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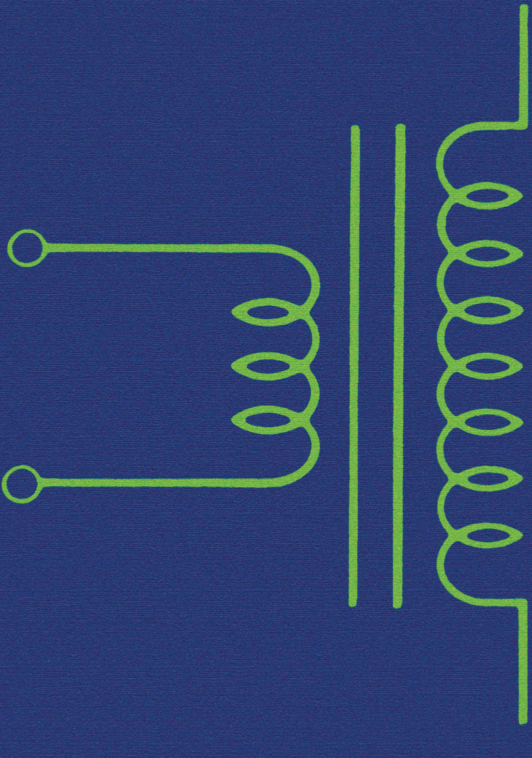
abc's of Transformers & Coils

BY EDWARD J. BUKSTEIN



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TRANSFORMERS
and
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Edward Bukstein

A Revision of
UNDERSTANDING TRANSFORMERS AND COILS
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PREFACE

Transformers and coils are basic components used in practically all electronic apparatus. A knowledge of their characteristics and behavior is therefore a prerequisite to a clear understanding of electronic circuitry. Although there is nothing mysterious about the electrical behavior of transformers and coils, there are many incorrect notions about them, even among experienced technicians.

The purpose of this book is to present the basic concepts in terms that even the beginning student of electronics can easily comprehend. Important mathematical relationships and formulas are presented in the text, but not as a substitute for adequate verbal explanation.

This revised edition of "Understanding Transformers and Coils" has been updated to reflect new developments in core materials and manufacturing techniques. It also contains new sections on toroidal and ferrite-bead inductors, and an added chapter on magnetic core memory and logic.

The author expresses acknowledgement and gratitude to the many manufacturers who supplied illustrative material for this book.

ED BUKSTEIN

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Chapter 1

INDUCTANCE

Although the inductor is one of the simplest of components as far as physical construction is concerned, its electrical behavior and properties may not be entirely obvious to the beginning student of electronics. Even among experienced technicians there may be some mystery as to how (1) a few turns of copper wire can have a current-limiting impedance of thousands of ohms, (2) voltage can appear across an inductor after it has been disconnected from the source, and (3) the voltage across the inductor can be greater than the source voltage. It is the purpose of this book to examine the construction, characteristics, and applications of inductors and transformers, and to show that the "mysterious" properties of these components are easily understood consequences of a few basic principles.

In its basic form, the inductor is simply a coil of wire. The turns may be wound on a core of magnetic material to increase the inductance, or they may be wound on a nonmagnetic coil form that serves no purpose except to provide mechanical support for the windings. If the coil has only a few turns, heavy-gauge wire can be used so that the turns will be self-supporting.

DEFINITION

Inductance is defined as that property of a component or circuit that opposes changes of electron flow. It is this opposition to changing electron flow that retards the build-up and decay of current through an inductor, causes the current to lag the applied voltage, and accounts for the fact that the impedance of the inductor is greater than its d-c resistance.

The inductor opposes changes of current because such changes alter the intensity of the magnetic field. The changing field, in turn, cuts across the turns and induces a voltage of such polarity that it opposes the change that produced it. A sudden increase of current, for example, will generate a counter emf that opposes the supply voltage and therefore opposes the increase in current.

HISTORY

Inductance is an electromagnetic phenomenon. For this reason, the history of inductance is not entirely distinguishable from the history of electromagnetism. Although many experimenters have contributed to our understanding of electromagnetism in general and inductance in particular, three names stand out: Oersted, Faraday, and Henry.

Hans Christian Oersted, a Danish professor of physics, discovered that a magnetic force is produced by a current-carrying conductor. By observing the deflection of a compass needle, he proved that a circular magnetic field is established around the conductor.

In a sense, Professor Oersted and Michael Faraday crossed the same bridge, only in opposite directions. Oersted discovered that an electric current produces a magnetic field; Faraday discovered that magnetism can produce an electric current. Faraday, an English physicist, experimented with two coils of wire and discovered that current could be produced in one of the coils by either starting or stopping the current in the other coil.

Joseph Henry has been referred to as America's Faraday. Faraday is credited with the discovery of mutual inductance, and Henry, with the discovery of self-inductance. In addition to his other experiments, Henry studied the spark discharge from a Leyden jar (an early form of the capacitor) and discovered that the discharge was oscillatory rather than unidirectional. He laid the foundation for the development of radiocommunication by demonstrating that the discharge current through one wire could induce current in another wire at a distance.

CLASSIFICATION

Inductors can be classified in many ways: according to core material (air or iron), frequency (audio or radio), or application (power-supply filter, horizontal-linearity control, peaking coil, etc.). Classification can also be based on the method of winding: single-layer, multi-layer, pancake, and pie sections.

The terms *air core* and *iron core* are employed in a very general sense. An "air-core" inductor, for example, employs a nonmagnetic core (not necessarily air; a tube or rod of ceramic or plastic may be used). Similarly, an "iron-core" coil may employ a magnetic material other than iron.

UNIT OF MEASUREMENT

The unit of measurement of inductance is the henry (in honor of Joseph Henry). A henry (h) is defined as the amount of inductance across which one volt will be induced when the current in it changes at a rate of one ampere per second. Expressed in another way, one henry is the amount of inductance that will have a reactance of 6280 ohms at a frequency of 1000 Hz*.

The millihenry (mh) and microhenry (μh) are subdivisions of the basic unit and are equal to a thousandth and a millionth of a henry respectively. An inductance of 5 henrys is therefore equivalent to 5000 millihenrys or 5,000,000 microhenrys. Inductors commonly employed in electronic circuits range in value from the large "heavyweight" filter choke (typically 5 to 30 henrys) to the small peaking coils used in tv receivers (about 50 to 500 microhenrys).

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*Hz (hertz) = cycles per second.

(*A*) *Air core* (*B*) *Iron Core*

Fig. 1-1. The iron-core coil has more inductance than the air-core coil.

FACTORS DETERMINING INDUCTANCE

What factors determine the inductance of a coil? What are the physical differences between a 5-henry and a 5-microhenry inductor? Inductance is determined primarily by the number of turns and the type of core material, and to a lesser extent by the diameter and spacing of the turns.

The effect of core material on inductance is illustrated in Fig. 1-1. The two coils shown are assumed to have the same number, size, and spacing of turns. As indicated, the coil with the iron core has a greater inductance than the one with an air core. In this example the *permeability* of the iron core is 400 (the coil with this core has 400 times as much inductance as the otherwise equivalent air-core coil).

Fig. 1-2 illustrates the relationship between inductance and the number of turns. The two coils shown are assumed to have identical cores and differ only with respect to the number of turns. For closely spaced turns, the inductance varies approximately with the square of the number of turns. The inductor with twice as many turns therefore has four times as much inductance.

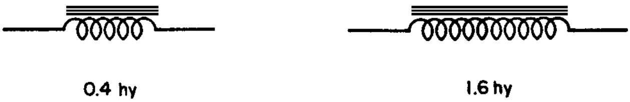


Fig. 1-2. Coil with twice as many turns has four times as much inductance.

Fig. 1-3. Coil with closely spaced turns has greater inductance.

In Fig. 1-3 the coils are assumed to be identical in every respect except for the spacing of the turns. As shown, the one with closely spaced turns has greater inductance.

Chapter 2

THEORY

The characteristics of the inductor can be understood in terms of two basic concepts:

1. *A magnetic field is established around a current-carrying conductor.*

The magnetic lines of force encircle the conductor as shown in Fig. 2-1, and the direction of these lines can be determined by means of the left-hand rule: If the conductor is held in the left hand with the thumb pointing in the direction of electron flow, the fingers will be wrapped around the conductor in the same direction as the magnetic lines of force. If the conductor is wound in the form of a coil as shown in Fig. 2-2, the magnetic fields of the individual turns will combine to form a composite magnetic field. The composite field is such that one end of the coil is a north pole and the other end a south pole (like the field of a bar

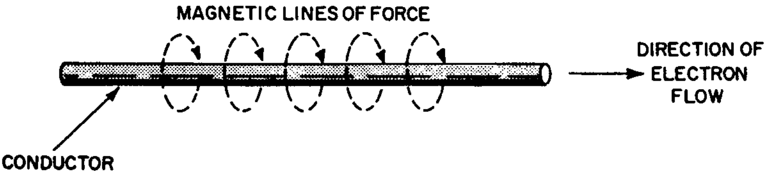


Fig. 2-1. Lines of force encircle current-carrying conductor.

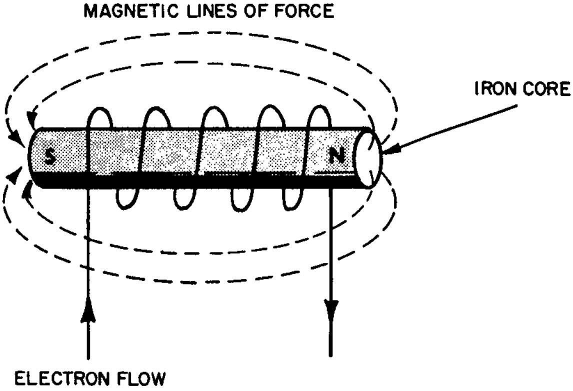


Fig. 2-2. Current-carrying coil generates a field like that of a bar magnet.

magnet). The direction of the magnetic field can be determined by means of another left-hand rule: If the coil is held in the left hand so that the fingers point in the direction of electron flow, the thumb points to the end of the coil that is a north pole.

2. *Voltage is induced in a conductor being cut by a magnetic field.*

In Fig. 2-3, the turns of the coil are cut by the lines of force of the approaching magnet. As a result, voltage is induced in the coil, as indicated by deflection of the meter pointer. If the magnet is now withdrawn from the coil, the turns will again be cut by the magnetic field, and voltage again induced in the coil.

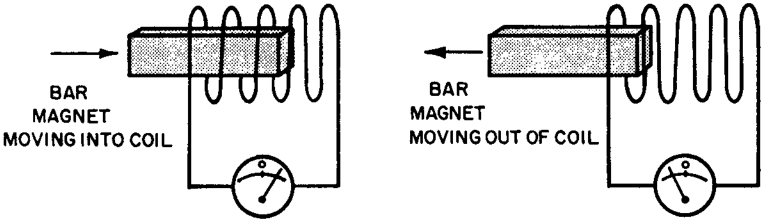


Fig. 2-3. Voltage is induced in coil cut by magnetic lines of force.

This voltage, however, is of opposite polarity to that induced when the magnet was moved *into* the coil. Voltage is induced in the coil only when there is *relative motion* of the field with respect to the coil. The effect is the same whether the magnet is moved and the coil is stationary, or the coil is moved and the magnet is stationary. If both the magnet and the coil are stationary, the turns are not cut by the magnetic field and no voltage is induced in the coil.

The bar magnet in Fig. 2-3 can be replaced by a current-carrying coil (Fig. 2-4). As before, motion of either coil with respect to the other will cause deflection of the meter. The need for mechanical motion can be eliminated by energizing coil L1 with alternating current rather than direct current. This produces an alternating magnetic field that cuts the turns of coil L2. Since the field itself is in motion (alternately expanding and contracting) mechanical motion of the coils is unnecessary. The reader may recognize this as the principle of transformer action.

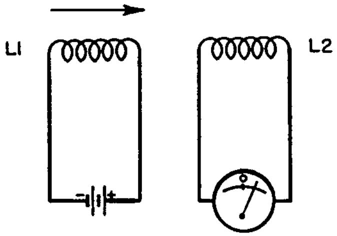
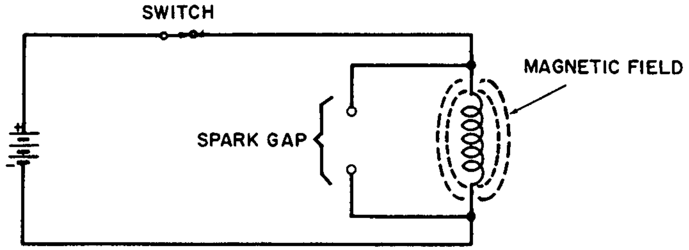


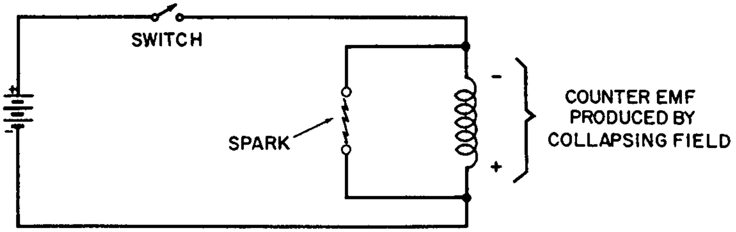
Fig. 2-4. Coil L1 replaces bar magnet of Fig. 2-3.

ENERGY STORAGE

It is well known among technicians that a capacitor can store electrical energy. That an inductor can also store energy is less well known and perhaps less obvious. In the inductor, energy is stored in the magnetic field established by the current. This is illustrated in Fig. 2-5A. If the switch is now opened as in Fig. 2-5B, the magnetic field will collapse and energy will be returned to the circuit. The collapsing field cuts across the turns and induces voltage in the coil. This voltage, the counter emf, produces a spark across the gap. The magnitude of the counter emf is determined by the intensity of the magnetic field, the rate at which it collapses, and the number of turns cut by the collapsing field. Because of the rapid collapse of the field in Fig. 2-5B, the voltage returned to the circuit is greater than the supply voltage. This technique of increasing voltage is employed in various electronic devices. The high voltage required to ionize a fluorescent lamp, for example, is the counter emf induced in the inductor (ballast) when the starter switch opens and allows the field to collapse. A similar technique, using the inductor as an autotransformer, is employed in the high-voltage circuit of the tv receiver. Automotive ignition systems employ the same principle. When the breaker points open, the collapsing field in the spark coil produces the high voltage for the spark-plug gap.



(A) Switch closed.



(B) Switch open.

Fig. 2-5. Energy stored in magnetic field is returned to circuit when field collapses.

The amount of energy stored in the magnetic field of an inductor is specified in joules (a joule is equal to one watt-second):

$$W = \frac{I^2L}{2}$$

where,

W is the stored energy in joules,
I is the current in amperes,
L is the inductance in henrys.

COUNTER EMF

When the current in an inductor changes, the magnetic field changes accordingly and cuts across the turns of the coil. In accordance with Lenz's law, the voltage induced in the coil by the changing magnetic field is of such polarity that it opposes the change of current. A decrease of current in the inductor, for example, produces a counter emf that attempts to increase the current. Conversely, an increase of current in the coil produces a counter emf that tends to limit the current. In a sense, the coil can be regarded as a current-regulator that attempts to maintain the current at a constant value.

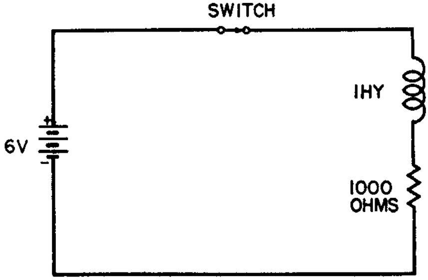
TIME CONSTANT

Although counter emf attempts to prevent changes of current, it does not entirely succeed in doing this. It does, however, increase the length of time required for the current to change. This *time constant* of the inductor is determined by both the inductance and the resistance of the inductor. In Fig. 2-6A, the inductance is one henry and the resistance (including that of the coil) is 1000 ohms. With a 6-volt supply as shown, the final value of current will be:

$$I = \frac{E}{R} = \frac{6}{1000} = 6 \text{ ma}$$

When the switch in this circuit is closed, however, the current cannot instantly rise to 6 ma. The buildup of current (Fig. 2-6B) is gradual rather than sudden because the increasing current produces an expanding magnetic field. The expanding field, in turn, induces a counter emf of opposite polarity with respect to the 6-volt supply. This opposing voltage effectively reduces the supply voltage and therefore limits the rate at which the current increases. As indicated in Fig. 2-6B, the current reaches its final value (approximately) after five time constants.

(A) Circuit.



(B) Current buildup curve.

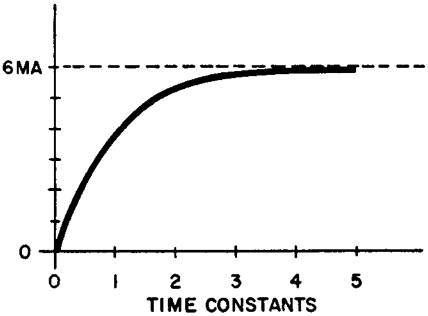


Fig. 2-6. When switch is closed, current rises gradually toward final value of 6 ma.

Numerically, the time constant is equal to the inductance divided by the resistance. The time constant of the circuit in Fig. 2-6A is therefore:

$$T = \frac{L}{R} = \frac{1}{1000} = 1 \text{ millisecond}$$

SELF-INDUCTANCE AND MUTUAL INDUCTANCE

When the current in a coil changes in value, voltage is induced in this coil (*self-inductance*) as well as in any other nearby coil (*mutual inductance*). Two coils possess mutual inductance when the flux of each cuts the turns of the other. The value of mutual inductance therefore depends on the magnetic "closeness" of the coils. This closeness is referred to as the coefficient of coupling and is represented by the letter K. If all flux lines of each coil link the turns of the other coil, the coils are said to be completely coupled and the coefficient of coupling is specified as $K = 1$. Since total coupling can exist only if the coils occupy the same space at the same time, practical values of K are always less than unity.

The mutual inductance of two coils depends on their individual inductances and on the degree of coupling. Mathematically, mutual inductance is expressed by the formula:

$$M = K\sqrt{L_1L_2}$$

where,

M is the mutual inductance in henrys,
K is the coefficient of coupling,
L_1 and L_2 are the individual inductances of the two coils in henrys.

PARALLEL AND SERIES INDUCTORS

Coils connected in parallel have a total inductance less than the value of the smallest inductor. In this respect coils are similar to resistors in parallel, and a similar formula is employed. Assuming there is no coupling between the coils, the total inductance is:

$$L_t = \frac{1}{\frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} + \dots}$$

In practice, coils are rarely connected in parallel to obtain a smaller value of inductance. Cost, size, and weight considerations make it preferable to use a single inductor of the required value.

Coils connected in series are directly additive (if there is no coupling). Four henrys in series with three henrys will therefore produce a total of seven henrys. If the coils are magnetically coupled, however, the total inductance may be either more or less than the sum of the individual inductances—depending on whether the coils are connected aiding or opposing. If the coils are aiding, the total inductance is:

$$L_t = L_1 + L_2 + 2M$$

If the coils are opposing, the total inductance is:

$$L_t = L_1 + L_2 - 2M$$

where,

L_1 and L_2 are the individual inductances in henrys,

M is the mutual inductance (also in henrys) and is equal to $K\sqrt{L_1L_2}$.

INDUCTIVE REACTANCE

Because inductance opposes changes of current, such changes lag the corresponding changes of supply voltage. If the d-c input to an inductive circuit is suddenly changed in value, the current will not reach its new value until a finite length of time after the applied voltage has reached *its* new value. The same is true for an a-c input voltage. In the case of a sine-wave input, for example, the current waveform will also be a sine wave but will lag the voltage sine wave. Each change of current lags the corresponding change of voltage. This is illustrated in Fig. 2-7; also shown is the waveform of the counter emf. Each time the current waveform reaches a peak (either positive or negative), for an instant the current is neither increasing nor decreasing—that is, the *rate of change* of the current is zero. Since the current is not changing, the counter emf at this instant is zero. It is for this reason that the counter emf waveform in Fig. 2-7 passes through zero at those instants when the current waveform is at its peak value. The rate of change of current is most rapid when the current changes direction (passes through zero). At these instants, the counter emf is maximum.

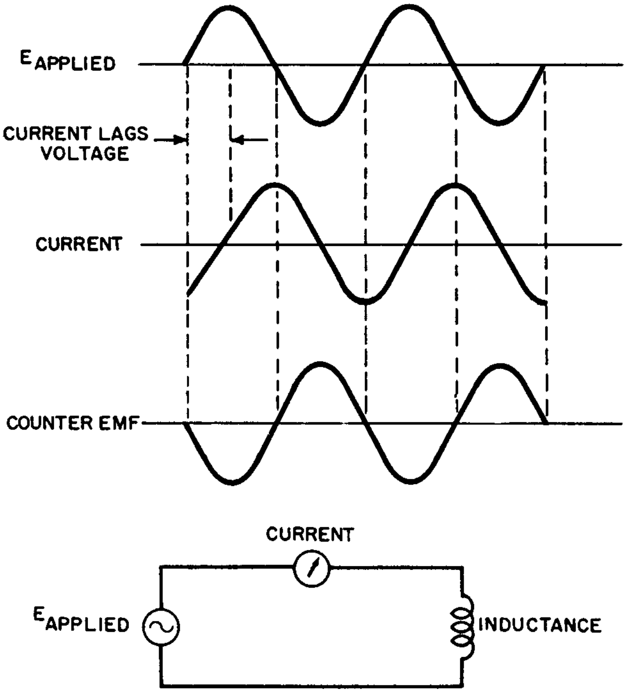


Fig. 2-7. Current lags voltage in inductive circuit.

As indicated in Fig. 2-7, the counter emf is 180° out of phase with the applied voltage. Since the counter emf "bucks" the applied voltage, current is limited to a smaller value than can be accounted for by the resistance of the coil. To the voltage source, the inductance therefore presents a high opposition to current.

This apparent resistance of the coil is known as the *inductive reactance.*

Inductive reactance is specified in ohms and is symbolized by X_L. Because the counter emf is larger if either the inductance or the rate of change of current is increased, the value of the inductive reactance depends on both the inductance of the coil and the frequency of the applied voltage. Numerically, inductive reactance is equal to:

$$X_L = 2\pi fL$$

where,

X_L is the inductive reactance in ohms,
f is the frequency in hertz,
L is the inductance in henrys,
π is a constant equal to 3.14.

A 1-henry inductance at a frequency of 1000 Hz will therefore have a reactance of:

$$\begin{aligned} X_L &= 2\pi fL \\ &= 2 \times 3.14 \times 1000 \times 1 \\ &= 6280 \text{ ohms} \end{aligned}$$

The factor $2\pi f$ is sometimes referred to as the *angular velocity* and is represented by a single symbol ω (Greek letter *omega*). The formula for inductive reactance can therefore be written:

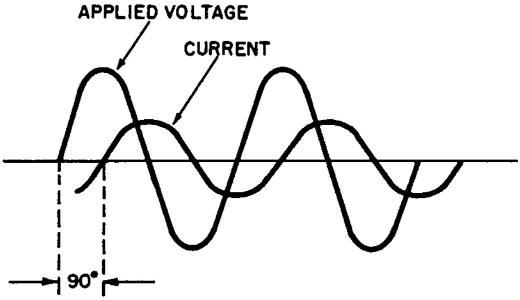
$$X_L = \omega L$$

PHASE RELATIONSHIPS

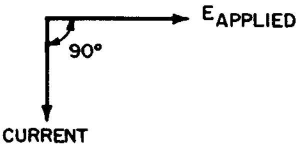
In a purely inductive circuit (one with no resistance) as in Fig. 2-8A, the current lags the applied voltage by 90°. This is illustrated in Fig. 2-8B. Pure inductance can exist only in theory, however; any practical inductor will exhibit some resistance. For this reason, the actual angle by which the current lags will be less than the theoretical maximum of 90° (although the theoretical limit can be approached to within a small fraction of a degree). The phase angle between voltage and current is often represented by a vector diagram as in Fig. 2-8C. Because vectors are assumed to rotate counterclockwise, Fig. 2-8C indicates that current lags voltage.

Since a purely inductive circuit has a phase angle of 90° and a purely resistive circuit has a phase angle of 0° (current in phase with voltage), a circuit containing both inductance and resistance will have a phase angle between 0° and 90°. An increase of resistance, either of the coil itself or any resistance connected in series with it, will therefore decrease the phase

(A) Circuit.



(B) Waveform relationship.



(C) Vector representation.

Fig. 2-8. Phase relationships in pure inductance.

angle. For any given values of R and X_L, the phase angle (θ) can be determined from the relationship:

$$\tan \theta = \frac{X_L}{R}$$

Example: By what angle does current lag applied voltage in a circuit having 3000 ohms of inductive reactance in series with 1000 ohms of resistance?

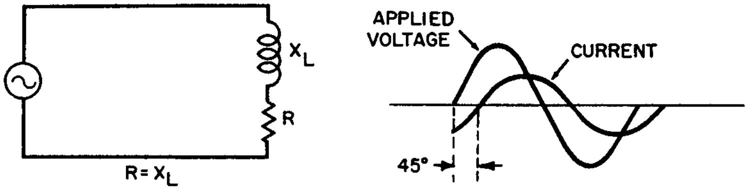
Solution:

$$\tan \theta = \frac{X_L}{R} = \frac{3000}{1000} = 3$$

Since the ratio of X_L to R expresses the tangent of the phase angle, the numerical value of this ratio must be looked up in a table of tangents. Reference to such a table indicates that a tangent of 3 corresponds to an angle of approximately 72°.

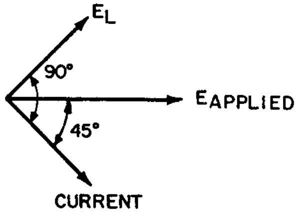
If the resistance of a circuit (Fig. 2-9A) is made equal to the inductive reactance, the tangent of the phase angle will be 1. Reference to a table of tangents indicates that the phase angle is 45°, as illustrated in Fig. 2-9B. Note that the 45° angle is between current and *applied* voltage, not the voltage across the inductor. The voltage across the inductive component (E_L) is always 90° out of phase with the current, as shown in Fig. 2-9C.

Fig. 2-10 illustrates the relationship of the voltages in a circuit containing both inductance and resistance. Here the voltage drop across the resistor (E_R) is assumed to be 30 volts, and the voltage across the inductor (E_L) is assumed to be 40 volts. The applied voltage, however, is *not* 70 volts; voltages E_R and E_L are not directly additive because they are out of phase. These are alternating voltages, and the voltage across R is not 30 volts at the same instant the voltage across L is 40 volts. Since the voltage across R is in phase with the current, and the voltage across L leads the current by 90°, E_R and E_L are 90° out of phase with



(A) Circuit.

(B) Waveform relationship.



(C) Vector representation.

Fig. 2-9. Phase relationship for R = X_L.

each other. For this reason these two voltages must be added vectorially (a useful form for adding quantities at right angles to each other):

$$
\begin{aligned}
E_{applied} &= \sqrt{E_R{}^2 + E_L{}^2} \\
&= \sqrt{30^2 + 40^2} \\
&= \sqrt{900 + 1600} \\
&= \sqrt{2500} \\
&= 50 \text{ volts}
\end{aligned}
$$

This can be compared to driving an automobile 30 miles north and then 40 miles east. At the end of the trip, the automobile is 50 miles (not 70) from its starting point.

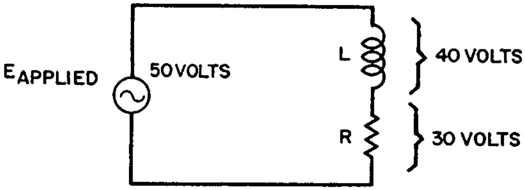


Fig. 2-10. Voltage relationships in circuit containing inductance and resistance.

IMPEDANCE

As shown in the preceding section, E_R and E_L must be added vectorially because they are out of phase. Likewise, the values of resistance and inductive reactance must be added vectorially to determine the total *impedance* of the circuit. A resistance of 80 ohms in series with a reactance of 60 ohms, for example, will not have an impedance of 140 ohms. Impedance Z is equal to the *vector sum* of R and X_L:

$$\begin{aligned} Z &= \sqrt{R^2 + X_L^2} \\ &= \sqrt{80^2 + 60^2} \\ &= \sqrt{6400 + 3600} \\ &= \sqrt{10{,}000} \\ &= 100 \text{ ohms} \end{aligned}$$

If the inductance and resistance are connected in parallel rather than in series, the total impedance will be smaller than either R or X_L (similar to resistors in parallel). As shown in Fig. 2-11, the input voltage is applied across both R and X_L in parallel (the coil resistance is assumed to be so much smaller than the reactance that it can be disregarded). The inductor draws 4 ma of current (100 volts divided by 25K), and the resistor draws 3 ma (100 volts divided by 33.3K). The total current supplied by the source is equal to the sum of these two branch currents. The currents, however, must be added vectorially be-

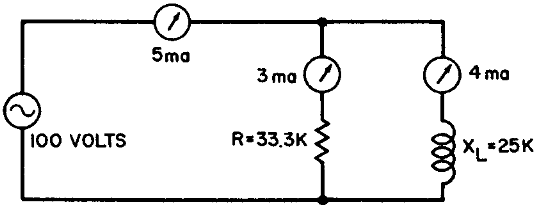


Fig. 2-11. R and X_L in parallel.

cause they are 90° out of phase with each other. The total current therefore is:

$$\begin{aligned} I_t &= \sqrt{3^2 + 4^2} \\ &= \sqrt{9 + 16} \\ &= \sqrt{25} \\ &= 5 \text{ ma} \end{aligned}$$

Since the 100-volt source supplies 5 ma of current, the total impedance (Z_t) of the circuit is 20,000 ohms:

$$Z_t = \frac{E}{I} = \frac{100}{5 \text{ ma}} = 20\text{K}$$

LOSSES AND Q

Pure inductance is only a theoretical concept; it can never be realized in practice. A practical inductor has resistance in addition to its inductance – the resistance of the wire with which it is wound. Current in the coil will therefore produce a power (I^2R) loss in the resistance of the conductor. For this reason a low-resistance coil is preferable for most applications, and the suitability of a given inductor for use in a particular circuit will depend on the resistance of the coil as well as the inductance. Two coils, for example, may have the same inductance but different resistances. The coil having the lesser resistance is of higher *quality,* or Q. This quality can be expressed as a numerical rating equal to the ratio of the inductive reactance to the resistance:

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

Example: A coil in a certain circuit has 3000 ohms of reactance.
If the resistance of the coil is 50 ohms, what is the value of Q?
Solution:

$$Q = \frac{X_L}{R} = \frac{3000}{50} = 60$$

Q is a particularly important factor in communication equipment operated in crowded frequency bands. The selectivity of a receiver, for example, is determined by the *Q* of the coils in its tuning (tank) circuits.

The *Q* of a coil is also affected by the well-known *skin effect.* At high frequencies, current tends to circulate on the surface of a conductor rather than through the interior. This reduces the effective cross-sectional area of the conductor, and the high-frequency resistance of the coil is therefore greater than the value that would be indicated by an ohmmeter.

Litz wire is often utilized for coils designed for use in high-frequency circuits. It is a conductor in which each strand is separately insulated. The combined surface area of these strands is greater than that of a single conductor of corresponding gauge (equivalent to the combined cross-sectional area of all the strands). Another means of compensating for skin effect is the use of hollow tubing instead of a solid conductor. Hollow tubing provides more surface area because it has two surfaces.

Another form of loss that has the same effect as increased coil resistance is *loading.* Assume that a second coil is placed near the first one for the purpose of coupling a signal. The additional coil is now the secondary of a transformer. If a load is connected across it, resistance will be reflected into the primary and will lower the *Q* of this coil.

Still another type of loss occurs in iron-core coils because the core behaves like a shorted single-turn secondary. As a result, the changing magnetic field produced by the coil induces *eddy currents* in the core material. An additional core loss, *hysteresis,* occurs at high frequencies because the core cannot reverse its magnetization as fast as the high-frequency current through the coil reverses polarity.

Chapter 3

CONSTRUCTION

The construction of an inductor is determined largely by the frequency range in which it is to operate. In general, low-frequency inductors have many turns and employ a laminated iron core. High-frequency inductors have fewer turns and employ either an air core, powdered-iron, or ferrite. The stray capacitance between the turns and between the layers of turns is an important factor in high-frequency coils, and special winding configurations may be employed to minimize this capacitance.

Current and voltage considerations also determine the constructional features of an inductor. The gauge of the wire, for example, is selected in accordance with the amount of current the coil must carry. Receiver coils, which normally carry only a few milliamperes of current, are therefore wound from fine wire. Transmitter coils, however, often carry much greater currents and are wound from heavier wire or copper tubing.

The spacing between turns, the insulation of the wire, and the insulation between layers of turns must be adequate to prevent voltage breakdown and arcing. An inductor designed for use in high-voltage circuits will therefore have heavier insulation than one designed for low-voltage applications.

LOW-FREQUENCY INDUCTORS

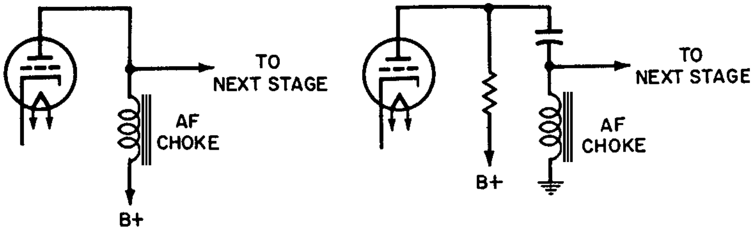
Inductors designed for low-frequency applications are generally large both in inductance and in physical dimensions. Such inductors include filter reactors and audio-frequency chokes. Large inductances are required to produce an appreciable amount of reactance at the relatively low frequencies of operation. These inductors therefore have many turns of wire on an iron core. (The "iron" core is frequently silicon steel to reduce core losses.)

Since core materials possessing suitable magnetic properties are electrically conductive, eddy currents are induced in the core as it is cut by the changing magnetic field of the coil. These currents produce power (I^2R) losses which must ultimately be made up by the source. To minimize such losses, the core is composed of many thin slices, or *laminations,* which are varnished to electrically insulate them from each other. As a result, the eddy currents are confined and cannot circulate from one lamination to another. A higher-resistance pathway is therefore presented to the eddy currents, the magnitude of which is consequently reduced. The result is decreased power losses in the core.

The technique of reducing eddy-current losses by dividing the core into smaller segments accounts for the *powdered-iron* core in some inductors designed for higher frequencies. The magnetic powder is mixed with an insulating binder material so that each magnetic particle is electrically insulated from all others. Widely circulating eddy currents are therefore prevented, and core losses are correspondingly smaller. The magnetic powder and insulating binder substance are molded (usually rod shaped) to fit into the coil. This rod of core material, known as a *slug,* is normally mounted so that it can be moved into or out of the coil, usually by a screw. This permits the inductance to be varied. Resonant circuits are often tuned this way, and the technique is known as *permeability tuning.*

CORE SATURATION

In many applications, the inductor carries a pulsating direct current (with a superimposed a-c component). An example is an inductor connected as a load in the plate circuit of an amplifier tube. The d-c component tends to saturate the core, which re-



(A) Pulsating direct current passes through inductor. *(B) Only alternating current passes through inductor.*

Fig. 3-1. D-c component of plate current saturates core in A but not in shunt-fed circuit B.

duces the inductance because the magnetic field in a saturated core tends to remain nearly constant. Since the constant field does not cut the turns of the inductor, it can no longer produce a counter emf. Core saturation can be prevented by using a capacitor to block the d-c component and allowing only the a-c component to pass through the coil. A shunt pathway, often a resistor, carries the d-c component. Fig. 3-1 illustrates this technique for preventing core saturation in an a-f choke. The same method may be used to prevent core saturation in transformer-coupled audio amplifiers.

Another technique, commonly employed in power-supply filter chokes, is to leave a small air gap in the magnetic pathway of the core. Since air does not saturate, the magnetic flux is limited to a less-than-saturation value.

HIGH-FREQUENCY INDUCTORS

High-frequency inductors such as r-f chokes and tank coils are generally more critical than low-frequency types with respect to core losses and stray capacitance. Laminated iron cores are not used in r-f components because (1) the core losses would be excessive at these high frequencies, and (2) less inductance is required than in low-frequency circuits. High-frequency inductors therefore employ either air cores, powdered-iron slugs, or ferrite cores. Ferrites are high-permeability ceramic materials made of metallic oxides such as iron, nickel, manganese, and zinc. Because of the high resistivity of ferrites, eddy-current losses are relatively small.

Coil forms for r-f applications must be made of "low-leakage" materials. Some substances which are good insulators in low-frequency circuits are poor insulators in high-frequency circuits. Low-loss materials commonly employed for r-f coil forms include mica-*Bakelite,* polystyrene, phenolics, and ceramics. Although paper-tube coil forms are still very popular, there is a strong trend toward the use of plastic forms. The plastic coil form is superior for high-frequency applications, and is easier to manufacture. Staple-on or riveted terminals are required with paper forms; with plastic forms, the terminals are simply embedded in and protrude from the plastic.

The coil may be "packaged" for mechanical and environmental protection. Depending on the application, a coating of lacquer or Durez (a thermosetting plastic) may provide sufficient protection. For high-reliability applications, *molded* or *capsulated* inductors are used. The molded type is similar in appearance to an ordinary resistor. In fact, some types have color stripes like resistors to indicate the value of inductance in microhenrys.

Capsulation is accomplished by placing the coil in a case, then pouring in potting compound. Coil leads are allowed to extend outward through the potting compound. When hermetic sealing is required, a completely closed case is used, and the coil leads are brought out through feed-through terminals in the case.

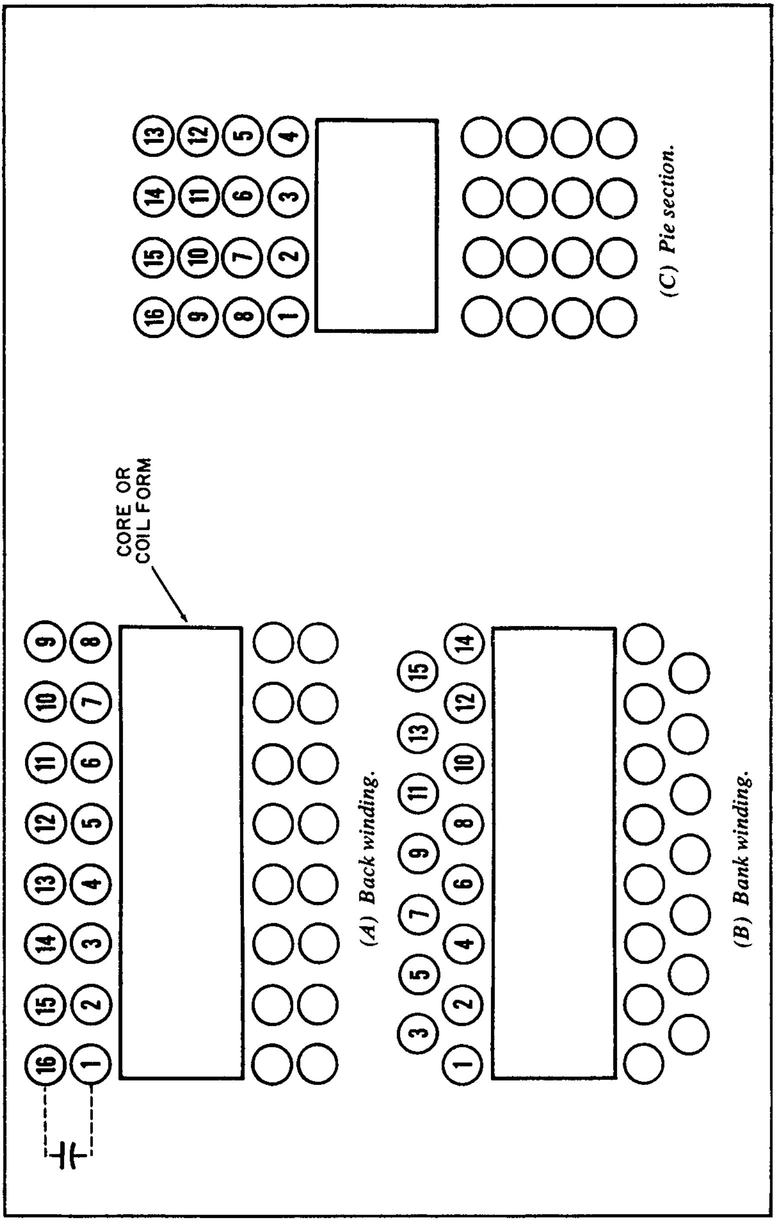
The *pot-core* inductor has its core both inside and outside the coil. The coil winding is placed in a cup-shaped piece of core material (powdered-iron or ferrite). Another cup is placed, inverted, on top of the first cup. In addition, a fixed or movable rod of core material extends into the coil. The coil is thus completely surrounded by core material. Pot-core construction produces a highly efficient path for the magnetic flux.

DISTRIBUTED CAPACITANCE

As stated earlier, pure inductance is a theoretical concept that cannot be realized in practice. A practical inductor always has a component of resistance. It also has some capacitance – between turns, between layers of turns, between the turns and the shield (if a shield is used), and between the turns and the chassis or other nearby components. This capacitance is known collectively as the *distributed* capacitance. In low-frequency circuits, the effect of this distributed capacitance is negligible. At higher frequencies, however, the capacitive reactance becomes comparable in value to the inductive reactance. At the frequency at which these two reactances are equal, the inductor becomes a resonant tank. Although this self-resonance is advantageous in some applications, it is more often regarded as an undesirable effect of the distributed capacitance of the coil. At frequencies above self-resonance, the capacitive reactance is smaller than the inductive reactance and tends to short out the coil for r-f signals. R-f chokes are used to "keep out" high-frequency signals. The distributed capacitance, however, allows the r-f signal to bypass the coil and therefore defeats the purpose of the choke. At the frequency of self-resonance and the odd multiples thereof (3f, 5f, 7f, etc.), the coil behaves like a parallel-resonant (high-impedance) circuit. At even multiples (2f, 4f, 6f, etc.), the coil behaves like a series-resonant (low-impedance) circuit.

The single-layer coil has the least distributed capacitance, but it also provides the least amount of inductance for a given volume. Multi-layer coils are therefore required to produce adequate inductance for most applications. The distributed capacitance, however, is relatively large because of the capacitance between adjacent layers of the coil.

Special winding configurations help minimize the distributed capacitance of multi-layer coils. This is illustrated in Fig. 3-2. In Fig. 3-2A, the second layer of turns is wound back toward the starting point of the first layer. The last turn of the coil is



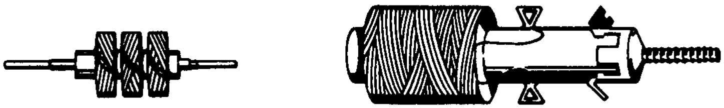
(A) Back winding.

(B) Bank winding.

(C) Pie section.

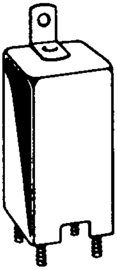
Fig. 3-2. Winding configurations.

therefore adjacent to the first turn, and the capacitance between these turns bypasses the entire coil. This bypassing effect can be minimized by *bank winding* as shown in Fig. 3-2B. Here, the first and last turns are more separated than the others, and the bypassing effect is reduced accordingly. Another method of reducing distributed capacitance is to use more layers, with fewer turns on each. Here again, as shown in Fig. 3-2C, the separation of the first and last turns is relatively large.



(A) Pie-wound.

(B) Slug-tuned.



(C) Shielded.

(Courtesy Stancor Electronics, Inc.)

Fig. 3-3. Various types of coils.

The *universal* method of winding is used extensively and is a compromise between the low capacitance of the single-layer coil and the higher inductance of the multi-layer coil. This method of winding employs a zig-zag motion so that adjacent layers are not parallel. Because adjacent turns, layer to layer, are not parallel, distributed capacitance is relatively small. This type of winding is illustrated in Fig. 3-3A. Further reduction of distributed capacitance is achieved by winding the coil in sections called "pies." This splits the capacitance into series elements, reducing total capacitance.

The use of a ferrite core also helps reduce distributed capacitance. Because of the extremely high permeability of the ferrite core, fewer turns are needed to produce a given amount of inductance. The physical size as well as the distributed capacitance of the coil are therefore reduced.

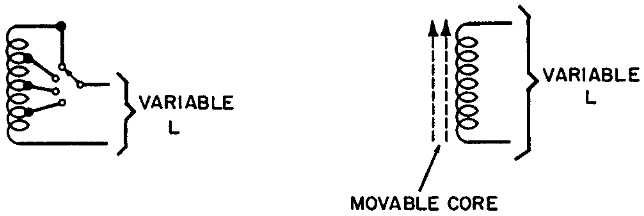
SHIELDING

Because a magnetic field is established by current in a coil, and because this field will induce voltage in any conductor it cuts, undesirable coupling effects may occur. Magnetic coupling between the coils of a receiver, for example, will produce feedback from one stage to another and may cause the receiver to oscillate. Such undesirable coupling can be eliminated by shielding each coil with a metal container that encloses the coil and therefore confines the magnetic field. Shield cans are generally made of aluminum, but copper or brass may be used. As the magnetic field of the coil cuts across the shield, it induces eddy currents in the shield material. These currents establish a "counter" magnetic field that cancels the portion of the inductor field that would otherwise escape.

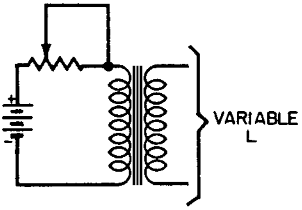
Eddy currents induced in a shield represent a power loss which must ultimately be made up by the signal source. This loss can be reduced by the use of a shield large enough that it does not fit the coil too closely. Another factor favoring an increased coil-to-shield spacing is the reduction of capacitance between the turns and shield (which is normally grounded).

VARIABLE INDUCTORS

Some applications, such as bandswitching, tuning, phase shifting, and telemetering, require the use of variable rather than fixed inductors. Several types of variable inductors are illustrated in Fig. 3-4. In Fig. 3-4A, the inductance is changed simply by switching to one of several taps on the coil. Another method (Fig. 3-4B) employs a movable core; the farther it is moved into the coil, the more magnetic material is placed in the pathway of the lines of force. The number of lines therefore increases, and the inductance increases accordingly. The slug-tuned inductor is representative of this method.



(A) Tap switching. *(B) Slug-tuned.*



(C) Saturable reactor.

Fig. 3-4. Variable inductors.

Variable-pitch windings are used to produce a more linear variation as the slug is moved into the coil. If the turns of the coil are evenly spaced, the inductance will vary most rapidly as the core first enters the coil. The inductance will increase more slowly as the slug progresses inward. With variable-pitch winding (turns spaced at one end and crowded at the other), nearly linear variation can be achieved.

In Fig. 3-4C, the inductance can be varied by changing the degree of core saturation. An increase of direct current through one of the coils increases the extent to which the core is saturated. As the core becomes more saturated, the inductance of the second coil decreases. This type of variable inductor, the *saturable reactor,* is frequently employed in industrial-control circuits and in magnetic amplifiers.

TOROIDAL INDUCTORS

The toroid, shown in Fig. 3-5, is a highly efficient shape for an inductor. The doughnut-shaped core provides a continuous magnetic path, and most of the flux is confined to the volume enclosed by the winding. This type of inductor has the advantage of providing a large inductance for a given physical size. The coil in Fig. 3-5 has only a few turns, but many more may be used (depending on the intended frequency of operation). In addition to providing large inductance in small physical size, the toroidal inductor has the further advantage of being relatively immune to stray magnetic fields. A disadvantage is its higher cost because of the greater difficulty of winding a coil on a core of this shape.

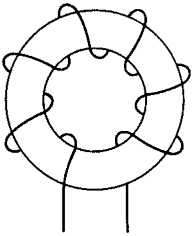


Fig. 3-5. Toroidal inductor.

The cores of toroidal inductors can be manufactured in several ways. One method utilizes a long, narrow strip of magnetic steel. The strip is then rolled (like a reel of recording tape) to produce a ring-shaped core. Another method is to stamp out washer-shaped pieces of steel, and then stack these "washers" to the desired thickness of the core. For either type of construction, the core often is coated with epoxy before the coil is wound. This protects the wire from sharp edges. Powdered-iron or ferrite cores also are used for high-frequency toroidal inductors.

Litz wire is frequently used to minimize skin-effect losses in toroidal inductors designed for radio frequencies up to about 1 MHz. At higher frequencies, so few turns are required that large-diameter solid wire can be used.

To cushion the coil and to protect the core from winding pressures that may alter its magnetic properties, the toroid core may be coated with silicone rubber. For environmental protection, the toroidal inductor may be either molded in Bakelite or capsulated in epoxy. A metal case may be employed when hermetic sealing is required. Both molding and capsulating are expensive procedures. When cost is a primary factor and environmental protection is secondary, the toroid may simply be mounted on a plastic coil form or attached to a piece of fiberboard.

FERRITE-BEAD INDUCTORS

Typically, an inductor consists of a coil wound on a magnetic core. The greater the permeability of the core material, the fewer the turns required to achieve a given value of inductance. The development of high-permeability ferrites has made possible an inductor of *inverted* construction: a magnetic core surrounding a wire. As shown in Fig. 3-6, a ferrite "bead" is strung on a wire to produce the equivalent of a radio-frequency choke. Even though the "winding" is simply a straight piece of wire perhaps an inch long, this choke may have an impedance of several hundred ohms in the megahertz frequency range.

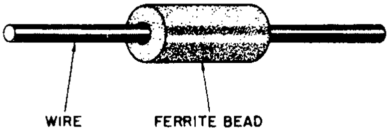


Fig. 3-6. Ferrite-bead inductor.

For increased inductance, the ferrite bead may have several holes through it and the wire may be threaded back and forth several times. Also, several beads can be strung in series on the same wire.

The ferrite-bead inductor, sometimes referred to as an inductance multiplier, has several advantages over the conventional radio-frequency choke. It is simple to manufacture, it introduces very little stray capacitance, and it has almost no d-c resistance. This bead type of inductor has found application in noise-suppression, anti-parasitic, and decoupling circuits.

Chapter 4

APPLICATIONS

Like the resistor and capacitor, the inductor is a basic component of electronic circuitry. It is therefore used in practically all types of electronic apparatus. Because its reactance increases as the frequency increases, the inductor can be used to attenuate high frequencies without appreciably reducing the amplitude of low frequencies or direct current. Or, with a different circuit configuration, it can be made to favor the high frequencies. With a capacitor, the inductor is used in tuning, bandpass, and band-rejection circuits.

POWER-SUPPLY FILTER CHOKE

The ability of the inductor to oppose changes of current accounts for its usefulness as a power-supply filter component. As indicated in Fig. 4-1, the filter choke is connected in series with

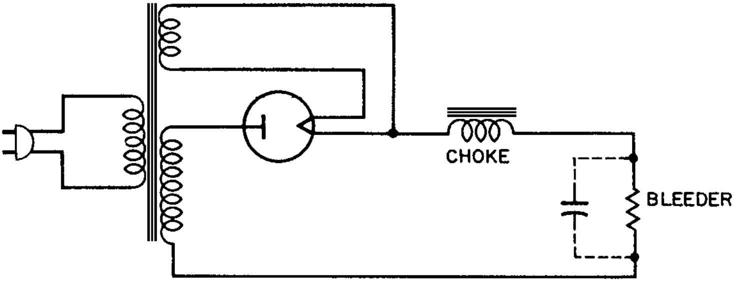


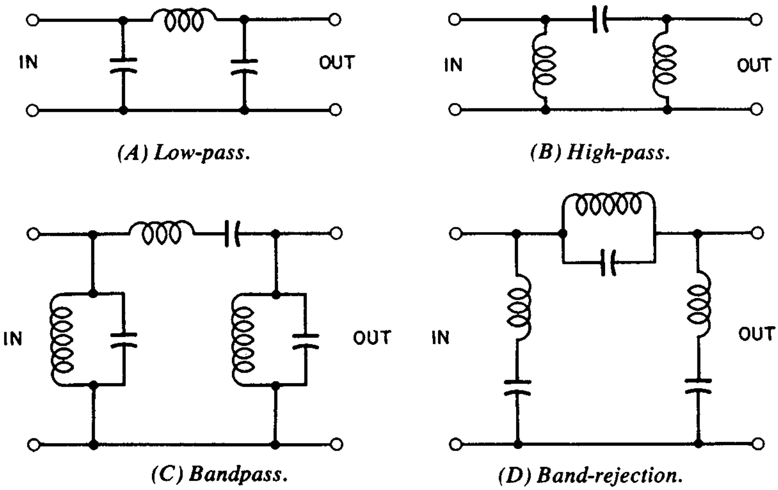
Fig. 4-1. Power-supply filter choke.

the rectifier and voltage source (transformer secondary). During the portion of the a-c input cycle when the rectifier current is increasing, the counter emf of the choke is positive on the cathode side. This prevents the current from increasing as much as it would, were it not for the counter emf. During the portion of the a-c input cycle when the rectifier current is decreasing, the counter emf of the choke is negative on the cathode side. This keeps the current from decreasing as much as it would if the choke were not in the circuit. Because the choke attempts to maintain a more nearly constant current, the voltage drop across the bleeder (and also across the load) tends to remain more constant. The output voltage does not rise as high as it would without a filter choke, nor does it drop as low. The variation of output voltage (ripple) is therefore held to a small value. The filter capacitor (dotted line in Fig. 4-1) further reduces ripple by holding the output voltage more constant. Additional chokes and capacitors may be added to Fig. 4-1 for improved filtering. Although a half-wave circuit is shown, the above comments also apply to a full-wave circuit.

The filter choke is wound onto a soft-iron core, with typical values of inductance ranging from 5 to 30 henrys. In electromagnetic speakers, the field coil serves also as a filter choke. Current in a filter choke tends to saturate the core and therefore to reduce the inductance. Some chokes have a small air gap in the iron core to reduce saturation effects. A choke designed to maintain a practical minimum (critical) value of inductance at maximum current is termed a *swinging choke.*

FREQUENCY-SELECTIVE FILTERS

Frequency-selective filters can be classified as (1) low-pass, (2) high-pass, (3) bandpass, and (4) band-rejection. A low-pass filter (Fig. 4-2A) is one which will attenuate high frequencies, but will allow low frequencies to pass practically undiminished in amplitude. High frequencies are attenuated because they encounter a high reactance in the series inductor. In addition, the high frequencies tend to be bypassed through the low reactance of the shunt capacitors. For low frequencies, the series reactance (X_L) is small and the shunt reactance (X_C) is large. The cutoff frequency (dividing point between high and low frequencies) is determined by the values of L and C. The filter of a power supply is actually a low-pass filter.



(A) Low-pass. *(B) High-pass.*

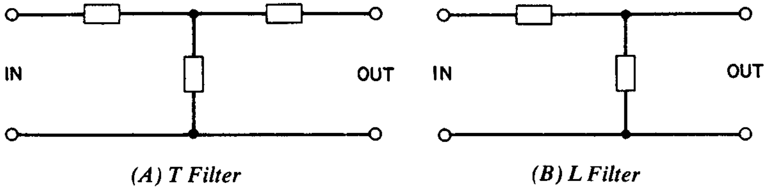
(C) Bandpass. *(D) Band-rejection.*

Fig. 4-2. Frequency-selective filters.

A high-pass filter is illustrated in Fig. 4-2B. Low frequencies are attenuated in it because they encounter a high reactance (X_C) in the series component and are bypassed through the low reactance (X_L) of the shunt components.

The bandpass filter in Fig. 4-2C employs resonant circuits ($X_L = X_C$). It will pass a narrow band of frequencies and attenuate those above and below this band. The series-resonant circuit offers low impedance to the frequency at which the inductive reactance is equal to the capacitive reactance (and to a narrow band of frequencies centered around this resonance point). In addition, the parallel-resonant circuits offer high impedance to this band. Frequencies outside the passband encounter high impedance in the series components and are bypassed through the low impedance of the shunt tanks.

The band-rejection filter shown in Fig. 4-2D will attenuate frequencies within a narrow band and pass those above and below it. Here, a parallel-resonant circuit is the series component of the filter, and the shunt pathways are series-resonant circuits. Frequencies at and near resonance are attenuated because they encounter a high impedance in the series component of the filter (parallel tank) and are bypassed through the low impedance of the shunt pathways (series-resonant circuits). This band-rejection (also known as a band-stop or band-exclusion) filter can be employed as a wave trap in a receiver, to attenuate an interfering signal.



(A) T Filter *(B) L Filter*

Fig. 4-3. T and L filters.

The circuits illustrated in Fig. 4-2 are classified as *pi* filters because the configuration of the components resembles the Greek letter π. Other configurations sometimes used are shown in Fig. 4-3; they are known as T and L filters because of their resemblance to these letters.

TELEMETRY

Telemetry is employed for remote measurement of pressure, temperature, acceleration, fluid flow rate, and other physical variables. Such systems are used extensively for remote instrumentation in aircraft, missile, and satellite experiments.

For a given value of capacitance in an oscillator tank circuit, the frequency of oscillation is determined by the value of inductance. An application utilizing this frequency-determining characteristic is illustrated in Fig. 4-4. Here, a movable-core inductor is used in the tank circuit of the subcarrier oscillator of a telemetering system.

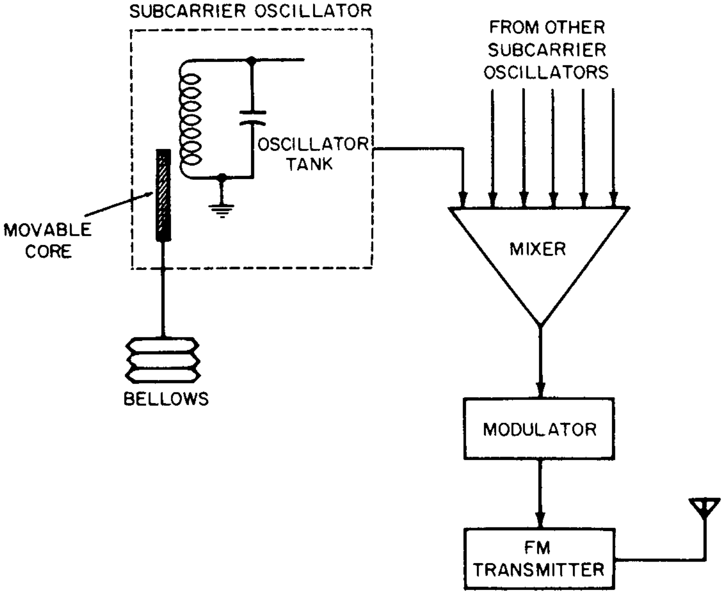


Fig. 4-4. Inductance-controlled subcarrier oscillator.

In Fig. 4-4 the movable core of the inductor is positioned by a mechanical linkage from the bellows. Since the bellows expands or contracts in accordance with the pressure changes to which it is exposed, the frequency of the subcarrier oscillator represents the pressure. The subcarrier output is fed to a mixer along with other subcarrier frequencies representing temperature, speed, flow rate, etc. These subcarriers then modulate the main carrier of an f-m transmitter. At the ground station, an f-m receiver picks up this transmission. The subcarrier frequencies are then separated and measured to provide indications of pressure, temperature, speed, etc.

PHASE-CONTROLLED RECTIFIER

In phase-controlled rectifiers, thyratrons instead of diodes are used as the rectifying elements. The advantage of this arrangement is that the rectified output to a load can be controlled simply by shifting the phase of the thyratron grid voltage. A half-wave, phase-controlled rectifier is shown in Fig. 4-5, but the circuit can be extended for full-wave operation by the use of two thyratrons fed from a center-tapped secondary winding.

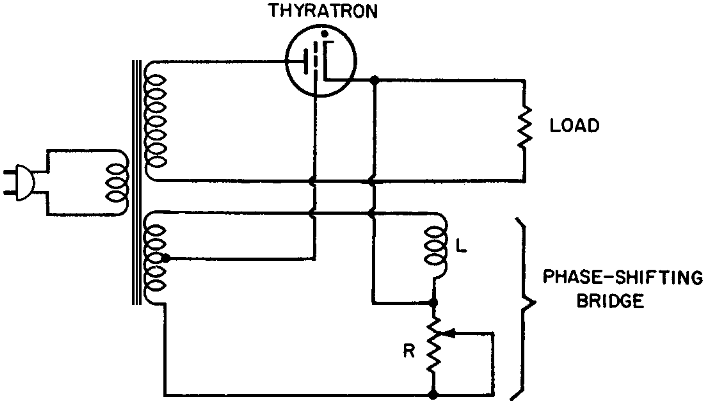
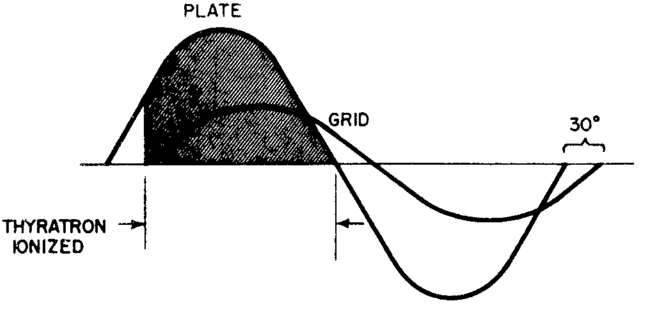


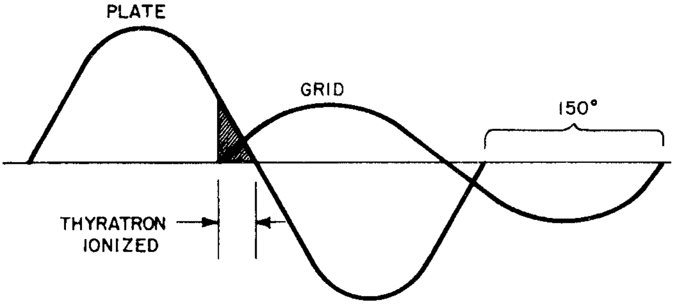
Fig. 4-5. Phase-controlled rectifier.

The relative values of inductance and resistance in the phase-shifting bridge determine the angle by which grid voltage lags plate voltage. If this angle is small, say 30°, the positive alternation of grid voltage will occur slightly after the start of the positive alternation of plate voltage. The thyratron therefore fires (ionizes) early in the cycle as shown in Fig. 4-6A. Assume now that the phase-shifting bridge is adjusted to make grid voltage lag plate voltage by a larger angle, say 150°. The positive alternation of grid voltage now occurs near the end of the positive alternation of plate voltage. As indicated in Fig. 4-6B, the thyratron now fires late in each cycle.

A comparison of Figs. 4-6A and B indicates that the average current through the load becomes smaller as the phase angle of the grid voltage is increased. The load is a resistor in Fig. 4-5, but in actual practice it might be the armature of a d-c motor, for example. The speed of this motor could then be controlled simply by varying the resistance in the phase-shifting bridge. This technique of motor control is used extensively in industry. By eliminating the need for pulley or gear changes, it permits smooth, stepless control of motor speed.



(A) Early firing.



(B) Late firing.

Fig. 4-6. Phase of grid voltage determines firing time of thyratron.

A fixed inductor and variable resistor are shown in the phase-shifting bridge in Fig. 4-5. An alternative is to use a fixed resistor with a variable inductor, an arrangement frequently employed where automatic control of motor speed is required. The inductor in such circuits is a saturable reactor (see Fig. 3-4), the d-c coil of which is connected to the plate circuit of a tube. The bias of this tube therefore determines the degree of core saturation of the reactor. Since the degree of saturation determines the value of inductance, the reactor functions as a variable inductor in the phase-shifting bridge. According to the signal applied to the grid of the tube that controls the reactor, the thyratron can be made to fire earlier or later in the cycle. If the motor speed is to be held constant, the control signal can be obtained from a small d-c generator coupled to the motor shaft. This is now a *closed-loop* control system: the thyratron controls the motor, the motor drives the d-c generator, the generator supplies bias for the control tube, the control tube determines the saturation of the reactor, and the reactor determines the phase angle of the thyratron grid voltage. A change of motor speed therefore shifts the phase of the thyratron grid voltage, bringing the motor back to its correct speed. Controls of this type are used to regulate the motor speed against power-line variations and changes of mechanical load on the motor shaft.

PEAKING COILS

The high-frequency response of an amplifier stage is degraded by stray capacitance in the plate circuit. As indicated in Fig. 4-7, this stray capacitance shunts the plate load resistor. Since the

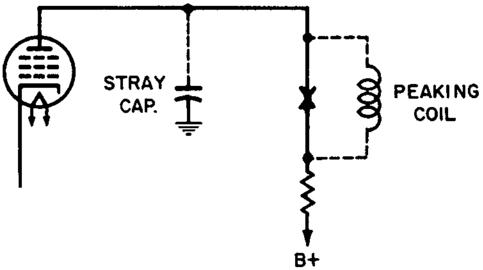


Fig. 4-7. Peaking coil extends high-frequency response.

reactance of the stray capacitance decreases as the frequency increases, the load impedance into which the tube works becomes smaller at higher frequencies. For this reason the high-frequency gain of the circuit drops off sharply.

The effect of stray capacitance can be counteracted by including an inductor in the plate circuit (Fig. 4-7) or in the grid circuit of the following stage. In either case, it becomes part of the plate load impedance. Since the reactance of this *peaking coil* increases as the frequency increases, the load impedance of the tube does not decrease at the higher frequencies. As a result, amplifier gain does not drop off until a much higher frequency is reached. In this manner an amplifier, the gain of which does not extend appreciably beyond the audio range, can be compensated for response up to several megahertz. High-frequency compensation of this type is commonly employed in oscilloscope amplifiers, radar receivers, and tv sets.

HIGH-VOLTAGE SUPPLY

The counter emf of an inductor can be used as a source of high voltage for the operation of high-voltage, low-current devices such as the Geiger counter. An inductive *kickback* supply for a portable Geiger counter is illustrated in Fig. 4-8. Capacitor C1 charges through resistor R1 until the voltage across it is sufficient to ionize the neon lamp. Capacitor C1 then discharges through the ionized gas until the remaining voltage is no longer adequate to maintain the ionization. The neon lamp now deionizes and the capacitor recharges. This repeated charge and discharge produces a sawtooth waveform across C1. In the differentiator circuit each cycle of sawtooth is converted to a negative pulse. As each pulse drives the 1U5 below cutoff, the magnetic field of the inductor collapses. The resulting counter emf charges capacitor C2 through the diode section of the 1U5, and the charge is then transferred through R2 to C3. The voltage across C3 (the output of the supply) is applied to the Geiger tube. Because of the rapid collapse of the magnetic field each time the 1U5 is driven below

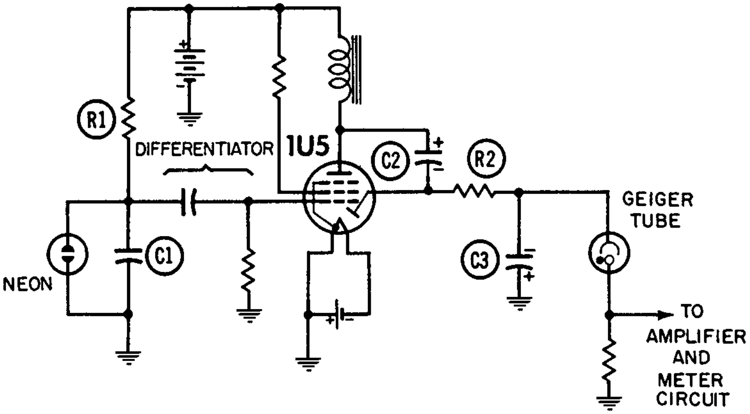


Fig. 4-8. Inductive kickback power supply.

cutoff, the counter emf is large in magnitude. For this reason the output voltage of the supply is considerably greater than the voltage of the B battery.

TV APPLICATIONS

Inductors employed in tv receivers include power-supply filter chokes, tank inductances, peaking coils, deflection yokes, focus coils, and width and linearity controls.

The focus coil is mounted on the neck of the picture tube so that it surrounds the electron beam. Direct current is passed through it to establish a magnetic field. Since the electrons in the beam tend to repel each other, the beam tends to spread as it approaches the screen. If this scattering effect is not counteracted, the scanning spot on the screen will be large and the picture will lack fine detail. The magnetic field of the focus coil "squeezes" the electron beam to a smaller cross-section area. When the current in this coil is properly adjusted, the electron paths converge toward the screen to produce a small, sharply defined scanning spot.

The deflection yoke contains both horizontal- and vertical-deflection coils arranged so that their magnetic fields are at right angles to each other. Sawtooth currents are passed through these coils to produce magnetic fields that increase linearly with time. One of the fields deflects the electron beam horizontally and the other deflects it vertically. Since the horizontal sawtooth is much higher in frequency (15,750 Hz) than the vertical sawtooth (60 Hz), the beam sweeps across the screen many times during each of its vertical excursions. As a result, the scanning spot traces many vertically displaced horizontal lines.

As shown in Fig. 4-9, the width control is connected across a portion of the secondary of the horizontal-output transformer.

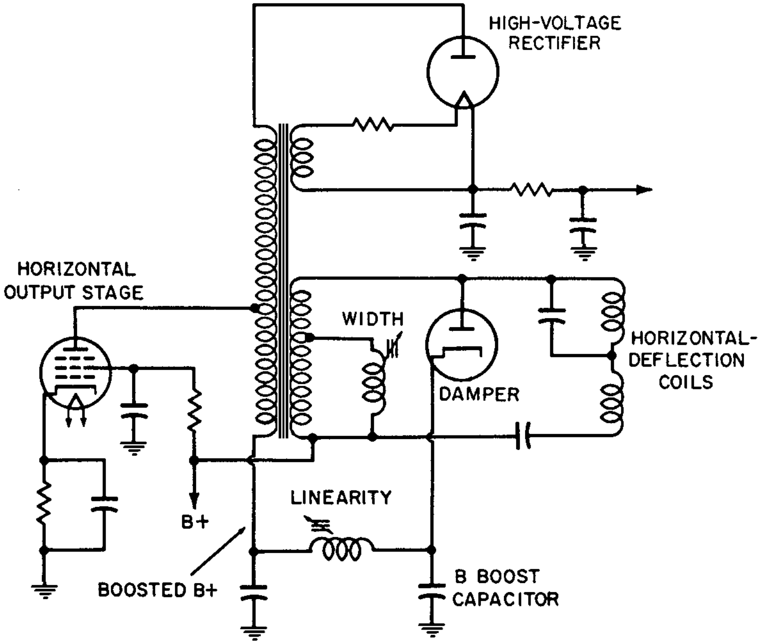


Fig. 4-9. Deflection, width, and linearity coils.

This secondary supplies deflection current to the horizontal coils in the yoke. Because it shunts a portion of the secondary winding, the width coil limits the magnitude of the signal coupled to the yoke. The deflection signal (and the width of the picture) can therefore be controlled by varying the inductance of the width coil.

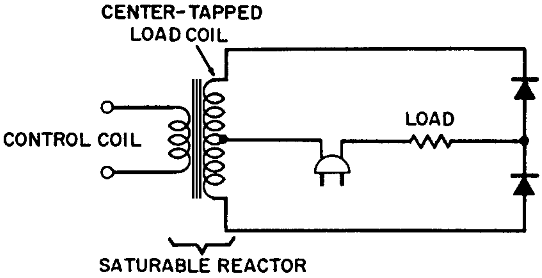
Boosted B voltage for the plate of the horizontal-output tube is produced by charging the boost capacitor through the damper diode. The source voltage of this charge is the B supply in series with the voltage in the output-transformer secondary. The boost capacitor therefore charges to the sum of these two voltages. A ripple component appears in the boosted voltage, at the frequency of the horizontal sawtooth. This ripple is shifted in phase by the inductance of the linearity control, and the amount of shift is determined by the amount of inductance. By proper adjustment of this control, the plate voltage of the output tube can be made to vary during the sawtooth cycle to improve the linearity of the sawtooth current needed for beam deflection.

MAGNETIC AMPLIFIERS

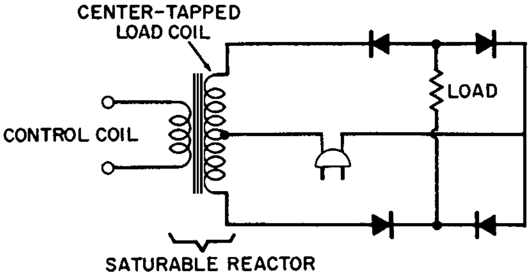
The inductance of a saturable reactor decreases with an increase in core saturation. This characteristic is utilized in magnetic amplifiers. In the two typical circuits shown in Fig. 4-10, a few milliamperes (or even microamperes) of current through the control winding can control amperes of current through the load. A small increase in control current, for example, will increase the core saturation. As a result, the inductance of the load coil will decrease. Since there is now less reactance in series with the load, the load current increases accordingly.

The load coil of the reactor is center-tapped, and the diodes are connected so that current through the two halves is in a direction that aids the control current. Since the load current helps to saturate the core, these circuits are referred to as *self-saturating* magnetic amplifiers. The load in Fig. 4-10 is shown as a resistor, but in practice it may be a relay, solenoid, motor, furnace heating element, etc. Alternating current flows through the load in Fig. 4-10A. The one in Fig. 4-10B, which provides both control and rectification, is used for controlling current through a d-c load.

Special core materials have been developed for use in magnetic amplifiers. Typically, they are such that the core suddenly saturates when current exceeds a critical value. This can be compared to the sudden "firing" of a thyratron. An additional bias winding is often included on the reactor. The magnitude of the bias current determines whether the reactor "fires" early or late during the a-c supply cycle.



(A) An a-c load.



(B) A d-c load.

Fig. 4-10. Magnetic amplifiers.

Like vacuum-tube and transistor amplifiers, magnetic amplifiers can be connected in cascade for increased gain. The load in Fig. 4-10B, for example, may be the control coil of a second stage of the same type. Likewise, the control coil of a third stage can be connected as the load of the second stage.

Chapter 5

TRANSFORMERS

When the magnetic field of an inductor changes, the lines of force cut across the turns and induce a voltage (counter emf) in the coil. Furthermore, the changing field also will induce a voltage in any other nearby coil. This is the principle of transformer action. A transformer consists of two or more coils on the same core, or at least close enough so that the flux lines of one coil will cut the turns of the other.

TURNS RATIO

The transformer coil to which the input voltage is applied is designated the *primary* winding. Current through it establishes a magnetic field that induces voltage in the other coil (*secondary* winding). Because the magnitude of the induced voltage depends on the number of turns on the secondary as compared with the number on the primary, the *turns ratio* is an important characteristic of the transformer. It is defined as the ratio of the number of primary to the number of secondary turns:

$$\text{turns ratio} = \frac{N_P}{N_S}$$

where,

N_P is the number of turns on the primary,
N_S is the number of turns on the secondary.

If the secondary has more turns than the primary, the transformer has a *step-up* ratio. A turns ratio of 1:3, for example, indicates that the secondary has three times as many turns as the primary. A *step-down* transformer has fewer turns on the secondary than on the primary. A turns ratio of 20:1 therefore indicates that the secondary has one turn for every twenty on the primary.

In general, step-up transformers are used to increase voltage, and step-down transformers to decrease it. Transformers with 1:1 ratios are sometimes employed when it is desired to retain the same amount of voltage but to isolate one circuit from another.

VOLTAGE RATIO

Because the voltage induced in the secondary of a transformer may be either larger or smaller than the voltage applied to the primary, the transformer can be regarded as a voltage-changing device. A transformer for operating a neon sign, for example, produces thousands of volts output by stepping up the power-line voltage (115 vac). By contrast, a filament transformer steps down the line voltage to 2.5, 5, or 6.3 volts, or any other value required by the heaters of the tubes.

Since the magnitude of the voltage induced in a coil depends on the number of turns being cut by the magnetic field, a secondary winding with many turns will have more voltage induced in it than a secondary with fewer turns. If, for example, the magnetic field induces a tenth of a volt in each turn of the secondary, a 2000-turn secondary will have 200 volts induced in it, and a 3000-turn secondary will have 300 volts induced. Mathematically, the voltage ratio (primary to secondary) is equal to the turns ratio:

$$\frac{E_P}{E_S} = \frac{N_P}{N_S}$$

where,

N_P and N_S are the number of turns of the primary and secondary,

E_P and E_S are the voltages of the primary and secondary respectively.

In the example shown in Fig. 5-1, the voltage induced in the secondary can be determined as follows:

$$\frac{E_P}{E_S} = \frac{N_P}{N_S}$$

$$\frac{115}{E_S} = \frac{500}{1500}$$

$$E_S = \frac{115 \times 1500}{500} = 345 \text{ volts}$$

As indicated in the calculation above, the secondary voltage is three times as great as the primary voltage because the secondary has three times as many turns as the primary. In practice, the secondary voltage is somewhat less than the calculated value. If a load is connected across the secondary, the resulting current will produce an IR drop in the resistance of the secondary winding. For this reason, the secondary voltage decreases when a load is connected. In a well-designed transformer, however, this decrease is negligible. The transformer designer can anticipate and compensate for the decrease by slightly increasing the number of secondary turns.

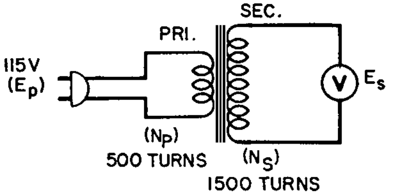


Fig. 5-1. Step-up transformer.

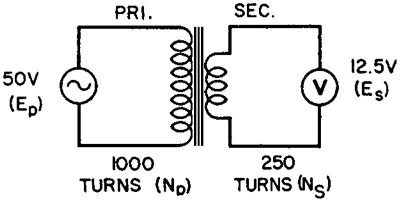


Fig. 5-2. Step-down transformer.

A step-down transformer is shown in Fig. 5-2. Here the secondary has only one-fourth as many turns as the primary. Secondary voltage is therefore equal to one-fourth the primary voltage:

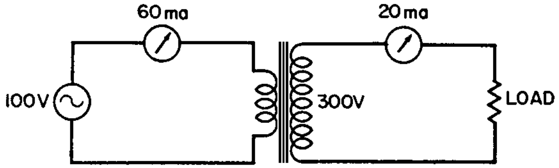
$$\frac{E_P}{E_S} = \frac{N_P}{N_S}$$

$$\frac{50}{E_S} = \frac{1000}{250}$$

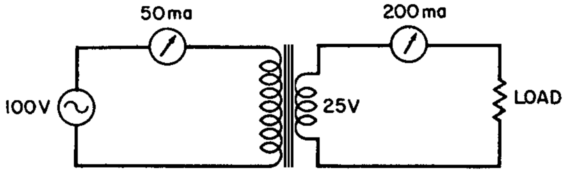
$$E_S = \frac{50 \times 250}{1000} = 12.5 \text{ volts}$$

CURRENT RATIO

Although a transformer can increase voltage, it does not provide "something for nothing." The voltage increase is accompanied by a current decrease. The current drawn from the secondary winding is determined by the load connected to it, but the primary current will be greater than the secondary current in the same ratio that the secondary voltage is greater than the primary voltage. If, for example, the secondary voltage is four times as great as the primary voltage, the primary current will be four times as great as the secondary current. A transformer that has a step-up voltage ratio therefore has a step-down current ratio.



(A) Step-down.



(B) Step-up.

Fig. 5-3. Current ratios.

In the example shown in Fig. 5-3A, the secondary voltage is three times as great as the primary voltage. If a load connected to the secondary draws 20 milliamperes of current, the primary current will be 60 milliamperes. In Fig. 5-3B the secondary voltage is one-fourth the primary voltage. If the load connected to the secondary draws 200 milliamperes, the primary current will be one-fourth this value, or 50 milliamperes.

Mathematically, the current ratio is related to the turns ratio as follows:

$$\frac{I_P}{I_S} = \frac{N_S}{N_P}$$

where,

N_P and N_S are the number of turns of the primary and secondary,

I_P and I_S are the currents of the primary and secondary.

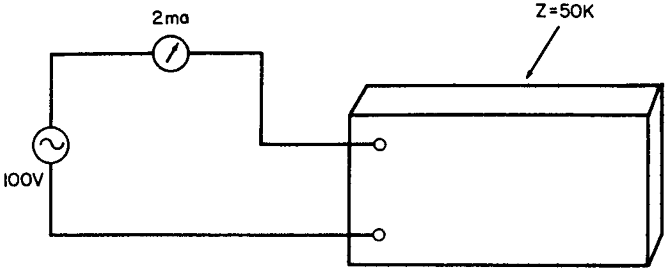
In practice, the primary current is slightly greater than the calculated value because the primary draws additional current to make up for core losses. For this reason, the output power of the secondary (E_S times I_S) is always less than the input power to the primary (E_P times I_P). The ratio of output power to input power is the *efficiency* of the transformer and is generally expressed as a percentage:

$$\%\ \text{efficiency} = \frac{\text{power out}}{\text{power in}} \times 100 = \frac{E_S \times I_S}{E_P \times I_P} \times 100$$

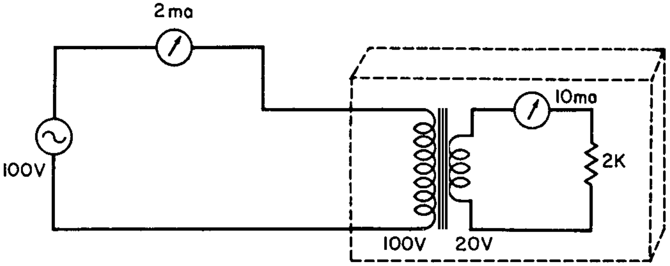
For iron-core transformers, the efficiency often exceeds 90%.

IMPEDANCE MATCHING

Because it can make one value of impedance appear to be another value, the transformer is useful as an impedance-matching device. This impedance-changing characteristic of the transformer is illustrated in Fig. 5-4. In Fig. 5-4A, a 100-volt source is connected to "something" inside the box.



(A) Source connected to unknown.



(B) Source connected to step-down transformer.

Fig. 5-4. Reflected impedance.

Since this "something" draws 2 milliamperes of current from the 100-volt source, its impedance is 50,000 ohms:

$$Z = \frac{E}{I} = \frac{100}{.002} = 50{,}000 \text{ ohms}$$

Fig. 5-4B shows that this 50,000-ohm "something" is actually a 5:1 step-down transformer with a 2000-ohm impedance connected across its secondary. Since the secondary output is 20 volts, the 2K load draws 10 milliamperes of current. Furthermore, since the turns ratio is 5:1, the primary current is one-fifth the secondary current, or 2 milliamperes. The 100-volt source therefore "sees" an apparent impedance of 50,000 ohms rather than the actual impedance of 2000 ohms. The apparent impedance is usually referred to as *reflected* impedance. In other words, 2000 ohms in the secondary is reflected as 50,000 ohms in the primary.

Numerically the impedance ratio is equal to the square of the turns ratio. In the above example, the turns ratio is 5 and the impedance ratio is therefore 25 (50,000 ohms to 2000 ohms). Expressed as a formula, this relationship is:

$$\frac{Z_P}{Z_S} = \left(\frac{N_P}{N_S}\right)^2$$

where,

N_P and N_S are the number of turns of the primary and secondary,

Z_P and Z_S are the impedances in the primary and secondary.

Example: What value of impedance is reflected into the primary of a 9:1 step-down transformer with a 10-ohm load across the secondary?

Solution:

$$\frac{Z_P}{Z_S} = \left(\frac{N_P}{N_S}\right)^2$$

$$\frac{Z_P}{10} = \left(\frac{9}{1}\right)^2$$

$$\frac{Z_P}{10} = 81$$

$$Z_P = 10 \times 81 = 810 \text{ ohms}$$

A typical use of an impedance-matching transformer is shown in Fig. 5-5. The transformer is used to match the low impedance of the speaker to the higher impedance of the output tube. Since the turns ratio is 40, the impedance ratio is 40^2, or 1600. The 4-ohm voice coil therefore reflects an impedance of 6400 ohms into the primary, a reasonable load impedance for the output tube.

A-F TRANSFORMERS

Audio-frequency (a-f) transformers are used for interstage coupling and for coupling microphones to amplifiers, and amplifiers to speakers. Both step-up and step-down ratios are employed, the former for increasing the signal level and the latter for impedance-matching applications. These transformers have laminated cores of iron or steel. Silicon steel is preferred, to reduce core losses at the higher audio frequencies.

Audio-frequency transformers are physically large except for the miniaturized types designed for transistor circuits. In vacuum-tube amplifiers, interstage transformers often have a step-up ratio (typically 1:3) to increase the signal voltage. In transistor amplifiers, however, step-down transformers are frequently employed to match the low input impedance of the transistor to the higher output impedance of the preceding stage.

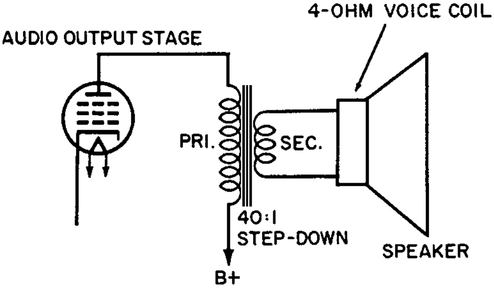


Fig. 5-5. Impedance-matching transformer.

Ideally, the a-f transformer should have a flat response throughout the audio range. In practice, however, the response tends to fall off at the low and high ends of the audio spectrum. Low-frequency response drops because the inductive reactance is small at these frequencies, and the amplifier therefore works into a smaller load impedance. This can be corrected by increasing the number of primary turns to increase the reactance. The distributed capacitance, however, also will increase, and high-frequency signals will be bypassed through this capacitance. Improved low-frequency response is therefore obtained at the expense of high-frequency response.

A better way of increasing primary inductance is to use core material of higher permeability. A number of nickel-iron alloys are available, some with permeabilities approaching 1,000,000. Higher primary inductance can therefore be obtained with fewer turns and consequently with less distributed capacitance. The self-resonance of the transformer windings can sometimes be utilized to improve the high-frequency response.

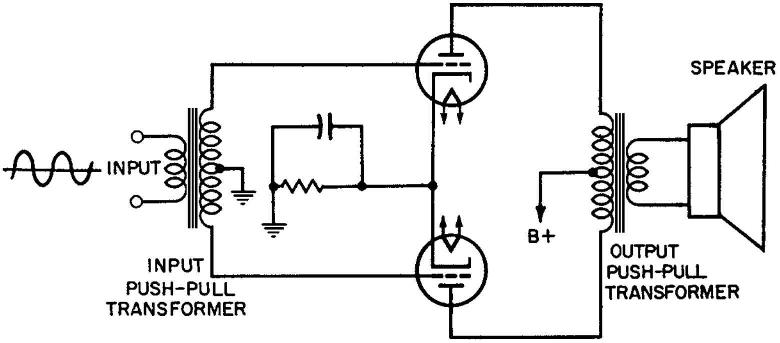
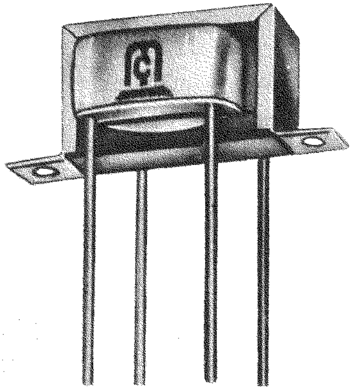


Fig. 5-6. Push-pull transformers.

Push-pull transformers have a center tap on either the primary or secondary. An input push-pull transformer, shown in Fig. 5-6, has a center-tapped secondary to feed the two grids 180° out of phase with each other. The output push-pull transformer has a center-tapped primary winding. Each tube draws current through half of this primary. Although the tubes draw current in opposite directions through their respective halves, the current through one half increases when the current through the other half decreases. An additive effect is therefore produced to provide an increase of output as compared to a single-ended stage. The output push-pull transformer in Fig. 5-6 has a step-down ratio to match the low impedance of the speaker voice coil.

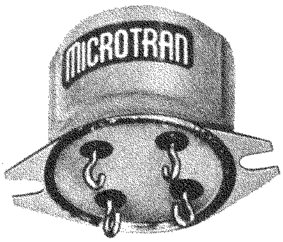
Fig. 5-7 shows several styles of transformer construction and packaging. Open-frame construction is illustrated in Fig. 5-7A, cast epoxy resin protects the transformer in Fig. 5-7B from extremes of temperature and humidity, and hermetic sealing is illustrated in Fig. 5-7C.



(A) Open frame.

(B) Cast epoxy resin.

Fig. 5-7. Transformer styles.
Courtesy Microtran Co., Inc.



(C) Hermetically sealed.

R-F AND I-F TRANSFORMERS

Laminations of nickel-iron alloy such as those used in a-f transformers are not suitable for r-f or i-f transformers. At these higher frequencies, eddy-current losses would be intolerably high. The nickel-iron alloy, however, can be produced in the form of fine particles, and coated with an insulating material and binder. It can then be molded into a rod-shaped core to fit inside the coil. This core of *powdered iron* has relatively little eddy-current loss; the insulating material between the particles produces the effect of a high-resistance core. The core may be threaded so that it can be turned into or out of the coil. This method of varying inductance is commonly employed in i-f transformers.

Intermediate-frequency transformers for communications receivers (as distinguished from home entertainment receivers) use temperature-stable ferrites rather than powdered iron. Used with temperature-compensating capacitors, ferrite-core coils assure stability of tuning. Ferrites are combinations of metallic oxides such as iron, nickel, manganese and zinc, pressed into the desired shape. Because ferrites have high electrical resistivity, eddy-current losses are low. It is therefore unnecessary to powder the ferrite core.

At frequencies above about 50 MHz, magnetic cores introduce considerable losses. Unless high-grade core materials are used, the *Q* of the coil may be less than that of an air-core coil. At these frequencies, magnetic cores should be used only for fine adjustment of frequency rather than for wide-range variation. Non-ferrous core materials such as copper or brass permit adjustment of inductance without introducing magnetic losses (although they do produce eddy-current losses).

Skin-effect losses and distributed capacitance become significant at radio frequencies. These effects can be minimized by the use of Litz wire, hollow tubing, and special winding configurations as described in Chapter 3. Radio-frequency transformers are usually shielded, as indicated in Fig. 5-8, to reduce undesirable coupling and feedback effects.

Radio-frequency transformers are used for interstage coupling and for coupling a signal to or from an antenna. One or both windings of the transformer may be shunted by a tuning capacitor. This combination of inductance and capacitance constitutes a resonant tank which tunes the circuit to a narrow band of frequencies.

The front end of a radio receiver in Fig. 5-9 shows some typical uses of r-f transformers. T1 couples the signal from the antenna to the grid of the r-f amplifier. The secondary of this transformer is tuned by one section of the tuning capacitor and its trimmer. This tank selects the desired signal from among the many signals in the antenna circuit.

Transformer T2 couples the r-f signal from the plate of the amplifier to the grid of the converter. Again, the secondary is resonated by the tuning capacitor for improved selectivity. T3 is the oscillator transformer. The cathode and first two grids of the converter tube function as a triode oscillator, the second grid operating as the triode plate. Oscillator "plate" current through one winding of T3 induces a voltage in the other (control-grid) winding. As a result of this feedback, the circuit oscillates and the electron stream in the converter is modulated at the frequency of oscillation. The grid tank of the oscillator is tuned by another section of the same variable capacitor that tunes the r-f and converter stages. The oscillator frequency therefore changes as the receiver is tuned from one station to another. A trimmer and padder in the oscillator tank are adjusted to make the local oscillator "track" with respect to the tuning of the r-f and converter stages. When these tracking adjustments are correct, the oscillator frequency will always differ by a fixed amount from the signal frequency being received. This fixed-frequency difference is the intermediate frequency (i-f) to which transformer T4 is tuned.

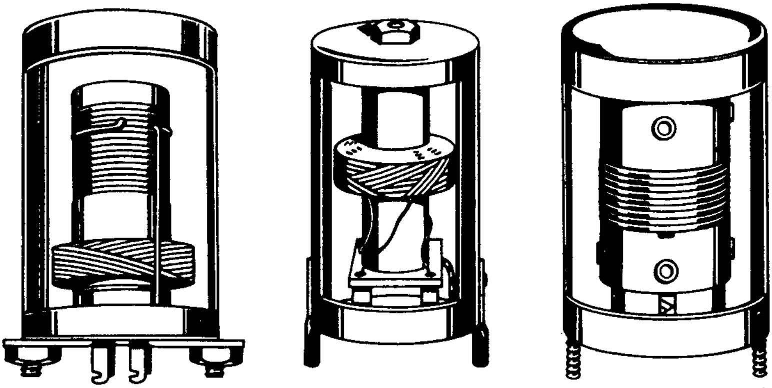

(Courtesy Stancor Electronics, Inc.)

Fig. 5-8. Shielded r-f transformers.

Intermediate-frequency transformers are similar to r-f transformers but are designed to operate at a fixed, or *intermediate,* frequency equal to the difference between the r-f signal and local-oscillator frequency. In broadcast-band receivers, the intermediate frequency is commonly 455 kHz. In other types of equipment (f-m, tv, and radar, for example), the intermediate frequency may range from 10 to 60 MHz. As indicated in Fig. 5-9, both the primary and secondary of the i-f transformer are tuned—either by trimmer capacitors as shown, or by movable slugs in the coils.

A modulated radio signal contains sideband frequencies as well as the carrier. Even after this signal has been converted to an intermediate frequency by the action of the local oscillator, it still includes sidebands above and below the intermediate frequency. The response of the i-f stages must therefore be sufficiently wide to include these sideband frequencies. In communication receivers, intelligibility is the primary requirement and a narrow response is adequate (and also desirable, to permit the receiver to separate the desired station from other stations operating on nearby carrier frequencies). In broadcast receivers, tone quality is important. The response must therefore be wide enough to include the sidebands corresponding to the high audio frequencies. In tv receivers the i-f response must be wider to accommodate the sidebands corresponding to the fine detail of the picture. This requires a bandpass approximately 4 MHz wide. By contrast, the entire standard radio broadcast band is approximately 1 MHz wide.

The bandpass of an i-f amplifier can be widened by (1) connecting loading resistors across the tanks to lower the Q, (2) stagger tuning the i-f stages, or (3) increasing the primary-to-secondary coupling of the i-f transformers. Stagger tuning is accomplished by tuning successive i-f stages to slightly different frequencies, allowing the amplifier to respond to a wider band.

The effect of increased coupling in i-f transformers is illustrated in Fig. 5-10. If the primary and secondary are loosely coupled, the selectivity curve will be as shown by curve A. If the primary and secondary are brought closer together (tighter coupling),

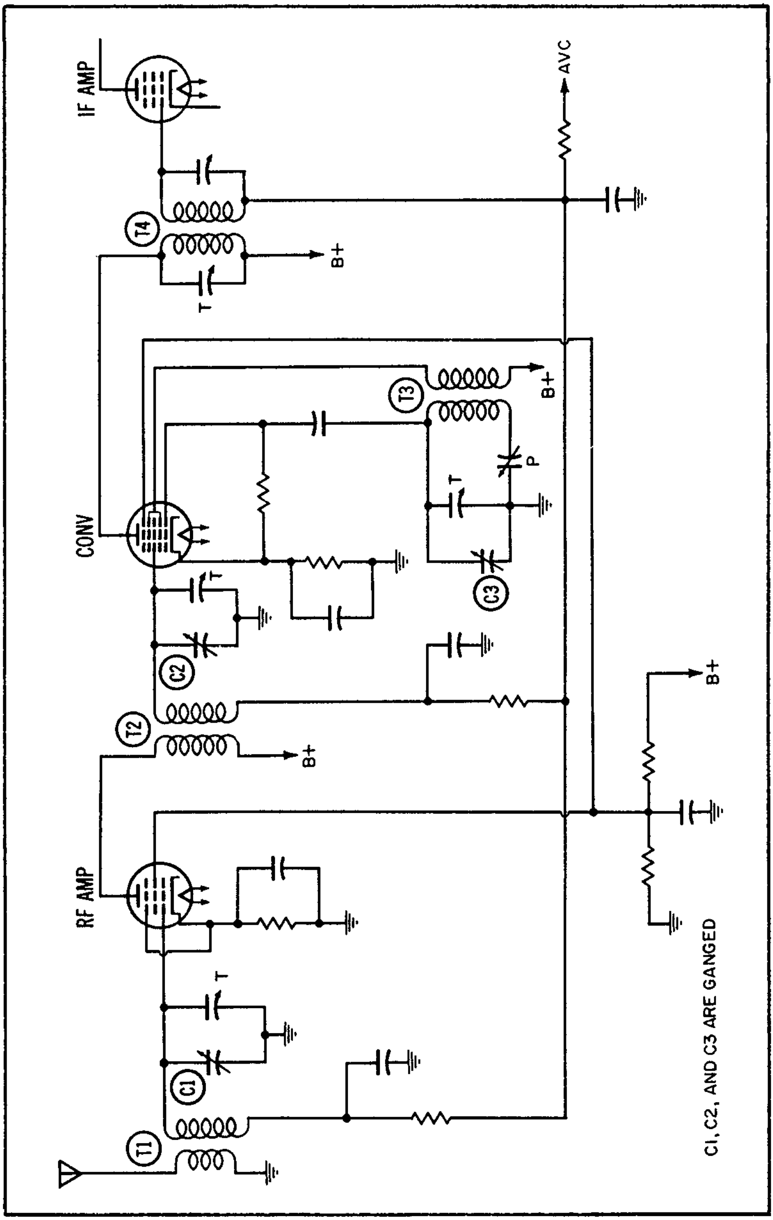


Fig. 5-9. Front end of radio receiver.

the selectivity curve widens and the response increases as shown by curve B. At critical coupling, the amplitude of this curve is maximum. If the coupling is increased beyond the critical value (overcoupled), the selectivity curve becomes wider but develops a double hump (curve C). Although some i-f transformers are constructed to permit variation of the primary-to-secondary coupling, these are exceptions. More often, the degree of coupling is determined by the designer, and the transformer built accordingly.

The *Q* of the tank coils also determines the width of the bandpass response. In general, communications receivers employ high-*Q* coils for narrow response, and broadcast receivers employ tanks of lower *Q* for wider response.

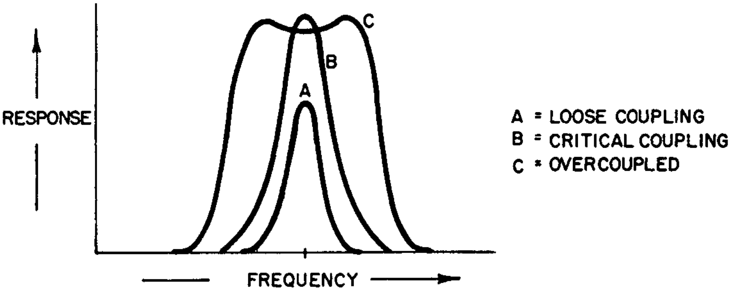


Fig. 5-10. Effect of coupling on bandpass response.

POWER TRANSFORMERS

The power transformer is a voltage-changing device which supplies the operating potentials in radio receivers and other types of equipment. Typically, the transformer has a high-voltage secondary (200 to 400 volts), the output of which is rectified to supply the B voltage for the plates and screen grids. In addition, the transformer has one or more low-voltage secondaries to energize the heaters of the tubes. In some types of equipment, separate transformers are employed for the B supply and for the heater voltages. More often, however, a single transformer with multiple secondaries is employed. A typical receiver-type power transformer is illustrated in Fig. 5-11. The high-voltage secondary steps up the 115 volts alternating current from the line to 350 volts on each side of the center tap (700 volts total). The center tap is provided for use with a full-wave rectifier. A 5-volt secondary supplies heater power for the rectifier tube, and a 6.3-volt winding supplies heater power for the other tubes. Heater windings are sometimes center-tapped to simulate a tap on the heater. This is useful for reducing hum. Several taps may be provided near one end of the primary winding (for use in localities where the line voltage is unusually high or low). Since switching to a different tap on the primary is equivalent to changing the turns ratio, this technique compensates for abnormal line voltage.

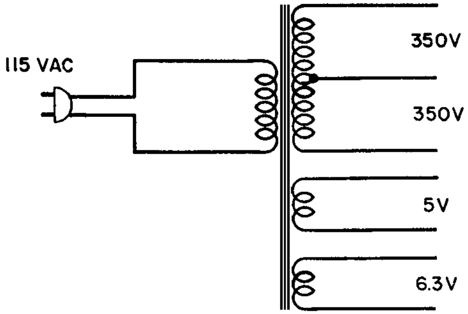


Fig. 5-11. Typical power transformer.

The gauge of the wire used for the various transformer windings is selected on the basis of expected current drain. Heater windings, for example, are wound with heavier gauge wire than the high-voltage secondary. Total heater current of the tubes in a receiver is generally several amperes. In contrast, total plate and screen currents rarely exceed a few hundred milliamperes. Transformer wire is enamel-insulated. This insulation and the insulation between the layers and between the windings and the core must be adequate to prevent arcing. The high-voltage secondary is most critical with respect to insulation requirements because the potential between opposite ends of this winding is generally 500 to 1000 volts. This is one reason for the use of separate plate and heater transformers in high-voltage equipment such as large radio transmitters.

Most of the magnetic flux produced in the transformer is confined to the iron core. Some flux, however, is established in the air around the transformer, and this flux will induce "hum" voltage in nearby wires and other components. For this reason, the transformer is usually encased in a metallic shield. In addition, an electrostatic shield is sometimes employed between the primary and secondary windings to prevent r-f and noise voltages from entering through the power lines.

Power-transformer characteristics are specified according to the voltage and current ratings of the windings. A typical rating, for example, would be 375-0-375 volts at 150 ma, 5 volts at 2 amps, and 6.3 volts at 6 amps. This indicates that the high-voltage secondary is center-tapped and produces 375 volts in each half. This voltage is specified at the rated value of current drain (150 ma). If the current drain is less than the rated value, the secondary voltage will be somewhat higher because of the reduced IR drop in the winding. The above ratings also indicate that the transformer has two heater windings with 5- and 6.3-volt outputs (at 2 and 6 amperes, respectively).

The efficiency of a transformer is limited largely by its core losses. Research by transformer and steel manufacturers has led to the development of improved core materials and therefore to more efficient transformers.

A principal source of core loss (explained briefly in Chapter 2) is *hysteresis*. This type of loss occurs because the core retains some of its magnetic flux after the current that produced it has been reduced to zero. As a result, each alternation of input power must overcome the magnetic flux of opposite polarity left from the preceding alternation. The expenditure of power to accomplish this is the hysteresis loss of the core. The greater the residual magnetism in the core, the greater the power required to overcome it when the current reverses. Hysteresis loss also increases with an increase of frequency (at higher frequencies, the magnetic flux of the core must be reversed more times per second).

Another form of core loss occurs because the core material is electrically conductive. Current is therefore induced in the core by the alternating magnetic field. The input power expended in inducing these *eddy-currents* is wasted because it does not produce any useful output from the transformer. Eddy-current loss can be reduced by the use of laminated core material of low conductivity. A laminated core consists of thin slices of core material insulated from each other to increase resistance to eddy-currents. Both hysteresis and eddy-current losses manifest themselves as heat in the core.

The "iron" core of a transformer is usually silicon steel. About three or four percent of silicon is added to the steel to increase its resistivity, reducing eddy-current losses. The core material is further improved by grain orientation. Grain orientation, accomplished by cold-rolling and heat treating, aligns the crystals of steel in the direction in which they can most easily be magnetized. The resulting steel therefore has a *preferred* or easy direction of magnetization; a characteristic called *anisotropy*. The reduced hysteresis losses in grain-oriented steel have led to increased use of 400-Hz transformers in military and airborne equipment. The advantage of 400-Hz operation over the usual 60-Hz operation is the significant saving in size and weight. All other things being equal, a 400-Hz transformer requires much less iron than the 60-Hz type. Before the development of grain-oriented steel, increased hysteresis loss at 400 Hz voided the advantage of lower weight. Now, even 800-Hz operation seems attractive.

C-core construction best utilizes the advantage of grain-oriented core material. The grain-oriented steel is produced in a long, narrow strip. This ribbon of core material is then rolled up (like a reel of recording tape) to produce a circular- or oval-shaped core. The core is then cut in half to produce two C-shaped pieces. After the prewound coils are placed on the core, the two halves are fitted together again. The advantage of this tape-wound core is that its "easy" direction of magnetization is the same as the direction of the lines of force established when the transformer is in operation.

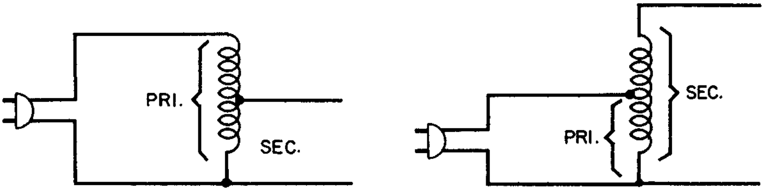
ISOLATION TRANSFORMERS

In addition to its other purposes, the transformer functions as an isolation device. There are no direct wire connections between the primary and secondary; these circuits are coupled only through the magnetic field of the transformer. This feature of isolation is essential, for example, in an amplifier where the plate voltage of one stage must be blocked from the following grid. The transformer couples the a-c component (signal) but blocks the d-c level.

Transformers designed to serve no other purpose but isolation usually have a one-to-one ratio (sometimes slightly higher to make up for losses). These transformers are rated in watts to indicate the magnitude of the load that can safely be connected to the secondary. Service technicians frequently employ such transformers while working on a-c/d-c receivers. The transformer isolates the chassis from the power line, reducing the possibility of accidental shock.

AUTOTRANSFORMERS

The autotransformer is an exception to the rule that there is no direct metallic connection between primary and secondary. In the autotransformer, the same turns are used for both windings.



(A) Step-down. *(B) Step-up.*

Fig. 5-12. Autotransformers.

If all of the turns are used as the primary, as in Fig. 5-12A, the autotransformer has a step-down ratio. A step-up autotransformer is shown in Fig. 5-12B. Here, the turns below the tap serve as the primary, and the entire winding is used as the secondary. The autotransformer is sometimes constructed with several fixed taps or a movable tap to permit variation of the secondary voltage.

FLYBACK TRANSFORMER

The flyback transformer employed in tv receivers utilizes autotransformer action. As indicated in Fig. 4-9, the portion of the winding between the tap and B supply serves as the primary. This primary is connected into the plate circuit of the horizontal-output tube. The entire winding functions as the secondary and is connected to the high-voltage rectifier tube. Because the horizontal-output tube is excited by a sawtooth input, the primary current alternately builds up and decreases. The decrease causes the magnetic field of the primary winding to collapse. This collapsing field cuts across the entire winding, inducing thousands of volts. Additional windings on the flyback transformer supply heater power to the rectifier tube and couple the sawtooth to the horizontal-deflection coils.

Chapter 6

TESTING INDUCTORS AND TRANSFORMERS

Inductors and transformers are employed extensively in electronic equipment. A simple radio receiver, for example, has an antenna coil, an oscillator coil, two i-f transformers, an audio-output transformer, a power transformer, and a filter choke (which may be the field coil of the speaker). More elaborate receivers, such as those used in communications work, include more r-f and i-f stages and therefore require a greater number of transformers. Television receivers use an even larger number of these components. Industrial apparatus, telemetering equipment, radar, navigational devices, and other electronic instruments also employ many inductors and transformers.

In general, inductors and transformers do not become defective as often as other components such as tubes and capacitors. When a defect does occur, it is usually an open (broken wire) or a short (insulation breakdown). A coil may open because of excessive current or because chemical action (corrosion) has eaten away the copper wire. Other causes are thermal expansion of the coil form, or mechanical damage caused by careless handling. Often, the break occurs at the solder terminal. In this event the coil can be easily repaired by cleaning the tip of the wire and re-soldering it to the terminal. Open coils can be easily located by checking for continuity with an ohmmeter. Shorted coils are more difficult to locate because only a few of the turns (or even a single turn) may be shorted. An ohmmeter will not reveal this defect because the short does not change the total resistance of the coil appreciably.

OHMMETER TESTS

The ohmmeter, used as a continuity checker, is useful for locating open coils. Depending on the associated circuitry, it may be necessary to disconnect one end of the coil from the circuit before making the measurement. A burned-out secondary winding in an audio-output transformer, for example, will still show a continuity reading because it is shunted by the voice coil of the speaker. Likewise, an open heater winding of a power transformer will show a continuity reading unless the tubes and pilot light are removed or one end of the winding is disconnected.

Manufacturer's schematics and service manuals frequently indicate the resistance of coils and transformer windings. When such information is available, the actual ohmmeter readings should be compared with these values. Even when such values are not available, an experienced technician will know the approximate ohmic values of various types of inductors and transformers. The windings of an i-f transformer, for example, generally range from 5 to 20 ohms, a power-supply filter choke is typically 150 to 1500 ohms, and a power-transformer primary is usually about 10 ohms.

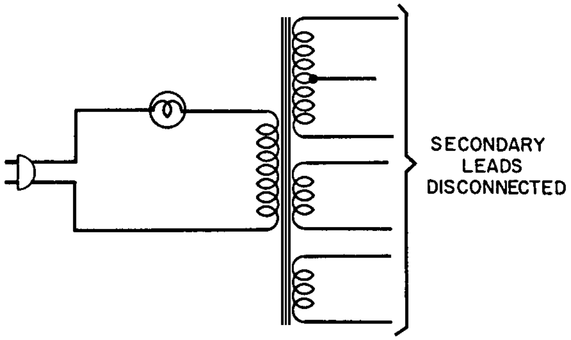
When an open coil is located, some thought should be given to the probable cause of this defect. An open caused by excessive current, for example, is distinguishable from an open caused by corrosion or mechanical damage. A power transformer or filter choke that has been burned open by excessive current can be identified by the characteristic odor of overheated insulation.

If a burned-out coil is replaced without adequate consideration of the probable cause, the new coil may burn out for the same reason as the original. An open filter choke or power transformer, for example, should not be replaced until the rectifier and filter capacitors have been checked for defects. Possible shorts in other circuits connected to the B supply should also be taken into consideration.

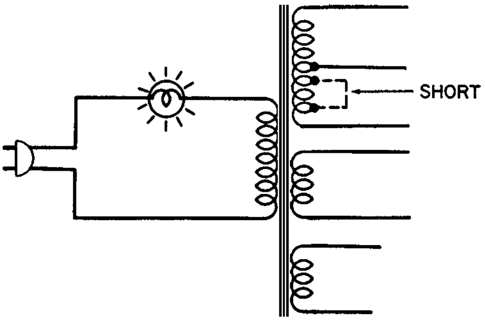
In addition to checking the resistance of coils and transformer windings, the ohmmeter is also useful for checking leakage and shorts. A primary-to-secondary short in an interstage transformer, for example, allows the B voltage from one stage to reach the grid circuit of the following stage. A primary-to-core short in an interstage transformer causes the B voltage to be grounded through the core. This short increases the current drain from the B supply, and may damage the filter choke, rectifier, or power transformer. Winding-to-winding shorts in a transformer are located by connecting the two ohmmeter leads to the two windings. The ohmmeter should show an extremely high reading – corresponding to the resistance of the insulating material in the transformer. In a good transformer, this insulation resistance is many kilomegohms. If the transformer has more than two windings, similar tests should be made between all pairs of windings: primary to secondary 1, primary to secondary 2, secondary 1 to secondary 2, etc. In addition, each winding should be checked for possible shorts to the core. If one of the transformer leads is connected to ground (chassis), this lead should be disconnected before the transformer is checked for winding-to-core shorts. All ohmmeter tests should, of course, be made with the power off.

Shorts between adjacent turns or adjacent layers are often difficult to detect with an ohmmeter because they produce only a small change in the total resistance of the winding. This does not imply that the short is not important if it involves only a few turns. Even a single shorted turn will prevent normal operation of the circuit and can cause excessive current. A shorted turn in the secondary of a power transformer, for example, can burn out the primary winding. Since a heavy current circulates through the shorted turn, and since this power must come from the primary circuit, primary current rises far above its normal value. Similarly, a short in the B+ circuit will often burn out the primary winding of the transformer.

Turn-to-turn or layer-to-layer shorts can sometimes be identified by the method illustrated in Fig. 6-1. All secondary leads are disconnected, and a light bulb is wired in series with the primary. If the transformer is not defective, only a small magnetizing current will circulate in the primary circuit – not enough to light the bulb (Fig. 6-1A). If the transformer has shorted turns, however, the primary current will be high enough to light the lamp as shown in Fig. 6-1B.



(A) Good transformer.



(B) Shorted turns.

Fig. 6-1. Testing for shorted turns.

VOLTMETER TESTS

Defective inductors and transformers often can be located with voltage checks. A power transformer, for example, can be tested simply by measuring the voltage across each winding. The voltage outputs of the two sections of a center-tapped secondary should be measured separately and compared. These voltages should be equal, or almost equal within manufacturing tolerances.

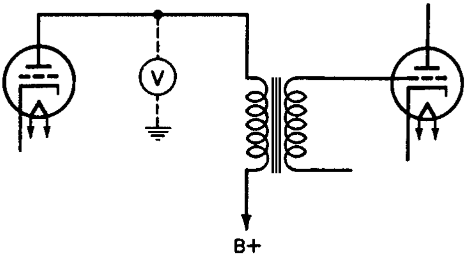


Fig. 6-2. Voltage test reveals defective coupling transformer.

Unbalance in the two halves may indicate shorted turns, particularly if the transformer has been running hotter than normal. Voltage measurement is also useful for checking a-f, r-f, and i-f transformers. The voltmeter used must be able to respond to these signal frequencies, or an appropriate probe must be used to convert the signal to a d-c potential.

A voltmeter check for revealing a defective coupling transformer is illustrated in Fig. 6-2. Assuming the B supply voltage has been measured and found to be reasonable in value, the voltmeter is now connected to the plate side of the transformer primary. At this point, the voltmeter shows no reading. The transformer primary is therefore assumed to be either open, or grounded through a short to the core. If the transformer appears to be overheating, this would lend credibility to the assumption that it is shorted. If the transformer is "cold," it can be assumed to be open. In either case, the results obtained by the ohmmeter will verify the assumption.

A technique for measuring the value of an unknown inductance is illustrated in Fig. 6-3. The inductor and a variable resistor are connected in series across an a-c input. This input may be obtained from an audio generator or from the power line (avoid excessive current, which might overheat the inductor or resistor). The variable resistor is now adjusted until the voltage across it is equal to the voltage across the unknown inductor. The Function switch of the voltmeter should, of course, be set to alternating current. Two meters are shown in Fig. 6-3, but only one is required. A single meter is, in fact, preferable because of possible differences in the calibration and accuracy of two separate meters. The meter is connected first across the inductor and then across the resistor which is adjusted to make these voltages equal. If desired, an oscilloscope can be used instead of the meter, and the variable resistor adjusted until the scope pattern across it is equal in height to the pattern obtained across the inductor. When this balance is established, the value of the resistor is equal to the impedance of the inductor. The power is now turned off and the resistor (left at the same setting) is measured with an ohmmeter. The resistance of the inductor is also measured with the ohmmeter, and the unknown inductance can now be determined from:

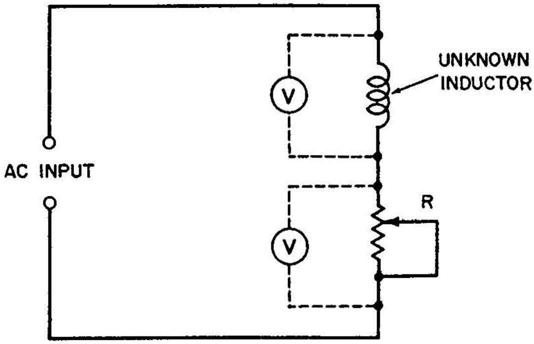


Fig. 6-3. Technique for determining value of unknown inductor.

$$L = \frac{\sqrt{R^2 - r^2}}{2\pi f}$$

where,

L is the inductance in henrys,
R is the measured value of the variable resistor in ohms,
r is the measured value of the coil resistance in ohms,
f is the frequency of the a-c input in hertz,
π is a constant equal to 3.14.

Examples: The variable resistor in Fig. 6-3 is adjusted for a condition of balance as described before. This variable is now measured and found to be 2100 ohms. The resistance of the coil when also measured is found to be 150 ohms. If the frequency of the a-c input is 60 Hz, what is the value of the unknown inductance?

Solution:

$$\begin{aligned} L &= \frac{\sqrt{R^2 - r^2}}{2\pi f} \\ &= \frac{\sqrt{2100^2 - 150^2}}{6.28 \times 60} \\ &= 5.5 \text{ henrys} \end{aligned}$$

Although this method does not yield laboratory accuracy, it is adequate for most applications and offers the advantages of being quick and convenient to use. In addition, it requires no special equipment such as an inductance bridge.

RESONANCE METHOD

Fig. 6-4 illustrates a technique in which the unknown inductance is resonated with a known capacitance. The inductor and capacitor are connected as a parallel-resonant tank, and this tank is connected through a variable resistor to a signal generator. In general, an a-f generator is preferable to an r-f generator, to minimize the effects of stray and distributed capacitance. An a-c voltmeter (or an oscilloscope) is connected across the tank as shown.

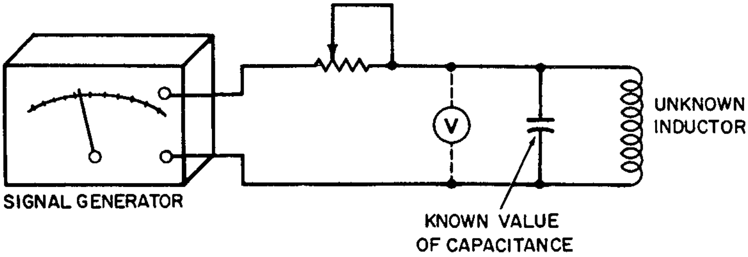


Fig. 6-4. Resonance method of determining value of unknown inductor.

The variable resistor and the signal generator are now adjusted so that the voltmeter pointer will swing sharply upscale as the generator is tuned through the frequency to which the tank is resonant (the generator frequency that produces maximum deflection of the voltmeter). The unknown inductance can now be determined from:

$$L = \frac{.0253}{f^2C}$$

where,

L is the inductance in henrys,
f is the resonant frequency in kilohertz,
C is the tank capacitance in microfarads.

Example: Maximum deflection of the voltmeter in Fig. 6-4 occurs when the generator is set to 8 kHz. If the tank capacitance is .01 microfarad, what is the value of the unknown inductance?

Solution:

$$L = \frac{.0253}{f^2C} = \frac{.0253}{8^2 \times .01} = \frac{.0253}{.64} = .0395 \text{ henry}$$

INDUCTANCE BRIDGE

When high-accuracy measurement of an unknown inductance is required, an inductance bridge must be used. This is a laboratory-type instrument capable of much greater accuracy than can be attained using the techniques illustrated in Figs. 6-3 and 6-4.

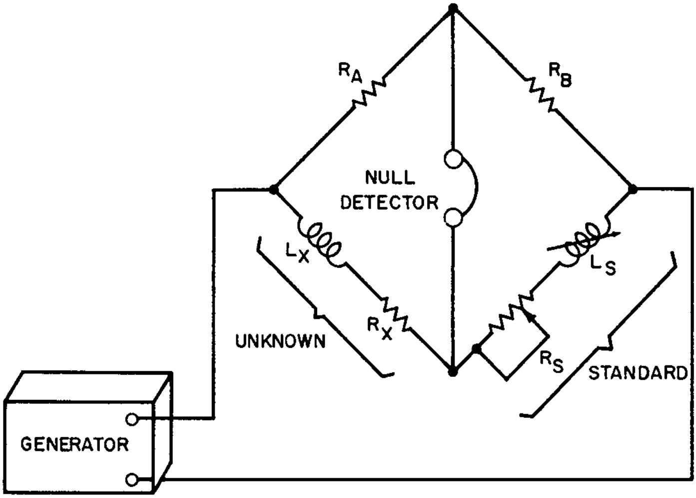


Fig. 6-5. Basic inductance bridge.

In the bridge circuit, the unknown inductance is compared against a known value of inductance called the *standard.* This standard inductance is variable, as shown in the basic inductance bridge of Fig. 6-5.

An a-c signal from the generator is applied to opposite terminals of the bridge. The frequency of this signal is commonly 60, 400, or 1000 Hz. A null detector, usually a headset or meter, is connected across the other terminals of the bridge circuit. The standard inductor (L_S) is now adjusted to balance the unknown inductor (L_X), and the standard resistor (R_S) is adjusted to balance the resistance (R_X) of the unknown inductor. When this balance has been established, the audio tone of the generator can no longer be heard in the headset. If a meter is used instead of the headset, the null or balance will be indicated by a zero reading of the meter. This occurs because the two terminals to which the null detector is connected are at the same potential when the bridge is balanced. The inductance and resistance of the unknown can now be determined from:

$$L_X = \frac{L_S R_A}{R_B}$$

$$R_X = \frac{R_S R_A}{R_B}$$

Note that the standard and unknown inductors need not be equal in value when the bridge is balanced, but that the ratio of the unknown to the standard inductance be equal to the ratio of R_A to R_B. For this reason, a switch may be provided in the instrument to select one of several different resistors for use as R_A (or R_B). Its setting determines the range of inductance that can be measured. One switch position, for example, may permit measurement in the microhenry range, another for the millihenry range, and still another position for the measurement of inductors of many henrys.

Calibrated dials generally are attached to variable standards L_S and R_S. When the bridge is balanced, these dials indicate the values of the unknowns, L_X and R_X. In most commercially available bridges, the variable standards are called *decades*. A resistance decade, for example, consists of a switch and several fixed resistors. According to the setting of the switch, these fixed resistors can be connected in various combinations to produce different totals. Typically, six decades are used, and the resistance values are selected so that the total resistance can be changed in steps of 1 ohm, 10 ohms, 100 ohms, 1K, 10K, and 100K. A panel arrangement for a six-decade resistance standard is shown in Fig. 6-6. With the switches set as shown, the total resistance is 374,205 ohms. Although each decade has eleven switch positions (including 0), only four resistors per decade are required. The one-ohm-per-step decade, for example, would have four resistors of 1, 2, 3, and 4 ohms. When the switch is set to the *5* position, the 2- and 3-ohm resistors are connected in series; in the *7* position, the 3- and 4-ohm resistors are in series; in the *9* position, the 2-, 3-, and 4-ohm resistors are in series; etc. Simi-

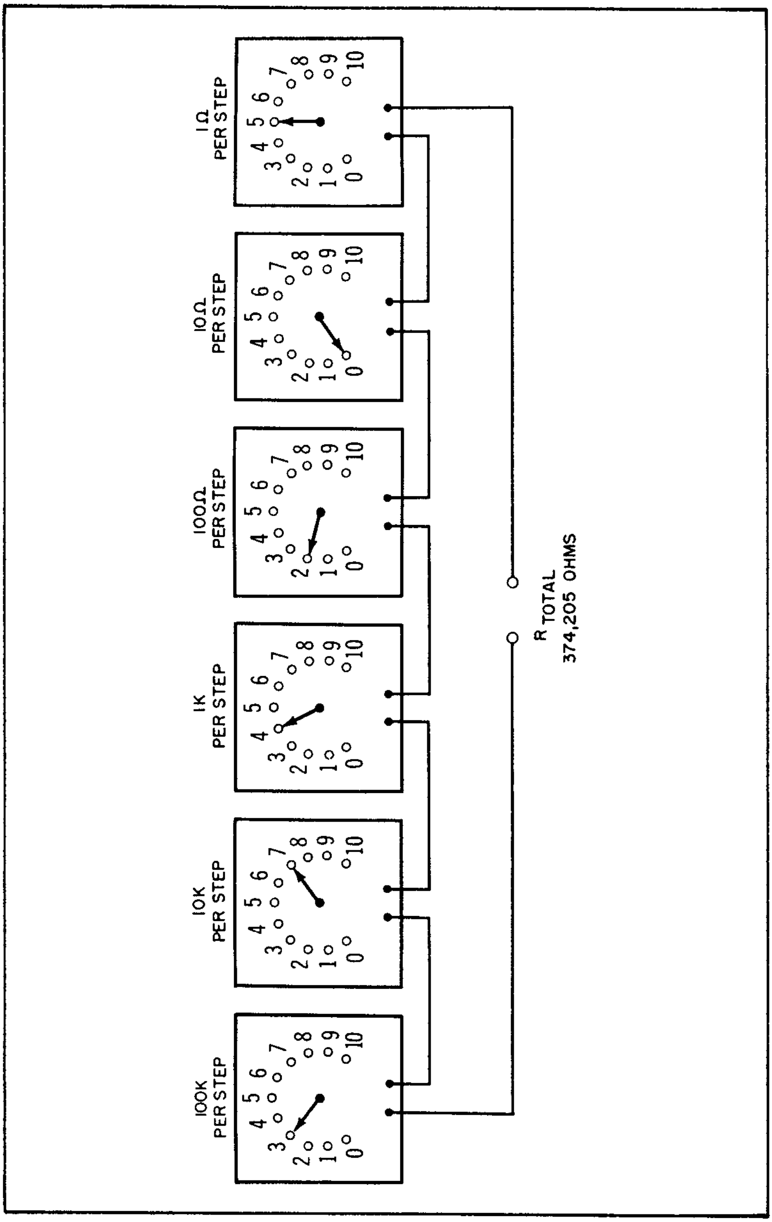


Fig. 6-6. Six-decade resistance standard.

larly, the standard inductor (L_S) consists of fixed inductors and appropriate switching arrangements.

A headset is shown as the null detector in Fig. 6-5, but a meter is often used instead. To permit more accurate bridge balance, a high-gain amplifier is used with the null detector. As a result, even a slight unbalance of the bridge will produce an observable indication on the null meter. The bridge can therefore be adjusted to near-perfect balance. Null amplifiers are sometimes designed to have a logarithmic response. This prevents the null meter from being driven off scale when the bridge is considerably off balance, but still provides high gain for small signals as the bridge is brought close to perfect balance. By the use of RC networks or LC tanks, the null amplifier is tuned to the frequency of the generator used to excite the bridge. The a-c input is applied to the bridge, and the bridge output to the null amplifier, through shielded leads to minimize direct pickup from the generator to the amplifier.

OWEN BRIDGE

Because low-tolerance inductance standards are expensive and difficult to manufacture, many inductance-measuring instruments employ a bridge that does not require a standard inductor. The *Maxwell* bridge, and also the *Hay* bridge, employ a capacitor as the standard. In the *Owen* bridge, shown in Fig. 6-7, the unknown inductor is balanced by a resistance decade (which can be more easily manufactured to a closer tolerance). A leading voltage (because of the lagging current) appears across the unknown inductor in one side of the bridge. Because of the capacitance in the other side of the bridge, a leading voltage is produced across the standard resistor. For this reason, the resistance in one side of the bridge can be used to balance the inductance in the other side. The resistance of the unknown inductor determines the phase angle of the leading voltage across this inductor. A variable capacitance determines the phase angle in the other side of the bridge and therefore balances the resistance of the inductor. The switch dials of the standard resistance decades indicate the value of the unknown inductance. The switch dials of the capacitor decades

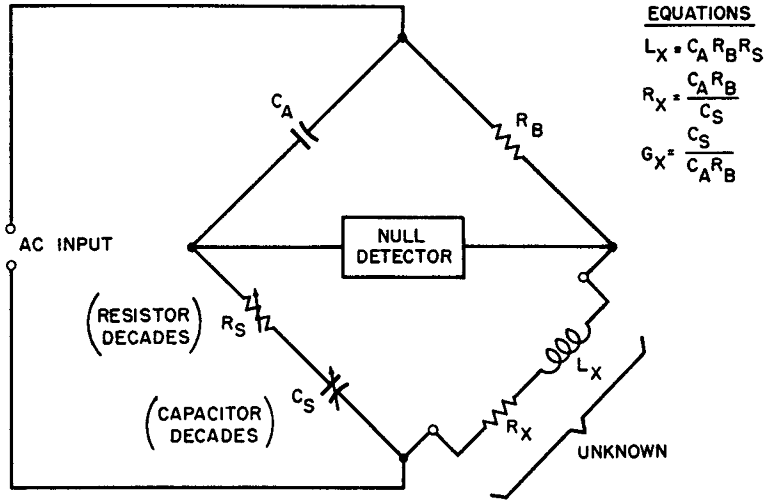


Fig. 6-7. The Owen bridge.

indicate the conductance (G) of the unknown. The resistance of the unknown inductor can be easily determined by:

$$R_X = \frac{1}{G}$$

The circuit diagram of an incremental inductance bridge is shown in Fig. 6-8. Switch SW1 selects the range of the bridge, to permit measurements up to 1111.1 henrys. Switch SW2 connects the resistor decades in either series or parallel with the capacitor decades (depending on the *Q* of the unknown inductor, sharper null balance may be achieved with either the series or parallel arrangement of the standards). Switch SW3 permits connection of an external vtvm to indicate the voltage across the unknown inductor. When this switch is released, the vtvm is disconnected to prevent its input capacitance from unbalancing the bridge. Since the value of an iron-core inductor may vary according to the d-c current through it, it may be desirable to mea-

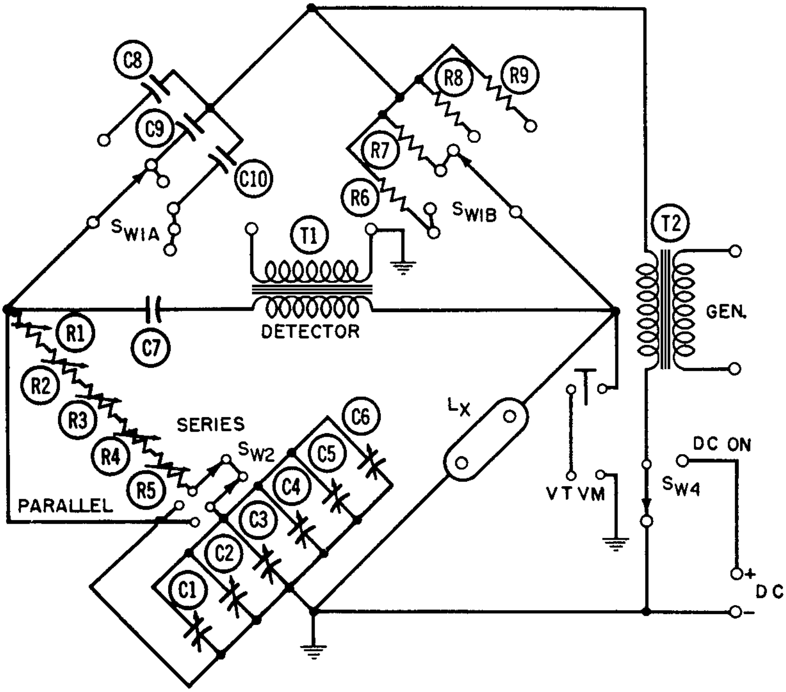
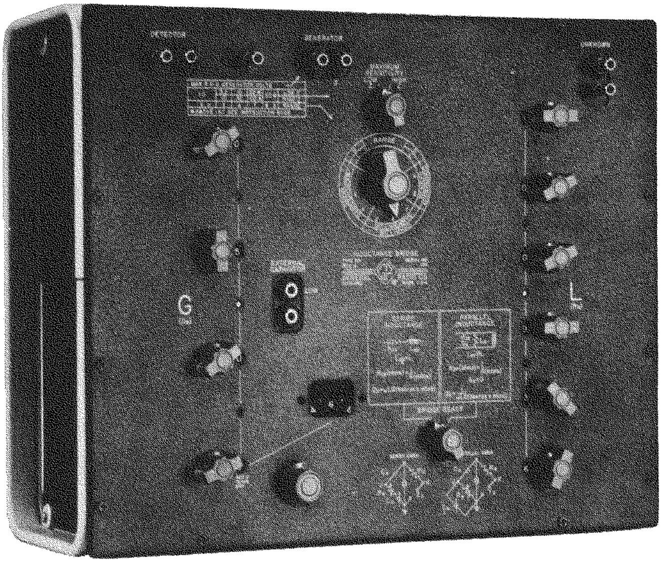


Fig. 6-8. Incremental inductance bridge.

sure the inductance at a particular value of current. A bridge that permits such measurement is known as an *incremental* inductance bridge. The instrument illustrated in Fig. 6-8 permits this type of measurement by means of SW4. Through this switch, an external d-c source can be connected in series with the input transformer from the a-c generator. Capacitor C7 blocks the d-c component from the output transformer that feeds into an external null-detector amplifier.

Another incremental inductance bridge is shown in Fig. 6-9. It has full-scale ranges from 111 microhenrys to 1111 henrys, and can be balanced to a precision of 0.1 per cent for an inductance as low as 0.1 microhenry. Full-scale conductance ranges are from 111 micromhos to 1111 mhos. The digits of the switch dials are visible through windows in the front panel, providing in-line digital readout of inductance and conductance.



Courtesy General Radio Co.

Fig. 6-9. Type 1632-A inductance bridge.

Chapter 7

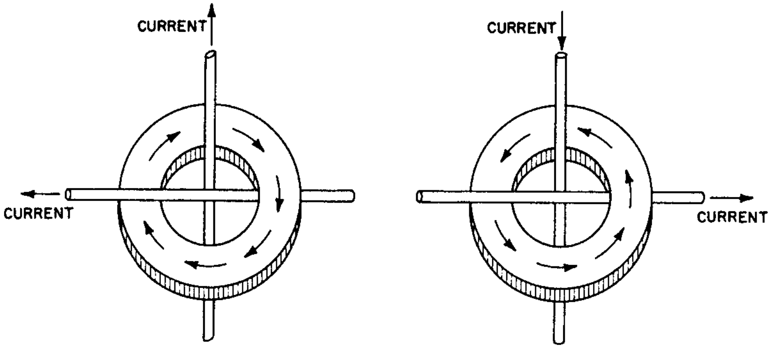
MAGNETIC CORE MEMORY AND LOGIC

In digital counters and computers, information is represented and manipulated in binary numbers. The binary number system employs only two symbols (0 and 1) as compared to the familiar decimal system with its ten symbols: 0, 1, 2, 3, 4, 5, 6, 7, 8 and 9. Typical binary numbers therefore look like this: 110100001 and 1000010111.

The ones and zeros of the binary system can be represented by transistors that are either conducting or nonconducting, by holes or no-holes at specified locations in a punched card, or by flux in either of two directions on a strip of magnetic tape.

Ferrite cores often are used to represent the ones and zeros of binary notation. A ring-shaped core (toroid) of magnetic material may be magnetized in either of two directions: clockwise or counterclockwise. One of these directions of magnetization can represent a binary *one*, and the other direction can represent a *zero*. The digits (bits) of a binary number can thus be represented by a group of magnetic cores, some magnetized in one direction and some in the other.

As shown in Fig. 7-1, the direction of magnetization of a core depends on the direction of electron flow in the wires passing through it. Actually, current is allowed to circulate for only a few millionths of a second; this is sufficient to magnetize the core. The core then retains its magnetism in the same direction until current of opposite polarity in the wires reverses the magnetic flux. This ability of the core to magnetize quickly and to retain its magnetism indefinitely accounts for the use of thousands of cores in computer memories. The ferrite materials for this application are selected for their ability to retain magnetism and to reverse rapidly.



(A) Core magnetized in "1" direction. *(B) Core magnetized in "0" direction.*

Fig. 7-1. Magnetic cores.

CORE SWITCHING

In addition to "remembering" binary data, ferrite cores are also useful for shifting data and for performing logical operations in the computer. A basic core arrangement is shown in Fig. 7-2.

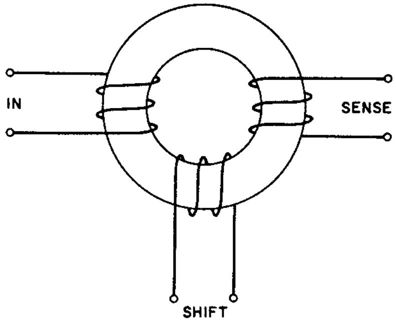


Fig. 7-2. Core switching.

If a pulse of current is passed through the "in" coil, the core will magnetize in the direction representing binary *one*. This process is referred to as *setting the core* or *writing a one*. If, at some later time, a pulse of current is passed through the "shift" coil, the core will magnetize in the direction representing binary *zero*. This process is referred to as *clearing, reading* or *resetting* the core. Note that the "in" coil is used to put a *one* into the core, and the "shift" coil is used to clear the core to *zero*.

The "sense" coil produces output when the "shift" pulse reverses the magnetic flux of the core. This output is the voltage induced in the sense coil when it is cut by the reversing magnetic field. Note that an output may or may not appear in the sense coil at the time the shift pulse is applied. This depends on the previous state (one or zero) of the core. If the core was already magnetized in the zero direction, the shift pulse would produce no reversal of magnetic flux. Under these conditions, the sense coil would not be cut by lines of force and would produce no output voltage. The shift operation can therefore be regarded as an interrogation of the core to determine whether it contains a one or a zero (in one case voltage will be induced in the sense coil, in the other case it will not).

THE SHIFT REGISTER

Fig. 7-3 shows a number of cores connected to form a *shift register*. Assume that the first core has previously received an input pulse and is therefore magnetized in the *one* direction. If a shift pulse is now applied, all cores will be switched to the *zero* state (if they were not already in that state). As the first core switches from one to zero, voltage is induced in its sense coil. The voltage charges a capacitor through a diode. After the shift pulse is completed, the capacitor discharges through the input coil of the second core. The second core therefore magnetizes in the *one* direction. The binary *one* has thus been shifted from the first core to the second. If another shift pulse is now applied, the *one* will move from the second core to the third. The diode connected in the output circuit of each core prevents the capacitor from discharging back through the sense winding of the same core. Discharge of the capacitor must therefore occur through the input coil of the following core. Shift registers are useful for moving a long string of ones and zeros into or out of various computer circuits.

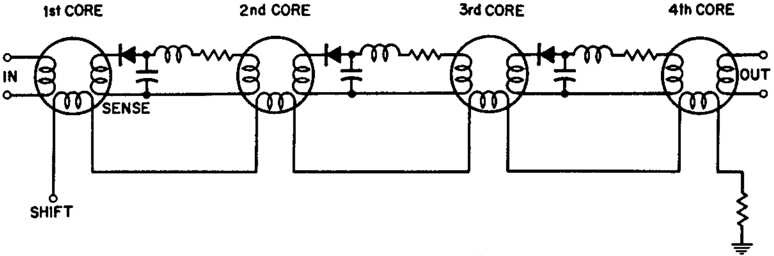


Fig. 7-3. Magnetic shift register.

CORE LOGIC

Magnetic cores also are used to perform *logical* operations in computers and related equipment. Fig. 7-4 shows a core with two input coils labeled A and B. The core can therefore be set to the one state by applying a pulse to either coil A or coil B or both. This corresponds to the logical operation "A OR B".

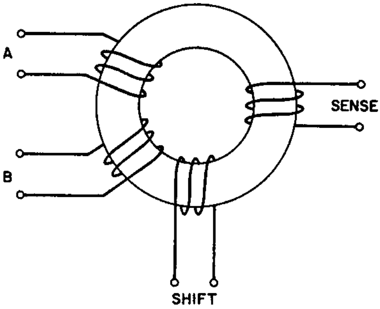


Fig. 7-4. Core with two input coils.

If current of opposite polarity is passed through coil B, it will cancel the effect of the current through coil A. Coil A is therefore inhibited and cannot write a *one* into the core. The only way to set this core is to apply a pulse to A but not to B. This corresponds to the logical operation "A AND NOT B", a basic and important operation in computer logic circuits.

In Fig. 7-5, the core has three input coils. A continuous inhibiting current is passed through coil C. Both A and B must therefore be pulsed in order to overcome the inhibiting current and set the core to *one*. This corresponds to the logical operation "A AND B".

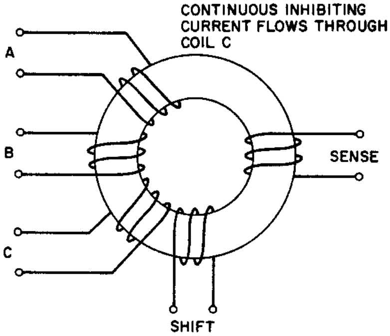


Fig. 7-5. Core with three input coils.

CORE TRANSISTOR LOGIC

For improved flexibility and reliability, a transistor may be employed in conjunction with the core. As indicated in Fig. 7-6, the transistor receives its input from the sense winding. When a shift pulse switches the core from the one to the zero state, the sense winding provides output voltage to "turn on" the transistor.

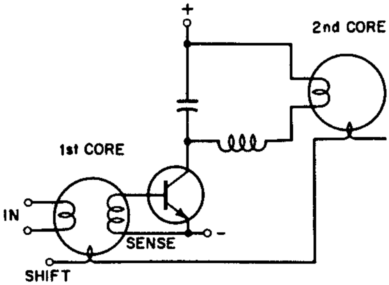
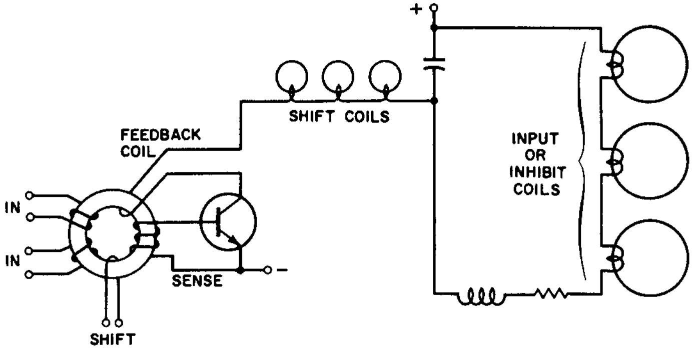


Fig. 7-6. Core-transistor shift register.

Courtesy DI/AN Controls, Inc.

The transistor now conducts, and its current charges the capacitor. When the magnetic field of the core has finished reversing, no more voltage is induced in the sense coil. At this time, the transistor turns off and the capacitor is free to discharge through the input coil of the next core. The capacitance and inductance provide sufficient time delay to assure that the shift pulse will be finished before the capacitor attempts to set the following core. This delay is necessary because a core cannot be set to the one state at the same time the shift pulse is clearing it to the zero state.

High-speed switching of the core is desirable because it permits a greater amount of information to be processed in a given length of time. The switching action of a magnetic core can be speeded up by employing a transistor in a regenerative feedback arrangement. A circuit of this type is shown in Fig. 7-7. Assume that a shift pulse is applied, and the core begins to switch from one to zero. Voltage is now induced in the sense coil, and the transistor conducts. Transistor current circulates through the feedback winding and aids the shift coil in switching the core to zero. As a result of this additional current through the feedback winding, the core reverses its magnetism very rapidly. As shown in Fig. 7-7, an undelayed output is available for the shift windings of other cores, and a delayed output is available for the inhibit or input coils.



Courtesy DI/AN Controls, Inc.

Fig. 7-7. Core-transistor logic.

Appendix

GLOSSARY

air-core inductor – A coil wound of heavy-gauge, self-supporting wire, or one wound on ceramic, plastic, or other nonmagnetic material.

autotransformer – A transformer consisting of a single winding with a tap. If the a-c input is applied across the entire winding and the output is taken between the tap and one end of the coil, the transformer has a step-down ratio. If the a-c input is applied between the tap and one end and the output is taken across the entire winding, the transformer has a step-up ratio.

back emf – Also known as counter emf. Voltage induced in a coil by a change of current through it. The back emf is of such polarity that it opposes the current change that produced it.

bandpass filter – A network that passes a narrow band of frequencies and attenuates frequencies above and below this band.

band-rejection filter – Also known as a band-stop filter. A network that greatly attenuates frequencies within a narrow band and passes frequencies above and below this band. This type of filter is useful for attenuating an interfering signal.

coefficient of coupling – A numerical value, between 0 and 1, expressing the magnetic "closeness" of two coils. If the coils are completely coupled, all of the magnetic lines of each coil are linked with the turns of the other coil, and the coefficient of coupling is 1. If no coupling exists, none of the lines of force of either coil link with the turns of the other coil, and the coefficient of coupling is 0.

core saturation – In an iron-core component, the condition whereby the core is completely magnetized. A further increase of current will therefore produce no appreciable increase of magnetic flux. Since the flux can no longer increase, no counter emf is produced and the inductance of the coil is greatly reduced.

distributed capacitance – The self-capacitance of a coil, consisting primarily of the capacitance between adjacent turns and layers. Because of its distributed capacitance, the inductor becomes a resonant tank circuit at the frequency at which the capacitive reactance is equal to the inductive reactance.

eddy currents – Currents induced in the magnetic core of an inductor or transformer as the core is cut by the magnetic flux of the coil. These currents produce heating of the core and represent a power loss.

henry – The unit of measurement of inductance, named in honor of Joseph Henry. Subdivisions of this unit are the millihenry and microhenry, equal to a thousandth and a millionth of a henry respectively.

high-pass filter – A network that favors the passage of high frequencies and attenuates the lows.

hysteresis loss – Loss that occurs in magnetic core components because the core is unable to change its magnetism as rapidly as the changes in current.

impedance—The opposition to alternating current of a circuit or component. The impedance of an inductor is the vector sum of its reactance and resistance.

impedance-matching transformer — A transformer used to couple circuits or components of different impedance — for example, the plate circuit of an amplifier tube to the low impedance of a speaker coil.

inductance — The property of a component or circuit that opposes changes of current.

inductive reactance — The opposition which an inductance offers to a changing current. It is specified in ohms and is represented by X_L. Numerically, $X_L = 2\pi fL$.

Litz wire — A type of stranded wire sometimes used to reduce skin effect in coils. The strands are separately insulated. Their total surface area is greater than the surface area of a solid conductor of equivalent cross-sectional area.

low-pass filter — A network that favors the passage of low frequencies and attenuates the highs.

magnetic amplifier — A type of amplifier utilizing the properties of a saturable-core reactor. The reactor is connected in series with a load and the a-c supply. Current through the load can therefore be controlled by varying the saturation of the core.

mutual inductance — A property existing when two coils are magnetically coupled (a change of flux of one coil induces a voltage in the other coil). Mutual inductance is specified in henrys, millihenrys, or microhenrys.

powdered-iron core — A magnetic core consisting of finely powdered magnetic material mixed with an insulating binder. Since each magnetic particle is electrically insulated from the others, eddy-current losses are reduced. The core material is pressed into shape to fit inside the coil. This slug of core material may be movable to permit variation of the inductance.

Q — A numerical rating specifying the quality of a coil in terms of the ratio of its reactance to its resistance.

saturable reactor — An iron-core inductor, the reactance of which can be controlled by varying the degree of core saturation. This is accomplished by varying the d-c current through another coil on the same core.

skin effect — The tendency of high-frequency current to flow on the surface rather than through the interior of a conductor. Since this effectively reduces the cross-sectional area of the conductor, its a-c resistance is greater than its d-c resistance.

slug-tuned coil — A variable inductor employing a movable core, usually of powdered iron.

step-down transformer — A transformer having more primary than secondary turns. Voltage induced in the secondary is therefore less than the voltage applied to the primary.

step-up transformer — A transformer having more secondary than primary turns. Voltage induced in the secondary is therefore greater than the voltage applied to the primary.

swinging choke— A power-supply filter choke so designed that its inductance will not decrease (because of core saturation) below a critical value, even at maximum current.

turns ratio — Ratio of the number of primary turns to the number of secondary turns of a transformer.

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