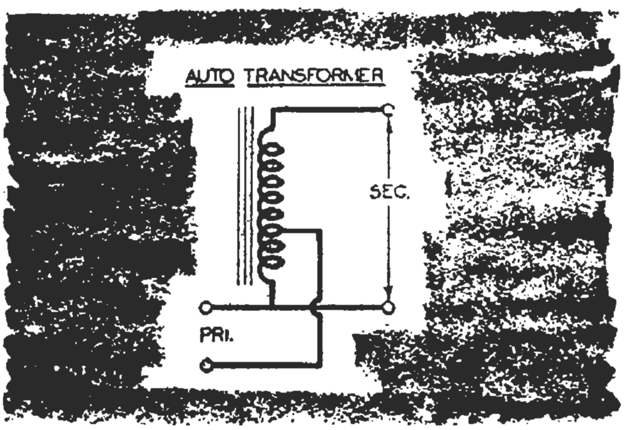


FIG. 19. An auto transformer has a single winding which serves both as the primary and the secondary.

is located so that the number of *turns* on each section of the winding is equal, the half of the winding that is closer to the iron core will use turns of smaller diameter. This requires less wire, so this half of the winding will have a lower resistance than the outer half of the winding.)

Iron-Core Chokes. You can distinguish iron-core chokes from iron-core transformers in radio receivers by counting the terminals (or leads). Iron-core *chokes* will have two or three terminals (or leads), while *transformers* have at least four leads. (Auto transformers may have only three leads, but are seldom found in radio receivers.)

Iron-core chokes used in radio receivers are of two types: those designed to handle a.f. signal currents, and those designed to filter the rectified current in the power pack. Signal current chokes are rare in the average modern receiver, so it is safe to assume any iron-core choke is a filter choke, unless you find a *direct wire* connection from this choke to the grid or plate of a signal circuit tube.

Audio Transformers. Audio transformers are usually the hardest to identify. It is safe to assume that a receiver that uses a dynamic loudspeaker always has an output transformer or impedance-matching transformer between the loudspeaker and the output stage. Generally, this transformer will be mounted on the frame of the loudspeaker, but it may be mounted on the chassis.

Since the impedance of the average loudspeaker is much lower than the a.c. plate resistance of an output tube, a step-down ratio is required in the output transformer. The primary winding therefore will have a much higher resistance than the secondary winding (which connects to the loudspeaker).

Most other a.f. transformers you encounter in receivers will have voltage step-up ratios, and can be identified through their connections to the grids and the plates of amplifier tubes. The primary winding of an interstage audio transformer will have a lower resistance than the secondary winding. Transformers of this type are heavier and usually much larger than output transformers, because of the larger secondary.

► These are merely general suggestions; for further information on a particular receiver, refer to the schematic circuit diagram and service instructions for that receiver.

Looking Ahead. Since you now have mastered the important fundamental features of most of the parts used in radio equipment, and have acquired a good idea of how these parts perform in vacuum tube circuits, you are ready to study in detail the uses for these vacuum tube circuits in radio apparatus. In the next lesson you will find a wealth of interesting and highly practical information on the power supply systems used in radio.

Lesson Questions

Be sure to number your Answer Sheet 11FR-2.

Place your Student Number on *every* Answer Sheet.

***Send in your set of answers for this lesson immediately after you finish them,* as instructed in the Study Schedule. This will give you the greatest possible benefit from our speedy personal grading service.**

1. What is the opposition effect in a magnetic circuit called?
2. What is the *practical unit* of magnetomotive force for **coils**?
3. What condition is said to exist in an iron core when increases in magnetomotive force produce little or no increase in magnetic flux?
4. How can eddy current losses be reduced considerably in low-frequency iron-core devices?
5. Does primary leakage flux induce any voltage in the secondary winding of a transformer?
6. Suppose a circuit uses a *step-down* transformer. Will the primary CURRENT be: *1, the same as; 2, larger than; 3, smaller than* the secondary CURRENT?
7. Would you expect a high-fidelity interstage transformer to have: *1, a high;* or *2, a low* step-up turns ratio?
8. Is the maximum power transferred when the load impedance is: *1, equal to; 2, greater than;* or *3, less than* the source impedance?
9. When checking the various windings of a radio receiver **power** transformer with an ohmmeter, which winding will have the highest resistance?
10. Although the number of turns on the two halves of a high-voltage winding of a power transformer are equal, are the resistances of the two halves exactly the same?