SECTION 2

ADVANCED
PRACTICAL
RADIO ENGINEERING

TECHNICAL ASSIGNMENT

INDUCTANCE

Capitol Radio Engineering Institute
Washington, D. C.

212 E

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INDUCTANCE

SCOPE OF ASSIGNMENT

It has been shown that the current caused to flow through a conductor by a voltage impressed across the conductor does not necessarily rise and fall in unison with the voltage. The current has actually three alternatives; it may be IN PHASE with the voltage, the condition in a circuit containing only resistance; the current will lag behind the voltage when the circuit is inductive; and the current will lead the voltage when the circuit is preponderantly capacitive.

If the circuit is made up of resistance only, Ohm's law can be applied in a very simple manner, in that the current at any instant is a direct function of the voltage AT THAT INSTANT. But in either the inductive or capacitive circuit that is not the case. The current may be near its zero value when the voltage is at maximum, or vice versa.

This assignment will deal with the effects of inductance in the circuit. The phenomena of inductance are fully explainable by the relations between *magnetism* and *electricity*—that is, between magnetic fields and current carrying conductors, although mechanical analogies are also useful.

CHARACTERISTICS OF INDUCTANCE

CHANGE IN FLUX LINKAGES.—The action of the generator, as explained in an earlier assignment, was based on the relative MOTION of a conductor in a magnetic field. If either moved past the other so that the conductor cut the magnetic field, a voltage was induced in the conductor.

There is another way of inducing a voltage that is very similar, and that is by varying the amount of magnetic flux linking a *closed* electric circuit. This is the transformer action, and it involves no physical motion of the magnetic field nor of the conductor loop but merely a CHANGE or VARIATION with TIME in the number of flux lines passing through (linking) the closed loop or circuit.

Note the difference. In the first case, that of the generator, the magnetic flux may be *constant* in magnitude, but as it moves crosswise and cuts the conductor, it generates a voltage in it. Note also that the conductor does not have to be a closed loop or circuit, although—to measure the voltage—a voltmeter has to be connected which acts to complete the circuit of the conductor.

In the second case, that of the transformer and inductance, the magnetic flux is stationary in space, but it varies in *strength* or flux density with TIME. A closed circuit surrounding it has a voltage induced in it and an induced current will therefore flow.

The manner in which the magnetic field can be made to vary in intensity with time is by causing the current flowing in a coil that produces the flux to vary with time. Since the flux is normally proportional to the current (barring saturation), the flux will vary in the same manner as the current, and by its RATE OF CHANGE WITH TIME will induce the voltage in the loop conductor.

Note that if the current INCREASES, the induced voltage has one direction in the loop; if it DECREASES, it has the opposite direction in the loop. Also note that the direction of the flux, and hence that of the current in the magnetic coil, also serves to determine the direction of the induced voltage. By this is meant that if the current *increases* in one direction in the coil, thereby causing the flux to *increase* in a certain direction through the loop, the voltage induced in the loop will have the same direction as if the current and flux were *decreasing* and flowing in the *opposite* direction.

In Fig. 1 (A), (B), (C) and (D) are shown the conditions that exist. Compare first (A) and (B) and (C) and (D) in pairs. In (A) and (B) the current* is shown as flowing in a clockwise direction in the coil when viewed from the right-hand end of the coil. It is also assumed to be increasing in (A). As a result the voltage induced in the loop is in a counter-clockwise direction as viewed from the same position, and it causes a current to flow in the loop in a direction OPPOSITE to that of the current flowing in the magnetic coil.

In (B) the current is assumed to be decreasing with time. Since it flows in the same direction in the coil as in (A), the voltage induced in the loop is in the OPPOSITE direction to that in (A). In (C) and (D), the current flow is opposite to that in (A) and (B), so that the magnetic flux proceeds from left to right instead of from right to left.

In (C) the current is decreasing; in (D), it is increasing. Hence the voltage induced in (C) is *opposite* to that induced in (D). This is in accord with the results obtained in (A) and (B).

Compare now (C) and (A), or (D) and (B). In either pair the current flows are OPPOSITE, but the directions of change (rise or drop) are also OPPOSITE. As a result, the voltage induced is in the SAME direction for (C) and (A), or for (D) and (B). In short, reversing EITHER the direction of flow of the current or its direction of change (increase or decrease), BUT NOT BOTH, changes the direction of the induced voltage in the loop.

LENZ'S LAW.—The induced voltage tends to produce a current flow in the *same* direction in the loop, hence the arrows shown on the loop in the four different cases can just as well represent the direction of the induced current flow in the loop. An inspection of any of these shows that the induced current flows *opposite* to that of the magnetic coil, so that the loop current tends to set up a magnetic field OPPOSITE to that set up by the current in the magnetic coil. This leads to a basic law of magnetic circuits known as LENZ'S LAW. LENZ'S LAW STATES: THE DIRECTION OF THE INDUCED E.M.F. IS SUCH THAT IT TENDS TO SET UP A CURRENT THE MAGNETIC FIELD OF WHICH ALWAYS OPPOSES ANY *CHANGE* IN

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*As stated in the assignment on magnetism, the conventional direction of current flow will be assumed when magnetic flux is involved, in order to conform with the conventions employed in standard text books. Hence the direction of current flow shown here is *opposite* to that of the actual electron flow.

THE EXISTING FIELD.

Lenz's Law does *not* state that the field of the induced current always opposes the field of the inducing or primary current; it always opposes any CHANGE in the field of the existing current. The word 'change' is the most important word associated with the phenomena of inductance and when used with inductance always implies a changing *current*. The effects of inductance in a circuit are due to *current* variations and are not related to voltage variations except for the effect of the voltage variations on the amplitude of the current.

Lenz's law has been illustrated by Fig. 1; the four arrangements shown consist of two circuits each, namely a magnetic coil and a loop. The two circuits constitute a kind of TRANSFORMER, as it is called, and the important point is that ANY CHANGE in the magnetic field set up by the current in the one circuit is opposed by the current induced in the other circuit.

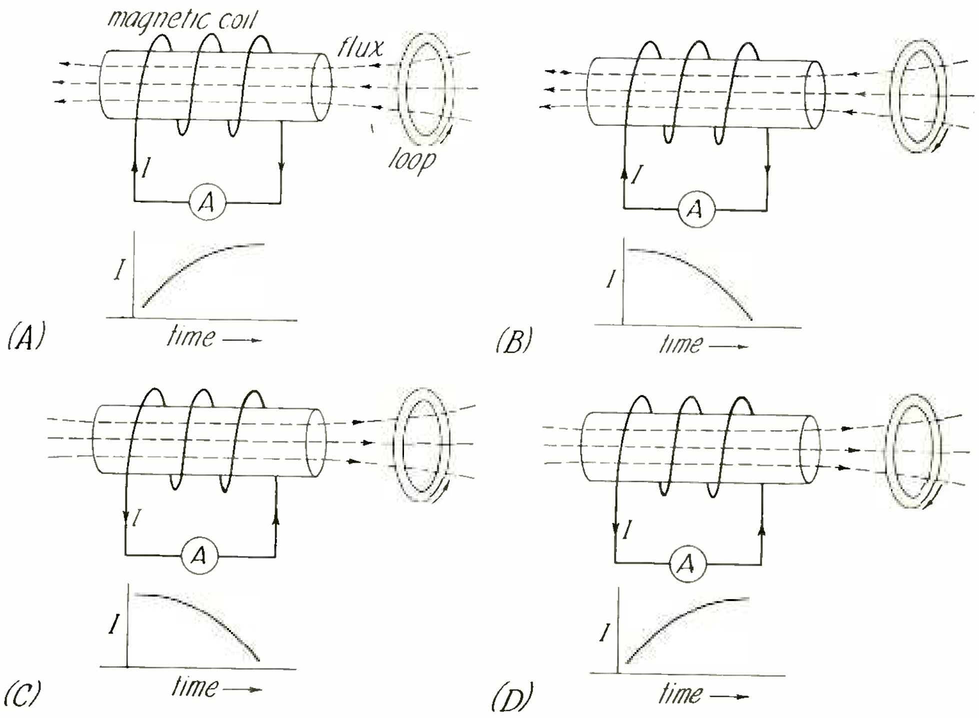


Fig. 1.—Relation of induced voltage to direction and variation of flux linking the loop.

This matter will be gone into in considerable detail in a later assignment, but it is desired to bring out here that whichever circuit sets up the initial flux, whether it be the one designated as the magnetic coil in Fig. 1 or the one designated as the loop, the *other* circuit opposes any change in that flux by the action of its induced current as set up by the induced voltage.

The action is therefore MUTUAL and RECIPROCAL; it works in either direction. The ability of the one coil to induce a voltage in the other is designated by the term MUTUAL INDUCTANCE; it is this phenomenon that will be taken up in detail in a succeeding assignment. The only further point to be taken up here is that *either* coil can act as the origin of the flux, and is known as the PRIMARY COIL; the other, in which the voltage is induced, is known as the SECONDARY COIL.

Since mutual inductance is the basis of transformer action, its importance in radio as well as in power work is indeed great. However, this assignment is concerned with another phase of induction, namely the counter voltage induced in the very coil in which the current and flux are caused to vary. The two phenomena are very closely related, and the only reason for taking up that of mutual inductance first was that it was easier to visualize.

However, as just indicated the changing magnetic flux plays no favorites: it induces a voltage in each and every closed circuit through which it passes including the closed circuit that produces it. This gives rise to SELF INDUCTANCE, in contradistinction to mutual inductance. It will therefore be of interest to examine the phenomenon of self inductance in greater detail, in order to see more clearly its action and properties.

INDUCTANCE IN D-C CIRCUITS.— When a voltage is impressed across a circuit, current will flow. The amount of current which flows is dependent upon various factors.

In a purely resistive d-c circuit as shown in Fig. 2, the value of the current is given by Ohm's law as being equal to E/R. This value will be the equilibrium current; i.e., in flowing through the resistor, this amount of current will produce a voltage drop (IR drop) across R of a value equal to the supply voltage. This is in accordance with Kirchhoff's voltage law that the applied voltage and the voltage drops must balance.

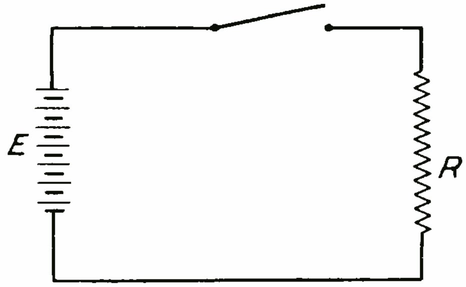


Fig. 2.—Purely resistive d-c circuit.

If the circuit is suddenly broken, the voltage and the current immediately drop to zero. This situation can exist only when the circuit is purely resistive.

On the other hand, if the resistor of Fig. 2 is replaced with a coil of wire as shown in Fig. 3, a different set of conditions will exist. Any circuit in which the current flow sets up a magnetic field is said to possess *self inductance*. For a given current, the circuit which has the most flux set up will have the largest self inductance; a coil is the usual method of obtaining the most inductance in a given space.

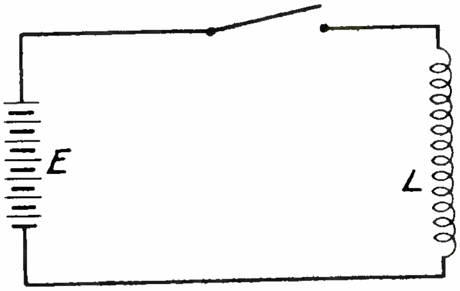


Fig. 3.—Purely inductive d-c circuit.

When the current in a circuit changes, corresponding variations occur in the flux. It was previously stated that a variation in the flux linking one or more conducting loops results in an e.m.f. being induced in the loop (or loops). In the specific case under consideration, the induced e.m.f. is in such a direction as to oppose such change in the current. Hence, as also stressed previously, it is clear from this that it is actually the VARIATION in the flux rather than the flux itself which causes an e.m.f. to be induced in a conducting loop linked by the flux.

In a purely inductive circuit, there is no opposition (voltage) to the current flow except that offered by the inductance, since the resistance is assumed to be zero. The opposition therefore appears only when the CURRENT CHANGES: the ensuing flux variations induce an e.m.f. which opposes the change in current. On the other hand, when the current is steady, there is no variation in the flux, so that no opposing e.m.f. is induced in the coil. If no opposing voltage is induced, then no external voltage need be impressed on the coil; i.e., no voltage need be impressed to maintain a steady current flow; it is required only to make the current *change*.

Suppose, then, that a constant d-c voltage is impressed across an inductance. Current will start to flow. By Kirchhoff's voltage law, it must somehow develop a counter voltage or electromotive force (c.e.m.f.) to balance the impressed voltage. However, it cannot produce this c.e.m.f. by merely flowing *at some constant value* through the inductance. Instead, it must do so by CHANGING with respect to time; i.e., by continuously INCREASING in value WITH TIME.

As a consequence, the current in this type of circuit cannot reach an equilibrium value as it did when the circuit was purely resistive. The purely inductive circuit will 'run away' with itself since there is no limit to the final value of current. Before pursuing this matter any further, it will be of value to consider how inductance is measured.

UNIT OF INDUCTANCE.—The unit of inductance is the HENRY. A coil has an inductance of one henry when a change of current at the uniform rate of one ampere per second will cause a constant potential of one volt to be induced in the coil.

The henry is a large unit and is encountered in communication work only in audio-frequency circuits of receivers and transmitter and in power-supply filters. I radio-frequency work, more commonl used units are the millihenr (1/1,000 henry) and the microhenr (one millionth of a henry).

The voltage present across

coil is a function of the inductance of the coil and of the rate of change of the current through the coil with respect to time. This statement can be formulized in the following manner:

$$e_L = L\frac{di}{dt} \qquad (1)$$

where,

e_L = voltage across L

L = inductance in henries

$\frac{di}{dt}$ is an expression meaning 'the rate of change of current with time'

The usage of this formula can be illustrated very simply; e.g., assume that a coil of 2 henries is connected in a circuit in which the current rises at a uniform rate from 0 to 10 amps in one second. The rate of change of current is evidently

$$\frac{di}{dt} = 10 \text{ amperes per second.}$$

From Eq. (1), it is evident that the voltage across the coil in this case will be equal to

$$L\frac{di}{dt} = 2 \times 10 = 20 \text{ volts.}$$

In the example a simplifying condition was assumed, namely, that the current increased *at the same rate* all the time. When the current is in the form of a sinusoid, its rate of change is not the same at every instant. This necessitates the use of a more detailed analysis, and will be developed later. For the present, only those circuits in which the current variation is a linear function of time will be discussed.

CHARACTERISTICS OF INDUCTIVE CIRCUITS.—In the circuit of Fig. 3, when the switch is closed, current flows and a magnetic field is established. As mentioned previously, any variation in the current will cause the magnetic field to vary, and the varying flux will induce a voltage in the turns of the coil through which it passes. The voltage induced in the coil will be of such polarity as to oppose the rise of current.

The current in this circuit will rise at such a rate that—dependent upon the amount of inductance present—the c.e.m.f. induced will just balance the constant impressed d-c voltage. A curve depicting the rise in current is shown in Fig. 4. As is evident from the figure, this circuit will 'run away' in the manner previously described because of the fact that the current can induce the c.e.m.f. balancing the impressed voltage only by constantly increasing.

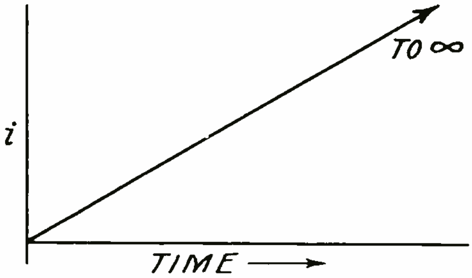


Fig. 4.—Curve showing the rise of current in a purely inductive circuit.

In order to avoid a discussion of infinity and to make the example conform with actual circuits, assume that the circuit in question contains both inductance and resistance as illustrated in Fig. 5. In a circuit of this type the maximum final value of the current is limited by the resistance of the circuit, or I = E/R (Ohm's law), whereas the rapidity with which the current approaches its maximum or limiting value is determined by the amount of inductance in the circuit. The larger the value of the inductance, the less rapidly will the current approach its maximum value E/R.

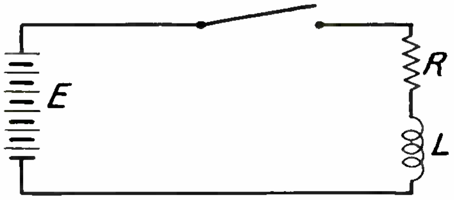


Fig. 5.—Series L-R circuit.

The curve which the current follows in rising in this type of circuit is shown by the solid line of Fig. 6. Here it is seen that the current rises gradually (because of the inductance present) and levels off more and more as it approaches its maximum value E/R. The reason for its leveling off in the manner shown is that as the current increases, the IR drop increases, and leaves less net voltage (E - IR) to produce further current rise. Hence the rise continuously slackens off, and the curve levels off as shown.

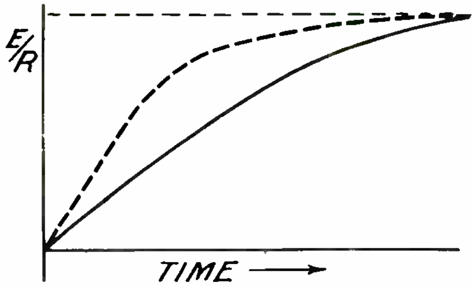


Fig. 6.—Current rise in a series L-R circuit.

The dotted-line curve is for a smaller value of inductance; the current is seen to approach its equilibrium value more rapidly since it requires less net voltage (E-IR) to produce a given rise in current when the inductance is decreased.

TIME CONSTANT.—Theoretically it takes the current an infinite time to attain its maximum *value* E/R; in actual practice, however, it differs from this *value* by a negligible amount in a relatively short time. The formula which is used to express the current rise in this type of circuit is as follows:

$$i = \frac{E}{R} - \frac{E}{R}\epsilon^{-Rt/L}$$

or factoring out E/R

$$i = \frac{E}{R}(1 - \epsilon^{-Rt/L}) \tag{2}$$

where

E = the battery voltage,
R = resistance in ohms,
L = inductance in henries
t = time
ϵ = 2.718, the base of natural logarithms

When $t = L/R$, $-Rt/L = -1$, and the above formula may be resolved into the following form:

$$i = \frac{E}{R}(1 - \epsilon^{-1}) = \frac{E}{R}(1 - \frac{1}{\epsilon})$$

$$= \frac{E}{R}(1 - \frac{1}{2.718})$$

$$= \frac{E}{R}(1 - .368) = .632\ E/R$$

It may be seen from this that the current rises to 63.2% of its final value in a period of time which is numerically equal to the ratio L/R. This ratio is known as the TIME CONSTANT of the circuit.

This same time constant will be shown to apply in the case of a current, initially established in an L-R circuit, that is allowed to decrease to zero.

Referring once again to the circuit of Fig. 3 suppose that, at the instant when the current reaches 100 ma, the battery is removed from the circuit and a 100,000 ohm resistor inserted in its place. This is illustrated in Fig. 7.

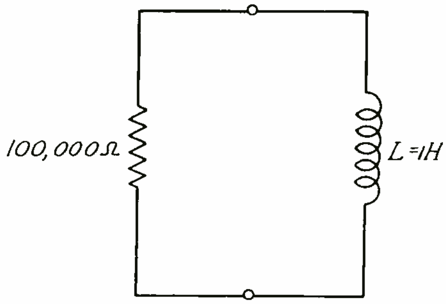


Fig. 7.—Circuit containing inductance and resistance.

Momentarily, a large voltage appears across R; in this particular case,

$$E = .1 \times 100{,}000 = 10{,}000 \text{ volts!}$$

This voltage also appears across the terminals of the coil. It is quite possible that both the coil and the resistor would be burned out as a result of such a large voltage. This will be described in more detail at a later point in this assignment.

Since the battery was removed, there is no longer any voltage present to balance the IR drop produced by the current as it flows through R. Hence it starts to decrease in magnitude. The rate of decrease of current can be determined by rearranging the formula for the voltage across L; which was given on a preceding page as

$$e_L = -L\left(\frac{di}{dt}\right)$$

Rearranged, it is

$$\left(\frac{di}{dt}\right) = \frac{e}{-L} \qquad \text{or } \frac{di}{dt}$$

$$= \frac{10{,}000}{-1} = -10{,}000 \qquad (3)$$

This means that I must decrease at the rate of 10,000 amperes per second, or 10 amps per millisecond (1/1,000 sec.) or 10 ma per microsecond.

The decrease in the current produces a corresponding decrease in the magnetic field, whereupon an e.m.f. is induced in the coil in such a direction as to oppose the decrease in the current; i.e., it acts in the direction of the current flow in an effort to maintain the current at its former higher value. It thereby assumes the role of the battery in maintaining a current flow through R, and illustrates the effect of the inductance in trying to prevent the current flow from DECREASING.

The current will therefore decrease gradually as illustrated in Fig. 8. Theoretically the current can never quite reach zero in this type of circuit; in reality, a comparatively short time is required for the current to differ from zero by a negligible amount.

The explanation for the theoretical behavior is that as the current decreases in value, the IR drop decreases in proportion. This, in turn, means that the inductance has to develop less voltage to maintain the reduced current flow; less voltage, in turn, means that the drop in current can be at a SLOWER RATE. Hence, as the current decreases, its *rate* of dropping decreases, and the current approaches zero more and more slowly.

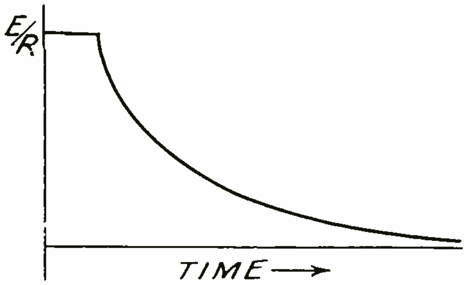


Fig. 8.—Current decay in a series L-R circuit.

On the other hand, when initially the current was large, the IR drop was also large, and a larger induced voltage was required. This, in turn, required that the rate of change of current with time had to be larger (i.e., the current had to drop more rapidly).

The rate at which the current falls off, as shown in Fig. 8, is also dependent upon the ratio of L to R; the lower this ratio (time constant), the more rapid the rate of decline. The formula expressing the current decay in this circuit is:

$$i = \frac{E}{R}\epsilon^{-Rt/L} \qquad (4)$$

Once again it is to be noted that if t = L/R, then -Rt/L = -1, and

$$i = \frac{E}{R}\epsilon^{-1} = \frac{E}{R}\left(\frac{1}{\epsilon}\right) = \frac{E}{R}\left(\frac{1}{2.718}\right)$$
$$= .368\left(\frac{E}{R}\right)$$

i.e., the current drops to 1/2.718 or 36.8 per cent of its initial value E/R in a time equal to L/R.

For example, if L = .025 henries and R = 10 ohms, then in a time t = L/R = .025/10 = .0025 sec., the current will have dropped to 36.8 percent of its initial value.

It is clear from the previous discussion that the effect of inductance on current is to impart to the current the property of INERTIA; any attempt to change the current in either direction brings into play an induced voltage tending to oppose such change.

It might be well at this point to consider the coil of Fig. 7 in a little more detail. Coil L acts like a generator and generates a voltage by virtue of the change of current with time; this generated voltage is used in overcoming the IR drops in the circuit. Hence, as previously mentioned, the induced voltage of the coil L will be equal and opposite to that across R, and if R is large, the voltage across it *and hence across L* may be dangerously high.

If the coil is not a perfect inductance (i.e., if it contains some resistance), the actual TERMINAL voltage of the coil will be less than the voltage generated internally, by an amount equal to the IR drop in the coil itself. The explanation of this is that a portion of the internally generated voltage of the coil will be expended in the coil's resistance, thereby leaving less for the terminal voltage of the coil, which is also the voltage across the external R.

Since the voltage across the coil terminals is equal to that across the external resistance, if the latter is high, the voltage across it and hence across the coil will be high. In the circuit of Fig. 7, the potential across R momentarily reached 10,000 volts. Not only may this cause the resistor to burn out, but the high voltage itself may break down the insulation between turns and/or layers in the coil. It will also cause an arc to appear between the switch contacts when the switch is opened.

AMPLITUDE OF INDUCED VOLTAGE.— Hence, in general, if the current in an inductive circuit is subjected to large and sudden surges or fluctuations (such as occur when the circuit is suddenly broken), a large voltage is developed across the coil; this voltage may be so high as to damage the coil's insulation.

Of course, the fact that a large voltage can be developed in an inductive circuit when the circuit is broken by no means prohibits the use of such a circuit. As a matter of fact, that property is utilized in some important applications, of which a few examples will be given here.

An important application of the principle under discussion is found in the deflection circuit of a television receiver, a simple block diagram of which is shown in Fig. 9.

The currents which flow in the horizontal and vertical deflection coils cause the electron beam to be deflected from its normal or straight path. The resulting deflection of the beam is dependent upon the waveshape of the deflecting currents.

The horizontal magnetic deflection current in the coil has the wave form shown in Fig. 10(A).

It can be seen from Fig. 10 that the entire period is 1/15,750 sec. The retrace period is generally taken as 1/157,500 sec. This wave form is known as a 'sawtooth' wave. Its effect on the electron stream is such that the beam moves back and forth across the object which is to be televised in the manner illustrated in Fig. 10B. The movement of the beam from left to right is referred to as the 'forward' stroke; and that from right to left, as the 'return' stroke.

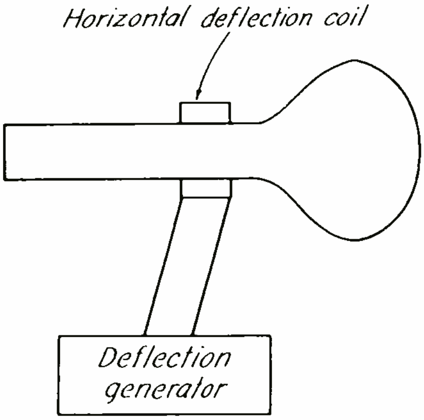


Fig. 9.—Block diagram showing deflection coil at "neck" of a "scope" tube.

Now refer to Fig. 11. From a tube manual, it can be found that the current in a 6L6 varies from 175 ma with maximum grid signal to 0 ma with no signal. From Fig. 10(A), it is evident that this variation of current from 175 ma to 0 ma must occur in 1/157,500 sec. Suppose that the coil has an inductance of .0725 H. Then from Eq. (1).

$$E_{ind.} = L\frac{di}{dt}$$

$$E_{ind.} = (.0725)\left(\frac{.175}{1/157,500}\right)$$

$$= 2,000 \text{ volts.}$$

This high value of E is shown

on the lower portion of Fig. 10 (A) by line BCD.

Such a high voltage may dangerously stress the insulation of the tube and socket, and is also capable of giving the serviceman a severe shock. On the other hand, this high voltage can be used to furnish the high potential required for the electron gun of the picture tube, and is so employed in many television receivers. It is known as a surge-deflection power supply, and is covered in a later assignment in the television course.

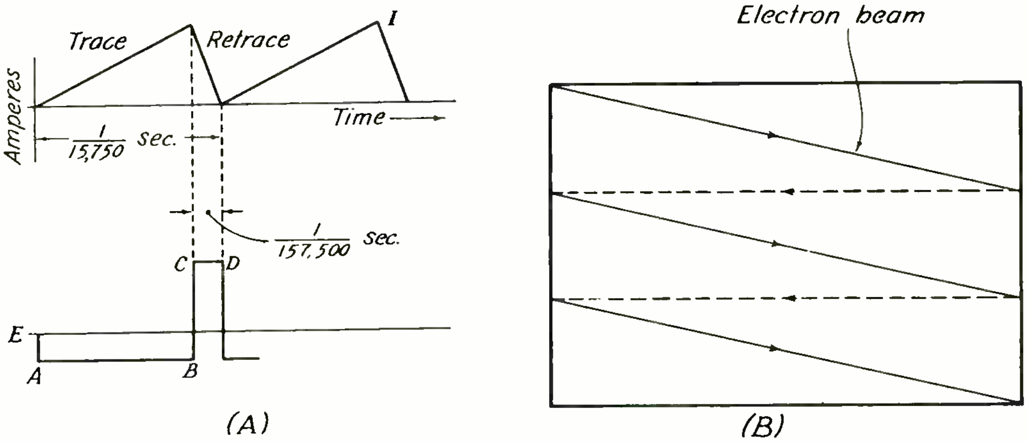


Fig. 10.— (A) Wave form of deflecting current. (B) Motion of beam upon application of deflecting current shown in 10 (A).

Another important application of the principle under discussion is the vibrator power supply used in the mobile operation of radio apparatus. By means of a vibrator pack, a low d-c voltage in the primary circuit is converted into a high a-c voltage in the secondary (owing to transformer action). This high a-c voltage is then rectified by one means or another to obtain a high d-c voltage to operate the radio equipment.

The danger of damaging a coil's insulation due to a high voltage is also encountered in other radio circuits. For example, consider the loudspeaker field of a receiver as shown in Fig. 12. R_c is the coil's internal resistance; this was mentioned previously. The current in this circuit may be as high as 100 ma. If L is a 20 henry coil and the circuit is broken in 1/1,000 sec., a voltage of (.1/.001) (20) or 2,000 volts may appear across the

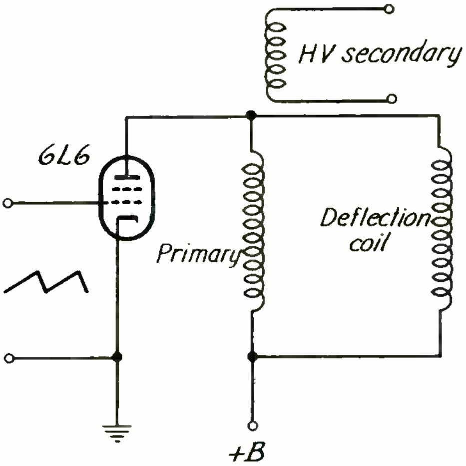


Fig. 11.—Schematic showing portion of deflection circuit.

coil terminals.

A method of overcoming this condition is illustrated in Fig. 13, where the speaker field coil is shunted by a resistor R_{sh} as shown.

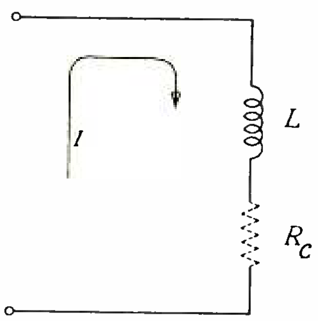


Fig. 12— Loudspeaker field coil.

This arrangement alleviates the danger of the coil's insulation breaking down when the switch is opened, since part of the induced voltage will be expended in the coil's internal resistance R_c, and the remainder in the external resistance R_{sh}, which shunts the coil.

The amount of voltage expended in R_c and that expended in R_{sh} is dependent upon the relative values of the two resistances. If R_{sh} had not been used, the voltage developed across R_c (and hence the coil terminals) would be many times the value of the supply voltage, and might damage the coil's insulation.

If R_{sh} is very high, then an extremely high voltage is developed across it, and since this is also the TERMINAL voltage of the coil, the latter may be broken down. Hence R_{sh} is made as low as possible to keep the voltage induced upon breaking the circuit to as low a value as possible. On the other hand, if R_{sh} is made too low, excessive current will be drawn by it from the voltage supply source during normal operation (when the switch is closed).

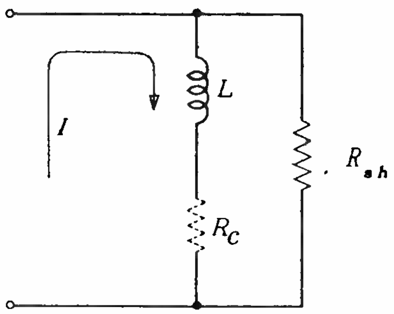


Fig. 13.— Use of shunt resistor to prevent damage to coil.

A reasonable value of R_{sh} is perhaps two or three R_c; in this case the voltage across the coil upon breaking the circuit is from two to three times the battery voltage,

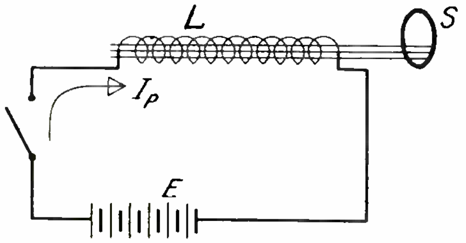
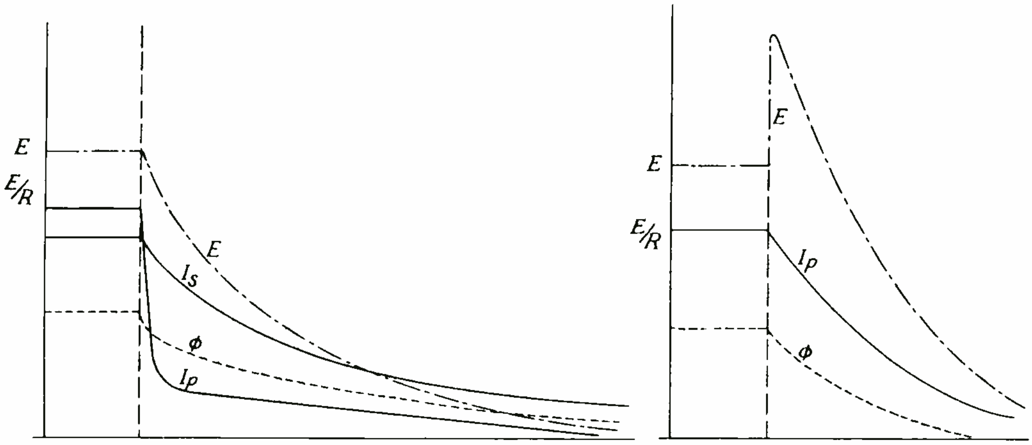


Fig. 14.—Use of shorted turn to prevent coil breakdown.

and therefore not excessive, and yet the additional current drain in R_{sh} when the circuit is closed will be but one-half to one-third that drawn by the coil itself.

Another method which may be utilized is shown in Fig. 14. The varying flux lines emanating from coil L link the shorted turn; in so doing, their variation causes an e.m.f. to be induced in it.

Assume that the switch has been closed for some time; thus the current is already established. When the switch is opened, the primary current drops to zero very rapidly as shown by curve I_p in Fig. 15(A). The flux also tries to decrease; in so doing, it causes an e.m.f. to be induced in the secondary (i.e., in the shorted turn). The direction of this e.m.f. is such that the current in the secondary flows in the SAME direction as the primary current.



(A) (B)

A B

Fig. 15.—Conditions existing when switch is opened. (A). Curves obtained when shorted turn is used. (B). Curves obtained if turn is not used.

Thus, the secondary current now acts in such a manner as to try to maintain the flux at its former higher value. The flux therefore drops at a slow rate just adequate to continue inducing an e.m.f. in S, which in turn causes a current to flow through the resistance of S, and this secondary current is sufficient to prevent the flux from decreasing any more rapidly.

Thus, there is a continued interplay between the currents, flux, and induced voltage which produces the behavior just described.

The curves designated I_s and ϕ show the decline of the secondary current and that of the flux, respectively. It is evident from the curves that the flux and the secondary current drop much more slowly than does the primary current I_p.

The secondary current, and hence the flux, ultimately drop to zero owing to the resistance of S; the lower the resistance, the more slowly do they decrease.

The presence of the shorted turn prevents a high voltage from being induced in the primary when the switch is opened, yet the secondary current flows only momentarily when the switch is closed or opened. The losses are therefore very low. Curve E depicts the decrease in the voltage of the circuit; it is observed to decrease gradually.

In Fig. 15(B) are shown the corresponding curves when the shorted turn is not used. In this case, when the switch is opened, the primary current decreases rather rapidly. Since there is no secondary, there will be no current flow acting to maintain the flux; therefore the flux also drops quickly. In so doing, the flux causes a very high voltage to be induced in the primary, as shown by curve E.

Another useful function of S is to 'iron out' any ripples in the current of the main field coil. Thus it is not necessary to filter the field current I_p so thoroughly if S is used.

The action is similar to that when the battery switch is opened or closed. Thus, any increase in I_p tries to cause a corresponding increase in the flux. But as the latter starts to increase, it induces a voltage in S; this voltage in turn causes a current to flow in S in a direction *opposite* to the primary current I_p and therefore opposes the increase in flux.

Ultimately, of course, the flux would rise to a higher value corresponding to the increase in I_p, but if the increase in I_p is but momentary, the flux will fail to follow and will increase by a small amount just sufficient to induce enough current in S to prevent the flux from increasing any more. The same reasoning holds true for a decrease in I_p; the flux cannot follow such decrease except to a small extent. Hence ripples in I_p will cause very much smaller ripples in the flux, and it will be substantially constant in magnitude.

This completes the discussion of the inductive characteristics of d-c circuits; the inductive characteristics of a-c circuits will be taken up next.

INDUCTANCE IN A-C CIRCUITS.—It was pointed out that when a pure inductance was connected across a d-c source, there was no upper limit to the final value of the current. That difficulty is not encountered when working with a purely inductive a-c circuit such as that shown in Fig. 16.

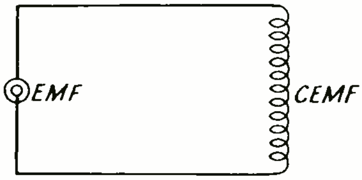


Fig. 16.—Purely inductive a-c circuit.

Since there is no opposition to current flow except that offered by the inductance, all of the a-c voltage must be expended in forcing the current through the inductance. It should be recalled here that the voltage developed across the coil is known as the counter-electromotive force (c.e.m.f.). Note that the c.e.m.f. is exactly equal and opposite to the e.m.f. at every instant in accordance with Kirchhoff's voltage law.

This may be shown vectorially as in Fig. 17(A); a sine wave representation of the same condition is given in Fig. 17(B). Observe in (A) that the two vectors are in opposition or 180° out of phase; and that in (B) the waves are correspondingly always equal and opposite to one another.

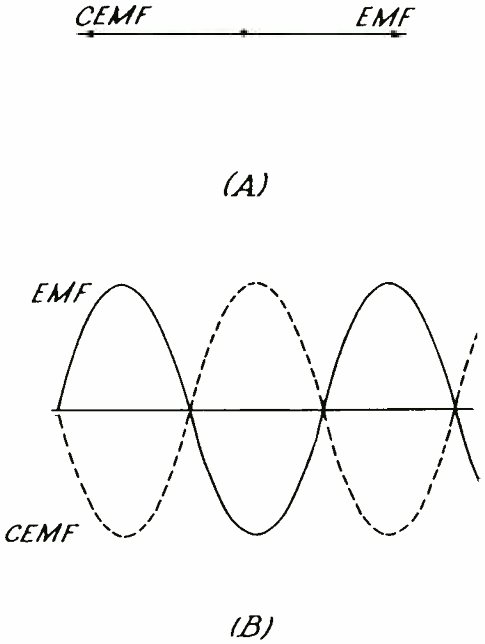


Fig. 17.—Vector and sine wave diagrams of voltages in a purely inductive circuit.

It is now to be noted that the c.e.m.f. is greatest when the VARIATIONS in the magnetic field are the greatest. The greatest variations in the magnetic field occur when the current is changing the most rapidly. In order to determine the phase relationships between the current, the e.m.f. and c.e.m.f., assume that a sinusoidal current is starting from zero as shown by the solid-line curve of Fig. 18.

It is clear from this diagram that the current (and therefore the magnetic field) is a maximum at 90° and 270°. The VARIATIONS, however, in the current (and the flux) will be zero at the above-mentioned points. The greatest variations of current take place as the current is crossing the horizontal axis (at 0°, 180°, 360°). In short, where the current and flux are in themselves zero, their RATE OF CHANGE is a maximum, and where the current and flux are a maximum, their rate of change is ZERO.

Since, as mentioned previously, the c.e.m.f. is greatest, not when

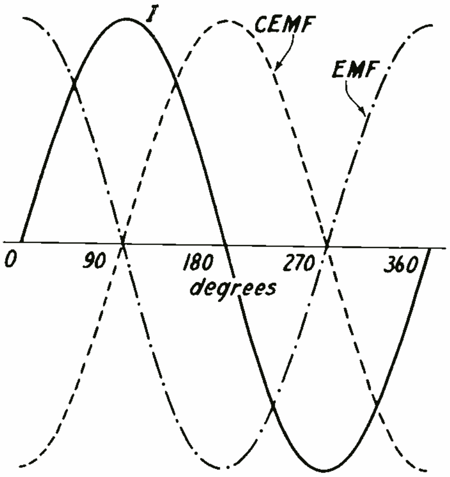


Fig. 18.—Sine wave representation of I, E, and c.e.m.f. in a pure inductance.

the current is at a maximum, but when the VARIATIONS in the current are greatest, a curve depicting the c.e.m.f. may be drawn as illustrated by a dotted-line curve of Fig. 18. Observe that the c.e.m.f. is a maximum (positive or negative) where the current is passing through zero, and that it lags the current by 90°. Since the c.e.m.f. is EQUAL and OPPOSITE to the e.m.f. at every instant, the e.m.f. may be represented by the broken-line curve of Fig. 18; it is 180° ahead of the c.e.m.f.; and therefore 90° ahead of the current.

The relative positions of the current, the e.m.f., and c.e.m.f. are shown vectorially in Fig. 19.

Fig. 19.—Vector representation of I, E, and c.e.m.f. in a pure inductance.

It may be seen from the diagram, too, that *the current will lag the voltage by 90° in a purely inductive circuit in order that its rate of change will produce a c.e.m.f. exactly 180° out of phase with the impressed voltage.*

The opposition to current flow in an inductive circuit is known as inductive reactance; it is this factor which is responsible for the current lagging the voltage by 90° in a purely inductive circuit. This will be discussed in greater detail in a later assignment

It has previously been shown that in a purely resistive circuit, the current and the voltage are *in phase* with each other. Since in actual practice it is impossible to have a circuit which does not contain some resistance, the angle of lag of the current with respect to the voltage in an inductive circuit will be between 0 and 90° (always less than 90°). The actual angle of lag will depend upon the relative amounts of inductance and resistance present in the circuit. However, in a highly inductive circuit the angle of lag will be essentially 90° for most practical purposes.

INDUCTANCE OF A STRAIGHT WIRE.—It is not necessary that a piece of wire be wound in the form of a coil for it to possess inductance. It is true that winding a given length of wire into a coil increases the inductive effect of that piece of wire; nevertheless, if the same piece of wire is perfectly straight, it will still possess a certain amount of inductance. This follows from the fact that a current through the straight conductor sets up concentric circles or whirls of magnetic flux within and also around the conductor, as mentioned in a previous assignment, and such flux indicates that the conductor has inductance.

Thus, when the current in the conductor changes, the flux changes too, and thereby induces a voltage in the conductor in a direction opposing the change in flux and current.

It is true that the amount of inductance of a straight wire is relatively small, so that its inductive effect or reactance (to be explained later) is small unless the current through the wire changes very rapidly (alternates at a high frequency).

For this reason, at low frequencies a short straight conductor is usually considered as being practically non-inductive, because its reactance or opposition to current flow is so small, it acts as a dead short if placed across a circuit. That same conductor, when used in the very high frequency range (such as in f-m or television circuits), will exhibit a large inductive effect or reactance. Such a condition, as will be shown subsequently, may have extremely detrimental effects on a circuit's operation.

Inductance and inductive reactance are manifest when the current changes; the more rapid the changes in current, the greater are the inductive effects. For example, at 300 mc/s the current completes 300 million cycles every second. From the study of the sine curve, it was seen that four complete changes occur in the current during each cycle. Thus, at 300 mc/s the current makes twelve hundred million complete variations every second, and a small amount of inductance will have a considerable reactive effect at that rate. On the other hand, note that the number of cycles of variation of the current per second (i.e., the frequency) has nothing to do with the inductance of a circuit; the inductive EFFECTS, however, vary DIRECTLY as the FREQUENCY. It is therefore possible that the leads used to connect the various prongs of tube sockets to the correct points in the circuit, may possess enough inductance at high frequencies (in conjunction with the interelectrode capacity of the tube) to render the circuit inoperative. Thus, when working with equipment which operates above about 300 mc/s, extreme caution must be used in connecting the various components in the circuit. Numerous examples of the precautions that must be exercised at the higher frequencies will appear at various points in the course.

SKIN EFFECT.—In the preceding paragraph it was mentioned that the flux existed both inside and outside the conductor.

The concentric whirls of flux set up around a straight conductor are of diameters varying from zero to an indefinitely large value. In other words, some of these circles or whirls of flux are so small as to lie entirely within the conductor; others are large enough to lie wholly outside of the conductor.

This is illustrated in Fig. 20.

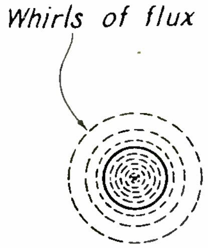


Fig. 20.—Cross section of a conductor showing how more whirls of magnetic flux encircles the center of the conductor than the periphery.

It is clear from this figure that the current flowing through the center of the conductor will be encircled by more flux than will the current closer to the conductor's surface. Thus the inductance and hence the inductive reactance *will be greater for current paths near the center of the wire than it will be for paths near the surface.*

As the operating frequency is increased, the center portion of the core carries less and less current compared to the amount carried at lower frequencies, because the central part of the wire, having more inductance than the surface portion, offers more and more opposition (inductive reactance) to the flow of current as the frequency is raised. As a result, at high frequencies practically all the current flows on the surface of the conductor. The higher the frequency, the less the penetration of the current below the surface—this is known as 'skin effect.' This is one of the principal reasons why at high radio frequencies practically the same resistance can be obtained by using a hollow tube as by using a solid conductor of the same diameter. Indeed, by silver plating an iron tube, a lower resistive circuit can be obtained than by using a copper tube, since silver has a lower resistance than copper. A tube, of course, is lighter and cheaper than a solid rod.

CHOKE COILS.—The property of an inductance which tends to prevent a current change through it is utilized in the design of so-called chokes at all frequencies. When it is desired to pass a direct current and at the same time to prevent fluctuations in that current from passing through, a series inductance is inserted in the circuit. If a sufficiently large inductance is used, rapid current fluctuations cannot take place to any appreciable extent, and the output is practically steady; the inductance 'chokes' off the fluctuations, and is for that reason often called a choke coil.

Choke coils will be discussed in greater detail later, where the calculation for the correct amount of inductance to be used will be given. Hence it will be merely mentioned here that the inductance of a coil depends upon the shape of the coil, its length, diameter, number of turns, spacing between turns, and the character of the surrounding medium.

Anything which tends to increase the density of the magnetic field produced by a given current through a coil, will increase the inductance of the coil. For example, an air-core coil has a certain amount of inductance. If an iron core is inserted within the coil, the inductance of the coil will be greatly increased because the same amount of current through the coil and hence the same mmf will produce more flux in the iron core owing to its lower magnetic reluctance. Fig. 21 illustrates a commercial form of an iron-core choke coil.

Fig. 21.—A commercial iron-core choke coil.

INDUCTANCE CALCULATIONS

COIL DESIGN.—How the various factors of turns, shape, and permeability of the surrounding medium enter into the calculation is shown in the following equation expressing the inductance of a coil*:

$$L = \frac{1.26\, N^2 \cdot A\mu}{10^8 \cdot l} \qquad (5)$$

where

L = Inductance in Henries
N = Number of turns
A = Area enclosed by a single turn in square cm.
l = Length of winding in cm.
μ = Permeability of core

(This equation may be used for a very long solenoid, a very compact coil, or where the magnetic path is through iron).

The factor 10^8 enters into the calculation because it requires a change of 10^8 lines of flux per second to induce one volt in one turn. The greater the area enclosed by each turn the greater the amount of flux contributed to the total by that turn. The greater the length l of the coil for a *given number of turns*, the more widely separated the turns will be and therefore the weaker the field of each turn cutting the other turns. It will be seen that the inductance of the coil is a direct function of the area and an inverse function of the length of the winding. There is also a direct relation between the inductance and the permeability of the core. Since the magnetic permeability of iron may be several thousand times greater than that of air, if a core of high permeability is used the dimensions of the winding may be very greatly reduced over what is required for an air core and still maintain a large value of inductance. For that reason, at low frequencies where large values of inductance are required, the cores of reactors, transformers, etc., are made of iron, or more commonly, special kinds of iron alloys, such as silicon steel.

The factor N^2 has been left until last because it is a factor of very great importance. N represents the number of turns on the coil. As a current rises and falls through the turns, the magnetic field goes through certain variations in density. It has been shown that the magnetizing force H varies directly as the number of ampere turns. Therefore with a given current amplitude the total amount of magnetic flux will be a direct function of the number of turns. If the number of turns of the coil is doubled, all other conditions being unchanged, the total magnetic flux will be doubled.

This leads however to another condition. With a given variation of magnetic flux the voltage generated or induced will be a direct function of the number of turns being cut. For a given flux variation, if the number of turns is doubled, the induced voltage will be doubled. Hence, if the number of turns, for example, is doubled, double the flux will be produced through twice as many turns, so that

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*There are several different formulas for the inductance of a coil; the one given here is quite simple and satisfactory, and illustrates the dependence of L on the various factors of the coil.

the induced voltage will 2 × 2 = 4 times as great. The inductance will therefore be quadrupled, too. In general, the combined effects will be the product of the two factors and *the total induced voltage for unit current variation in amperes per second will be a function of* N^2. Therefore, with a coil of given area, length, and core permeability, if the turns are tripled L will become nine times as great; if the number of turns is reduced to one-quarter, the inductance will be reduced to one-sixteenth, etc.

Eq. (5) is not at all difficult to use. Consider the following coil: 1000 turns having a mean diameter of 2.5 inches with a length of winding of 3 inches. Permeability of steel core, including airgap, at the flux density at which it is designed to operate, 250. What is the inductance in henries? First, convert the dimensions from inches to cm. Diameter = 2.5". = 2.5 × 2.54 = 6.35 cm. Length of winding = 3". = 2.54 × 3 = 7.62 cm. The mean turn area = πR^2. R = 6.35/2 = 3.18 cm. Then $A = 3.14 \times 3.18^2 = 31.4\ \text{cm}^2$. The formula,

$$L = \frac{1.26\ N^2\ A\mu}{10^8\ l} \qquad (5)$$

becomes,

$$L = \frac{1.26 \times 1000^2 \times 31.4 \times 250}{10^8 \times 7.62}$$

$$= \frac{99 \times 10^8}{7.62 \times 10^8}$$

L = 13 henries

The actual inductance of this coil will, of course, vary somewhat with the current through the winding due to the change of permeability of the steel core with flux density.

This equation is very useful in radio where it is necessary to design audio frequency choke coils, filter reactors, etc. It may be used in conjunction with magnetic circuit calculations—as discussed in an earlier assignment—to obtain a coil having not only certain magnetic characteristics but also some specified value of inductance. An example of where such combined features are required is the field winding of a dynamic reproducer in a ordinary broadcast receiver. Such a winding is ordinarily required to perform three functions: First, to supply the required magnetic flux density in the airgap in which the voice coil moves; second, to act as a filter reactor of the required inductance for the power supply; third, to form the first voltage divider resistance in the power supply output.

To satisfactorily perform three functions several factors must be balanced against each other. First, the number of turns N must be such that, combined with the plate current load I of the receiver, NI is correct to produce the required flux density in the airgap; second, N must be such that combined with the other coil dimensions and μ of the core, the inductance is correct for its function as a filter reactor; third, the size of wire must be such that it will have the necessary resistance for its third function and at the same time safely carry the load current of the rectifier.

Considerable ingenuity is required in such a design problem. Several combinations of coil dimensions, number of turns, and wire size must be tried, if no approximate figures are available, and the complete problems worked out. When a fair approximation of required values is reached, the core should be built up with the actual grade of steel to be used, measurements made to check the accuracy of the calculations, and then corrections made to bring all the factors to the predetermined specifications.

In the adjustment of a radio transmitter circuit where the coils are usually wound on a form with a magnetic core of air, variations of L are ordinarily made by moving a tap from one turn to another. If it is desired, in order to obtain a lower frequency, to double the inductance connected into the circuit, the number of turns should be increased to $\sqrt{2}$ or 1.4 times the former value. To obtain 3 times as much inductance, the turns should be increased to $\sqrt{3}$ times, etc.

The inductance formula given as Equation 5, when used with an air core winding *assumes a coil length of at least 10 times the coil diameter.* For most radio coil purposes a length of at least 10 times the diameter would be very inconvenient. Therefore the formula for the inductance of a single layer coil as given below (Equation 6) is more practical. This formula takes into consideration a form factor K which is a function of diameter or length. Tables giving the value of K for different ratios of diameter or length may be found in various electrical texts and handbooks. One such table is given on page 283 of the Bureau of Standards circular 74. A partial Table is given on the following page. The equation

$$L = \frac{.03948\ r^2\ N^2 \cdot K}{l}\ \mu h \qquad (6)$$

where

r = radius of coil measured from the axis to the center of any wire in cm.
N = Number of turns in winding
l = Length of coil in cm.
L = μhenries

This is shown in Fig. 22.

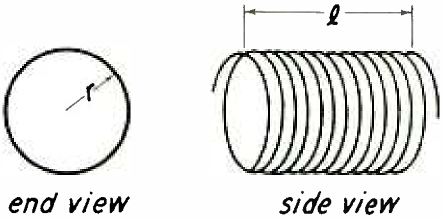

Fig. 22.—Showing pertinent dimensions of an inductance as given in Eq. (6).

The value of K extends over wide limits. Where the ratio of diameter to length is less than .1 the constant may be taken as unity without appreciable error. When the diameter and length are equal, K = .6884; when the diameter to length equals 2, K = .5255; when diameter to length equals 6, K = .2854, etc. It will be seen that with a single layer coil on a core of unit permeability, to obtain the maximum inductance for a given amount of winding, the coil should be short and of large diameter. A coil shape very commonly used in radio is one in which the length of the winding is 2.5 times the diameter. This is a diameter to length ratio of .4 and the value of K is .8499.

Eq. (6) is also quite easy to use. Consider the following r-f coil. Diameter = 1.4″, Length of winding 1.4″, N = 60 turns. In the equation,

$$L = \frac{.03948\ r^2\ N^2\ K}{l}$$

$$\frac{2r}{l} = 1,\ K = .6884$$

$$r = 1.4/2 = .7'' = 2.54 \times .7 = 1.78\text{cm}$$

$$L = \frac{.03948 \times 1.78^2 \times 60^2 \times .6884}{3.56}$$

$$= 87\mu\text{h}$$

Eq. (6) may be rearranged to find any other factor. For example, suppose it is desired to design a coil to have a given inductance when the diameter and length of the winding have been selected. How many turns will be required?

$$N = \sqrt{\frac{l\text{L}}{.03948\ r^2\ K}} \qquad (7)$$

It is suggested that the student make inductance calculations for a number of receiver coils that may be available in order to gain familiarity with the use of this formula.

The writer would like to bring out at this point the fact that in coil design—just as in all other design work—some factors must be arbitrarily taken as a starting point. As an example, in the use of Eq. (7), in order to find the number of turns required for a given amount of inductance, it is necessary to first arbitrarily select dimensions, diameter and length, of the winding. After this has been done it is necessary to select a size of wire which, *including* the *insulation*, will allow the calculated number of turns within the arbitrarily selected length of winding. If this results in too small a wire size so that the resistance may be excessive, it will be necessary to select a winding of greater dimensions and again make the turn calculations.

An engineer who has an original coil design problem for which data on optimum dimensions, shape, wire size, etc., are not available, usually makes a number of coil calculations over a considerable range of

TABLE

VALUES OF K FOR USE IN EQUATION 6.

DIAMETER LENGTH	K	DIAMETER LENGTH	K
.1	.9588	1.75	.5579
.2	.9201	2.00	.5255
.3	.8838	3.00	.4292
.4	.8499	4.00	.3654
.5	.8181	5.00	.3198
.6	.7885	6.00	.2854
.7	.7609	8.00	.2366
.8	.7351	10.00	.2033
.9	.7110	12.00	.1790
1.0	.6884	15.00	.1527
1.25	.6381	20.00	.1236
1.50	.5950	30.00	.0910

(Values in between those listed may be determined by interpolation.)

dimensions and shapes, plots the data in the form of curves, and then builds up the coils to experimentally verify the calculations. This also allows the actual r-f resistance and distributed capacities of the various coils to be measured and plotted so that facts are obtained which are extremely difficult to calculate with any great degree of accuracy.

Engineers doing design engineering ordinarily have access to tables, charts and curves which have been accumulated during previous design work by themselves or others. If such data are not available it is necessary to make numerous calculations, experimentally verify the results, and then from the accumulated data select the arbitrary values that best suit the problem at hand.

After all the data have been accumulated the selection of arbitrary values will ordinarily be largely influenced by circumstances. For example, in the design of a broadcast receiver coil, if the space available definitely limits the coil to a diameter not to exceed .75 inch and a length of not more than 1.5 inches, it is necessary to build the best coil *that will go into that space*, regardless of what the data may indicate as the best size and shape. Many factors enter into a design problem, not the least of which may be cost, and it is the job of the design engineer to turn out the best possible product to suit the conditions prescribed.

Suppose it is desired to employ the same diameter of coil form as used in the 87 μh inductance calculated above, to wind a coil to have inductance of 200 μh. The coil is to have a diameter-to-length ratio of .4. In other words the length of the winding is to be 2.5 times the diameter. The diameter was given as 1.4″ or 3.56 cm so that in the formula r = 1.78 cm. Length is 2.5D so that l = 3.56 × 2.5 = 8.9 cm. For $2r/l$ = .4, K = .8499 To find the number of turns required and the maximum size of enamel covered wire that can be used. Using Eq. (7)

$$N = \sqrt{\frac{lL}{.03948\ r^2K}}$$

$$= \sqrt{\frac{8.9 \times 200}{.03948 \times 1.78^2 \times .8499}}$$

$$N = \frac{1780}{.106} = 129 \text{ turns}$$

The length of the winding in inches is 1.4 × 2.5 = 3.5 inches. The allowable space per turn is 3.5/129 = .0271 = 27.1 mils per turn. Allowing 1 mil per turn for the thickness of the enamel, the wire diameter must not exceed 26.1 mils. Reference to a copper wire table shows that No. 22 wire has a diameter of 25.3 mils, well within the limit, and that No. 21 has a diameter of 28.5 mils, considerably too large. Thus the best size of wire in this particular case will be No. 22.

EFFECT OF IRON CORE SATURATION.—It will be seen that neither Eq. (5) nor Eq. (6) take into consideration the current in the turns. However, in Eq. (5) the permeability (μ) is a factor. So long as an air core coil is used μ remains constant, (unity), regardless of the current amplitude. When an iron core is used that is not true. By definition, magnetic permeability is equal to B/H. In an earlier assignment it was shown that in the B-H curve, the slope B/H represents μ, and this flattens out at large values of H due to magnetic saturation of the iron, and correspondingly reduces μ for large values of H produced by a large current flowing in the turns. This is illustrated here in Fig. 23.

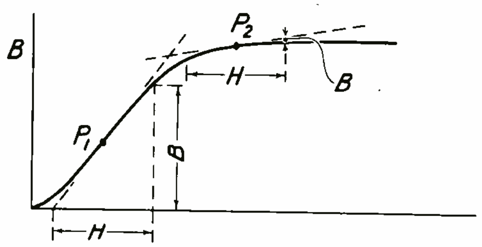

Fig. 23.—Slope at P_1 is much greater than at P_2. Hence μ at P_1 is greater than at P_2.

In radio transmitters and receivers a common use for iron-core reactors is in the filters of high voltage rectifiers, where the inductance is used to smooth out the ripple or fluctuations in the rectifier output current. Such an output usually consists of a large direct current with a component of amplitude variations at a constant frequency, the amplitude variations being what it is desired to suppress. If the d-c component of current is sufficiently small so that, flowing through the turns of the reactor, H is far below the value required for saturation, μ will be high and a large value of inductance will oppose the fluctuations. If, on the other hand, the d-c component of current is so large that the core is saturated, μμ will be almost negligible and, since the high permeability of the core was depended upon to develop a large value of L, (see Eq. (5), the fluctuations of current will cause little change in the flux density in the already saturated core and hence very little inductive opposition will be offered to the current variations.

Thus an iron core will have a specified value of inductance *only* when carrying a current which is below a specified maximum value. This must be carefully taken into consideration when designing or selecting an iron core reactor for a specified use.

INDUCTANCES IN SERIES AND PARALLEL—It should be mentioned at this point that when coils are connected in series the total inductance will be equal to $L_1 + L_2 + L_3 \ldots$, assuming perfect shielding (i.e., none of the flux of any coil links the turns of the others). When coils are connected in parallel the total inductance is calculated in the same manner as is used for resistances in parallel. This formula assumes perfect shielding of each coil.

$$L = \frac{1}{1/L_1 + 1/L_2 . \ . \ . \text{ etc.}}$$

If, however there is any coupling between any of the coils the solution becomes more involved; this will be discussed in greater detail in the assignment on inductive coupling.

RESUME'

This concludes the assignment on inductance. First were discussed the characteristics of inductance and then the effects of inductance in d-c circuits.

The study of inductive a-c circuits was taken up next. It was learned that one of the principal effects of inductance in a circuit is to cause the current to lag the voltage. The fact that even a straight piece of wire possesses inductance was also stressed. Skin effect was taken up next; in connection with this, the difference between d-c and r-f resistance was discussed, and it was explained how each could be reduced: d-c, by using wire of greater cross section, and r-f by the use of tubing to increase the surface area.

The design of a coil along with the effects of iron core saturation was discussed; following this was the method of calculating inductances when connected in series and parallel.

INDUCTANCE

EXAMINATION

Underline all correct answers.

1. (A) Lenz' Law has a practical application in dealing with:

   (a) Generators.

   (b) Capacitors.

   (c) Transformers.

   (d) Resistances.

   (e) Incandescent d.c. lighting circuits.

   (f) Inductors.

   (g) Motors.

(B) The fundamental factor in the relationship expressed by Lenz's Law is:

   (a) The theory of electro-magnetism.

   (b) The magnitude of induced EMF.

   (c) The effect of change of magnetic flux.

(C) In an inductive circuit, the current which flows due to an induced EMF creates a magnetic field which (has no bearing upon, tends to oppose, tends to aid) the change in resultant magnetic field.

(D) The primary of a radio receiver power transformer is supplied from a d-c source by a potential low enough to prevent burning out the primary. A zero-center d-c meter which will read both positive and negative voltages without reversing the leads is connected across the secondary. If the meter indicates a positive voltage at the instant the switch is closed, it will indicate (positive, negative, practically zero) voltage ten seconds after the switch is closed. It will indicate (positive, negative) at the instant the switch is opened. The meter will indicate (a greater, a smaller, the same) voltage at the instant the switch is closed compared to when the switch is opened, provided the switch is operated rapidily.

2. (A) In an inductance connected to an a-c source, the current (is in phase with, leads, lags) the voltage applied.

(B) Given a transformer with a certain number of primary and secondary turns. When the primary current increases at the rate of 5 amperes per second, ten volts are induced in the secondary. What voltage is induced in the secondary when the primary current changes at the rate of 2 amperes per second.

(C) In a transformer supplied by an a-c source and whose secondary is open-circuited, the instantaneous voltage of the secondary is (maximum, minimum, of average value) when the current in the primary is changing most rapidly, i.e. at zero degrees or 180 degrees of the electrical cycle of the current.

(D) In a transformer supplied by an a-c source the voltage of the secondary, when open-circuited, is (in phase with, 90 degrees out of phase with, 180 degrees out of phase with) the current of the primary.

3. (A) When the switch is closed in a circuit which has an inductance, such as a relay, connected to a d-c power source, for all practical purposes the current (rises to full value immediately, rises to full value over a finite length of time, will never rise to full value) owing to the action of the self-induced voltage.

(B) In the same circuit, the rate of change of current is greater at the instant the switch is (opened, closed) than when the switch is (opened, closed) provided the switching action is rapid.

(C) In (opening, closing) an inductive circuit, care must be taken in this operation to prevent arcing at the switch contacts. This arcing is caused by (electrolysis, local action chemically, ionization).

(D) The burning due to arcing mentioned in (C) is the dissipation of the *energy* (from the nuclear fission, from the I^2R losses, from the change in the magnetic field).

4. (A) Inductance is that property of an electrical circuit which (resists current flow, resists a change of current, increases voltage).

(B) The inductance of a coil is directly proportional to which one of the following:

(a) permeability of the core material, (b) type of metal used in the wire,

(c) diameter of the coil, (d) length of the coil,

(e) number of turns on the coil,

(C) A straight piece of wire may be used as an r-f choke at high frequencies. This is possible because (the inductance increases at high frequencies, the inductive effect is greater at high frequencies, as frequency is increased less power is required).

5. (A) The unit of inductance is the ________________ which is defined as that inductance in which an EMF of ______ volt (s) is (are) induced when the current changes at the rate of ________________________ ampere(s) per _____________________.

(B) A current change of 5 amperes per second produces a constant induced EMF of 5 volts. The inductance of this circuit is ______________________________. (give units).

6. (A) At high frequencies, i.e. 10 mc, the current (travels in the center, is somewhere between the surface and the center, travels on the surface) of the conductor for all practical purposes.

(B) A solid conductor with the same cross-sectional area of copper as a tubular conductor has (a higher, the same, a lower) radio—frequency resistance owing to (hysteresis, Edison effect, voltaic action, skin effect).

(C) Stranded wire has a lower r-f resistance because of its (molecular structure, capacity between strands, increased surface area) than a solid conductor of the same area taken as a cross section.

6. *(Continued)*

(C) A straight piece of wire, isolated in space, (will, will not, can but probably doesn't) possess the property of inductance.

7. (A) It is impossible to saturate an air core inductance such as an r-f coil because the ______________________ remains constant regardless of the current flowing in the inductance.

(B) To saturate an iron core inductance, such as a filter choke, the current must be raised until (the steepest portion, the middle portion, the flattened portion) of the B-H curve is reached.

(C) When the current of an iron core inductance such as a filter choke is increased to saturation, the inductance has (reached a maximum efficiency as, decreased in efficiency as, become practically worthless as) a ripple filter.

(D) A filter choke for use in a television regulated power-supply unit has a rating of 10 henries at 200 ma d.c. flowing through it. Its inductance will be (increased, decreased, unchanged) if 300 ma d.c. are passed through it instead of 200 ma.

8. The number of turns on a coil is doubled and the current remains the same as before (saturation is not a factor):

(A) The total magnetic flux will be ________________ times as great as before.

(B) The voltage induced will be __________________ times as great as before.

(C) The inductance will be ______________________ times as great as before.

8. *(Continued)*

(D) Given a coil with 50 turns and a certain inductance. To make a coil with an inductance 3 times the value of the first coil, what will be the total number of turns that will be required? *Show work.*

9. Given a receiver r-f coil wound with 120 turns of No. 28 wire. The diameter of the coil from center to center of the wires is 0.75 inch and the length of the winding is 1.88 inches. What is the inductance in microhenries? Use eq. 6.

10. Using Equation 5, design a coil to have an inductance of 8 henries, with a length of winding = 1.8 inches, a mean diameter of winding = 1.5 inches, μ of the core including the air gap at the flux density to be used = 300. How many turns will be required?