**Reading 14**

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## INDUCTANCE

Coils of wire were mentioned in the reading on magnetism when we discussed the magnetic field about a coil carrying a current. An equally important aspect of the operation of a coil is its property to oppose any change in current through it. This property is called inductance.

> Inductance is that property of a circuit that opposes changes of current.

Not to be confused with capacitance, which is the property of a circuit to opposes changes of voltage.

When a current of electrons starts to flow along any conductor, a magnetic field starts to expand from the centre of the wire. These lines of force move outward, through the conducting material itself, and then continue into the air. As the lines of force sweep outward through the conductor they induce an emf in the conductor itself. This induced voltage is always in a direction opposite to the direction of current flow. Because of its opposing direction it is called a counter emf, or a back emf.

The effect of this backward pressure built up in the conductor is to oppose the immediate establishment of maximum current. It must be understood that this is a temporary condition. When the current eventually reaches a steady value in the conductor, the lines of force will no longer be in the process of expanding or moving and a counter emf will no longer be produced. In other words there will be no relative motion between the conductor and the magnetic field. At the instant when current begins to flow, the lines of force are expanding at the greatest rate and the greatest value of counter emf will be developed. At the starting instant the counter emf value almost equals the applied source voltage.

The current value is small at the start of current flow. As the lines of force move outward, however, the number of lines of force cutting the conductor per second becomes progressively smaller and the counter emf becomes progressively less. After a period of time the lines of force expand to their greatest extent, the counter emf ceases to be generated, and the only emf in the circuit is that of the source. Maximum current can now flow in the wire or circuit, since the inductance is no longer opposing the source voltage.

This property of a coil or more correctly and inductor to oppose changes of current by self-inducing an opposing (counter) emf is called inductance. The unit of inductance is the Henry, and the symbol for inductance is 'L'.

## SELF-INDUCTION

When the switch in a current-carrying circuit is suddenly opened, an action of considerable importance takes place. At the instant the switch breaks the circuit, the current due to the applied voltage would be expected to cease abruptly. With no current to support it, the magnetic field surrounding the wire should collapse back into the conductor at a tremendously high rate, inducing a high-amplitude emf in the conductor. Originally, when the field built outward, a counter emf was generated. Now, with the field collapsing inward, a voltage in the opposite direction is produced. This might be termed a counter counter emf, but is usually known as a self-induced emf. This self-induced emf is in the direction of the applied source voltage. Therefore, as the applied voltage is disconnected, the voltage due to self-induction tries to establish current flow through the circuit in the same direction, aiding the source voltage. The inductance induces a voltage to try and prevent the circuit current from decreasing. With the switch open it would be assumed that there is no path for the current, but the induced emf immediately becomes great enough to ionise the air at the opened switch contacts and a spark of current appears between them. Arcing lasts as long as energy stored in the magnetic field exists. This energy is dissipated as heat in the arc and in the circuit itself.

With circuits involving low current and short wires, the energy stored in the magnetic field will not be great and the switching spark may be insignificant. With long lines and heavy currents, inductive arcs many centimetres long may form between opened switch contacts on some power lines. The heat developed by arcs tends to melt the switch contacts and is a source of difficulty in high-voltage high-current switching circuits.

In a previous reading I gave you an example of the capacitance of a telephone line. A telephone line also has inductance. The normal operating voltage of a telephone line is about 50 volts DC. When a telephone line is suddenly open circuited by a technician or a linesman, the self-induced voltage on the line can be in the order of 2000 volts and provides a harmless but significant electric shock. The shock is harmless, as the amount of current is so small.

Remember, regardless of how current changes in a circuit containing inductance, the induced emf by the inductance will oppose the change of current.

The unit of measurement of inductance is the Henry, defined as the amount of inductance required to produce an average counter emf of one volt when an average current change of one ampere per second is under way in the circuit. Inductance is represented by the symbol L in electrical problems, and henrys is indicated by H.

## COILING AN INDUCTOR

It has been indicated that a piece of wire has the ability of producing a counter emf and therefore has a value of inductance. Actually, a small length of wire will have an insignificant value of inductance by general electrical standards. One Henry represents a relatively large inductance in many circuit applications, where millihenries and microhenries are more likely to be used. A straight piece of No. 22 wire one meter long has about 1.66 uH. The same wire wound onto an iron nail or other high-permeability core may produce 50 or more times that inductance.

Even without the iron core, a given length of wire will have much greater inductance if wound into a coil form. The diagram in figure 1 show two loops of wire separated by enough distance so that there is essentially no interaction between their magnetic fields. If the inductance of the connecting wires is neglected, these two loops, or turns, have twice the inductance of a single turn.

When the two loops are wound next to each other as shown in figure 2, with the same current flowing there are twice the number of magnetic lines of force cutting each turn. With 2 turns, 4 times the counter emf is developed.

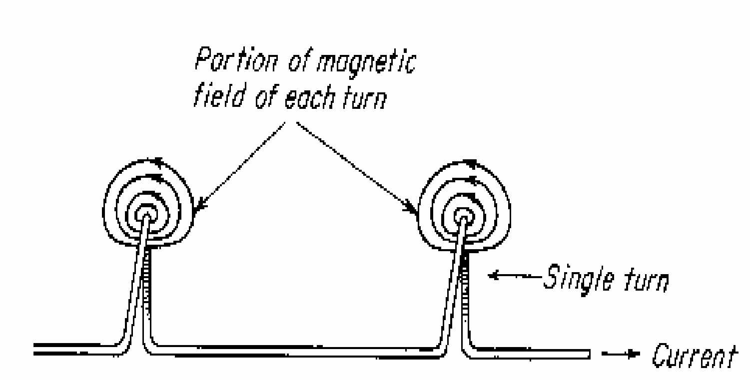


**Figure 1.**

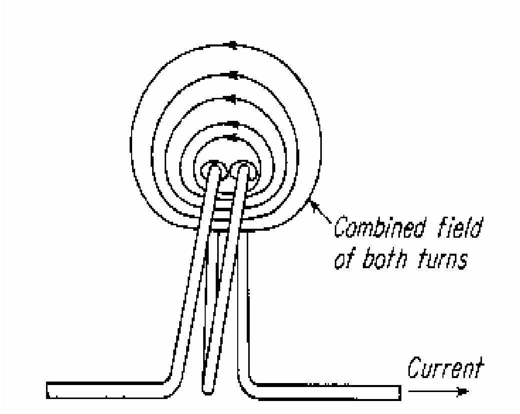


**Figure 2.**

With 3 turns, 3 times the number of lines of force cut 3 turns, so 9 times the counter emf is developed. The inductance of a coil varies as the number of turns squared. It can be seen that the length of the coil is also going to enter into the exact equation of the inductance of a coil.

If the turns are stretched out, the field intensity will be less and the inductance will be less. The larger the radius or diameter of the coil, the longer the wire used and the greater the inductance. In single-layer air-core coils with a length approximately equal to the diameter, a formula that will give the approximate inductance in microhenries is:

$$L = \frac{r^2N^2}{24r + 25\,l}$$

Where L = is the inductance in uH.
N = the number of turns.
r = radius in centimetres.
l = length in centimetres.

The inductance of straight wires alone is found in antennas, in power lines, and in ultra high frequency equipment. In most electronic and radio applications where inductance is required, space is limited and wire is wound into either single layer or multilayer coils with air, powdered-iron-compound (ferrite), or laminated (many thin sheets) cores. The advantage of multilayer coil construction for high values of inductance becomes obvious when it is considered that, while 2 closely wound turns produce 4 times the inductance of 1 turn, the addition of 2 more turns closely wound on top of the first 2 will provide almost 16 times the inductance. Direction of winding has no affect on the inductance value of a given coil.

In many applications coils are constructed with ferrite cylinders (slugs) that can be screwed into or out of the core space of the coil. This results in a controlled variation of inductance, maximum when the iron-core "slug" is in the coil and minimum with it out.

A special type of coil is the toroid. It consists of a doughnut shaped ferrite core, either single layer wound as shown in figure 3 and bottom left of figure 4. Its advantages are high values of inductance with little wire, and therefore little resistance in the coil, and the fact that all the lines of force are in the core and none outside (provided there is no break in the core). As a result it requires no shielding to prevent its field from interfering with outside circuits and to protect it from effects of fields from outside sources. Two toroids can be mounted so close that they nearly touch and there will be almost no interaction between them.

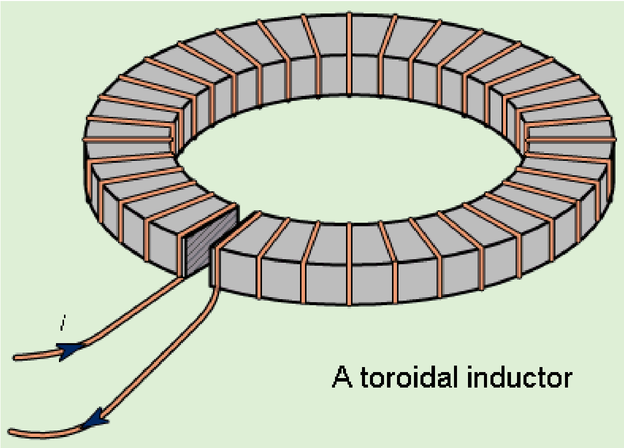


**Figure 3.**

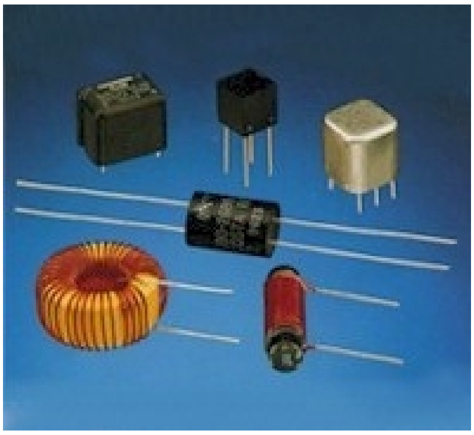

**Figure 4.**

## SCHEMATIC SYMBOLS OF INDUCTORS

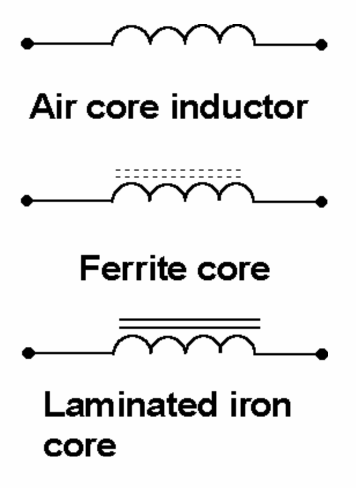


**Figure 5.**

## THE TIME CONSTANT OF AN INDUCTANCE

The time required for the current to rise to its maximum value in an inductive circuit after the voltage has been applied, will depend on both the inductance and the resistance in the circuit. With a constant value of resistance in a circuit, the greater the inductance, the greater the counter emf produced and the longer the time required for the current to rise to maximum. With a constant value of inductance in a circuit, the more resistance, the less current that can flow.

As with capacitive and resistive circuits, the time required for the current to rise to 63% of the maximum value (called the time constant) can be determined by:

$T = L/R$

Where $T$ = time in seconds.
$L$ = inductance in henrys (H).
$R$ = resistance in ohms.

## EXAMPLE

Calculate the time constant of a 10 Henry inductance with 10 ohms of resistance.

$T = L/R = 10/10 = 1$ second

Suppose the emf applied to this inductor was 10 volts. What would be the current flowing after 1 second?

The final current after 5 time constants will be:

$I = E/R = 10/10 = 1$ A

After 1 time constant the circuit current will have reached 63% of what will be its final value, or 63% of 1A = 630 mA.

## CURRENT LAGS IN AN INDUCTIVE CIRCUIT

In a resistive circuit the current and voltage obey Ohms law. If you increase the voltage across a resistance, the current increase straight away to the new Ohms law value determined by I=E/R. In an inductive circuit it takes time for the current to build up to its final value. The current lags behind. The current will eventually reach its Ohms law value after 5 time constants. However, if the voltage is continually changing as in an AC circuit, the current will always lag the voltage by 90 degrees.

Think of ‘L’ for inductance and ‘L’ for lag – current lags voltage in an inductive circuit.

## THE ENERGY IN A MAGNETIC FIELD

Current flowing in a wire or coil produces a magnetic field around itself. If the current suddenly stops, the magnetic field held out in space by the current will collapse back into the wire or coil. Unless the moving field has induced a voltage and current into some external load circuit, all the energy taken to build up the magnetic field will be returned to the circuit in the form of electric energy as the field collapses.

## CHOKE COILS

The ability of a coil to oppose any change of current can be used to smooth out varying or pulsating types of current. In this application an inductor is known as a choke coil, since it chokes out variations of amplitude of the current. For radio frequency (RF) ac or varying dc an air-core coil may be used. For lower frequency circuits greater inductance is required. For this reason iron core choke coils are found in audio frequency and power frequency applications.

A choke coil will hold a nearly constant inductance value until the core material becomes saturated. When enough current is flowing through the coil to saturate the core magnetically, variations of current above this value can produce no appreciable counter emfs and the coil no longer acts as a high value of inductance to these variations. To prevent the core from becoming magnetically saturated, a small air gap may be left in the iron core. The air gap introduces so much reluctance in the magnetic circuit that it becomes difficult to make the core carry the number of lines of force necessary to produce saturation. The gap also decreases the inductance of the coil. An air coil cannot be saturated.

## DEFINITION OF A HENRY

If a coil has a rate of change of current of one ampere per second and this produces a counter emf of 1 volt, then the coil is said to have an inductance of one Henry.

## MUTAL INDUCTANCE

If one coil is placed near another so that the magnetic fields interact with each other then the moving magnetic field in one will induce voltage into the other. This ability of one coil to effect another is called mutual inductance.

The farther apart the two coils are, the fewer the number of lines of force that interlink the two coils and the lower the voltage induced in the second coil.

The mutual inductance can be increased by moving the two coils closer together or by increasing the number of turns of either coil.

When all the lines of force from one inductor are linked to another, unity coupling is said to exist and the mutual inductance is:

$$M = \sqrt{L1 \times L2}$$

Where M is the mutual inductance in Henries.

The above formula assumes 100% coupling between the two inductors $L_1$ and $L_2$. This equation assumes that all the magnetic lines of force from $L_1$ cut all the turns of $L_2$. If this is not the case then M is determined by:

$$M = k \sqrt{L1 \times L2}$$

Where k is the percentage of coupling.

For example: suppose a 5 Henry coil has 75% of its lines of force cutting a 3 Henry coil. What is the mutual inductance?

$$M = 0.75 \sqrt{5 \times 3}$$

$$M = 2.9\ H$$

## COEFFICIENT OF COUPLING

The degree of closeness of coupling of two coils can also be expressed as a number between 0 and 1 rather than as a percent. A percentage of 100 is equal to a coefficient of coupling of 1 or unity. 75% coupling is 0.75 as above. No coupling is 0.

The formula for mutual inductance can be transposed for coefficient of coupling:

$$k = \frac{M}{\sqrt{L1 \times L2}}$$

## INDUCTANCES IN SERIES

When you add inductances in series you are in effect simply increasing the size of the inductor. Therefore, to find the total inductance, sum the individual inductances.

$L_t = L_1 + L_2 + L_3 + \ldots$ etc

## INDUCTANCES IN PARALLEL

If the inductances are connected in parallel the total inductance is calculated by using a formula similar to the parallel resistance formula.

$1/L_t = 1/L_1 + 1/L_2 + 1/L_3 + \ldots$ etc

Both of these equations assume that the magnetic lines of force from all the inductors are not coupled (linked) to the others i.e. the mutual inductance is zero. Another way of describing how inductances are linked is called coefficient of coupling (k). If k=0 then there is no coupling. If k=1 the two inductances are completely coupled.

## INDUCTIVE REACTANCE

It has been explained that dc flowing through an inductance produces no counter emf to oppose the current. With varying dc, as the current increases, the counter emf opposes the increase. As the current decreases, the counter emf opposes the decrease. Alternating current is in a constant state of change, and the effect of the magnetic fields is a continual induced voltage opposition to the current. This reacting ability of the inductance against the changing current is called inductive reactance. Inductive reactance is the opposition to current flow present by an inductance in a circuit with changing current, and is measured in ohms.

$X_L = 2\prod fL$

So inductive reactance is directly proportional to frequency and inductance.

Just as with resistance and capacitive reactance, the total inductive reactance in ohms is found using the same form of the equation.

In series:

$X_L(\text{total}) = X_{L1} + X_{L2} + X_{L3} + \ldots$ etc

And parallel:

$1/X_L(\text{total}) = 1/X_{L1} + 1/X_{L2} + 1/X_{L3} + \ldots$ etc

The voltage across and the current through an inductive reactance can be determined using Ohms law.

EXAMPLE

An inductance of 100 uH is in series with an inductance of 200 uH, and connected to a 10 volt AC supply with a frequency of 500 kHz. How much current will flow in this circuit?

We need to find the total inductive reactance of the circuit. We could find the individual reactances of each inductor and add them, or we could find the total inductance and then the total inductive reactance. I will do it using the latter method.

$L_t = L_1 + L_2 = 100$ uH + 200 uH = 300 uH
$X_L = 2\pi fL$
$X_L = 2\pi \times 500 \times 10^3 \times 300 \times 10^{-6}$
$X_L = 942$ ohms

I=E/R = 10/942 (x 1000 for milliamps) = 10.6 mA

How much power is dissipated in the above example?

There is no resistance in the circuit so no power is dissipated. You cannot/must not substitute $X_L$ or $X_C$ for R in the power equations. For example $P=I^2 R$ is okay but $P=I^2 X_L$ is not. Reactance, either inductive or capacitive does not dissipate power – only resistance does.

Take a pure inductance reactance of 240 Ohms and imagine it being connected to a power point. The current that flows would be $I=E/X_L = 240/240 = 1$ Ampere. Even though 1 Ampere would flow in the circuit no power is dissipated as there is not resistance. All of the power supply charging the inductor during once cycle is returned to the power point (the power supply) on the alternate half cycle. A pure inductor has no losses.

ONLY resistance dissipates power

Power authorities dislike reactive loads like this as current drawn does not register on the Energy Meter. The power lines to your house carry the charge and discharge 'reactive' currents *do* have resistance – the lines *do* dissipate power – and this power loss is *not* metered.

End of Reading 14.
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