An inductor may be defined as a component that will oppose any change in current and store energy in its electromagnetic field.

The physical description of an inductor will help the student get a better over all picture of its use.

Any conductor carrying current has some inductance. The reason is that all inductors are associated with a magnetic field or flux.

The size of the wire used will be determined by the amount current carried by the inductor.

As shown in FIGURE 3, there are several physical dimensions that will determine the inductance.

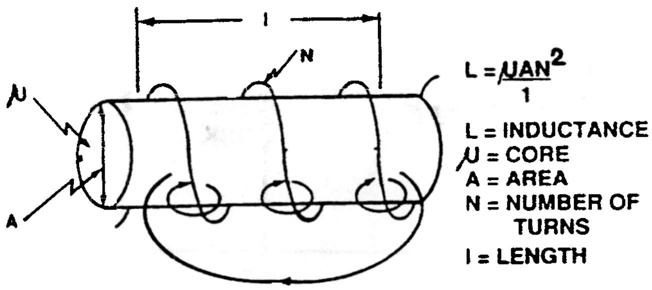


FIGURE 3

N, represents the number of turns in the inductor. If N, is increased the inductance increases, thus N and (L), are directly proportional.

NOTE: Inductors are referred to as coils and chokes.

The letter (l) represents the length of the inductor (coil). The longer the coil the more turns thus an increased inductance. We may conclude that (l) is proportional to the inductance (L).

A describes the cross-sectional area of the core. Increasing the area increases the inductance. The formula for a circle is $A = \pi r^2$, therefore if we double the radius (r), then the area (A) increases four times, thus the inductance will increase four times.

The turns per length ratio will affect the inductance as follows; $N/_1$ or turns per length increases, this means that we have increased the spacing or separation between the turns. If the spacing is greater, the inductance is less.

U represents the permeability of the core material. The term permeability describes the ease with which the lines of flux travel through the material or core. Air has the lowest permeability (μ), soft iron has the highest. This really amounts to the fact that magnetic lines of force (flux), has very little loss in soft iron, however, air core offers the greatest loss. See FIGURE 4. A represents the air core and B, the iron core. The formula for inductance (L), based on physical dimensions is as follows:

$$L = \frac{\mu A N^2}{1}$$

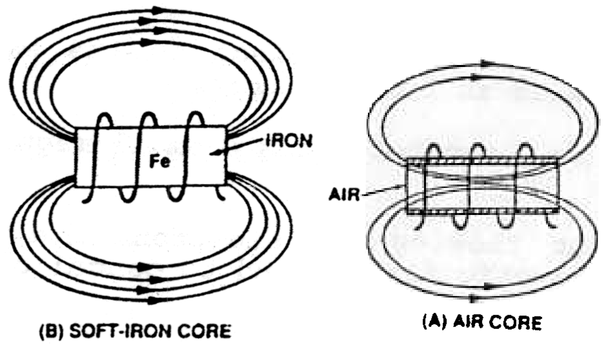


FIGURE 4

Some physical inductors will be shown in FIGURE 5, along with the schematic symbols for the iron core inductor in A, and the air core in B.

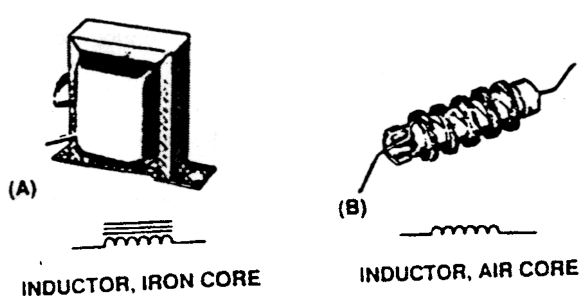


FIGURE 5

The letter symbol for all inductors is the upper case letter L. The unit value for the inductor (L) is the henry. The henry (h), like the resistor may be described as the henry (h) the millihenry (mh) or microhenry (μh).

The henry (h) is the value of the inductor or a measure of the amount of opposition to current flow that the inductor is capable of delivering.

The inductor is like a heavy weight that is to be moved. If we try to push a automobile it doesn't move immediately. This means there is a lag time between the application of the force and the movement of the automobile. Once it begins to move, the process is reversed, and it cannot be stopped immediately.

Inductor action or induction is the process by which an EMF is produced in a circuit by varying the magnetic field associated with the circuit.

As shown in FIGURE 6, the effect of the magnetic field on electron field results in current flow.

Each electron is a conductor has a small magnetic field associated with it.

With no current flowing the electrons are aligned in a random manner, thus the magnetic fields tend to cancel one another, i.e.,: no current, no magnetic field.

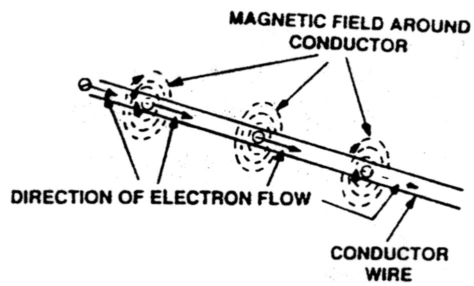


FIGURE 6

When voltage is applied, current begins to flow, thus aligning the electrons so that their magnetic fields will add.

The total strength of the magnetic field is the sum of individual fields.

The magnitude of the magnetic field surrounding the conductor will increase as the amount of current flow increases. The magnetic flux density is a function of the (1) type of conductor, (2) cross sectional diameter of the conductor, (3) turns per unit area, (4) type of core and (5) number of turns.

Based on the fact that a moving magnetic field causes current to flow in a conductor we may come to the following conclusions:

First, there must be a conductor.

Second, there must be a magnetic field.

Third, there must be relative motion. This simply means either the conductor must be moving through the field or the field moving across the conductor.

If the conductor is moving the result is a generator. If the field is moving the result is an inductor or a transformer. The transformer will be covered in a later lesson.

The key to understanding the inductor is called SELF INDUCTION.

Self induction can best be explained by self infliction, that is, if a person begins to hurt himself the body nerves cause pain thus limiting the self infliction.

Self induction simply means the conductor is inducing a current into itself.

As shown in FIGURE 7, an electromotive force is developed whenever there is <u>relative</u> <u>motion</u> between a magnetic field and a conductor.

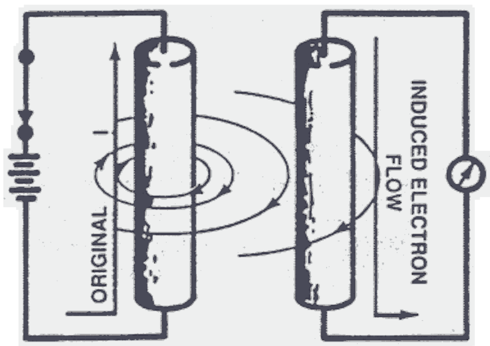


FIGURE 7

Electromotive force <u>(EMF)</u> is a difference of potential or voltage which exists between two points in an electrical circuit. In generators and inductors the emf is developed by the action between the magnetic field and the electrons in a conductor.

In FIGURE 8, a length of conductor is looped so that two portions of the conductor lie next to each other. These portions are labeled conductor 1 and conductor 2. When the switch is closed, current (electron flow) in the conductor produces a magnetic field around ALL portions of the conductor. For simplicity, the magnetic field (expanding lines of flux) is shown in a single plane that is perpendicular to both conductors.

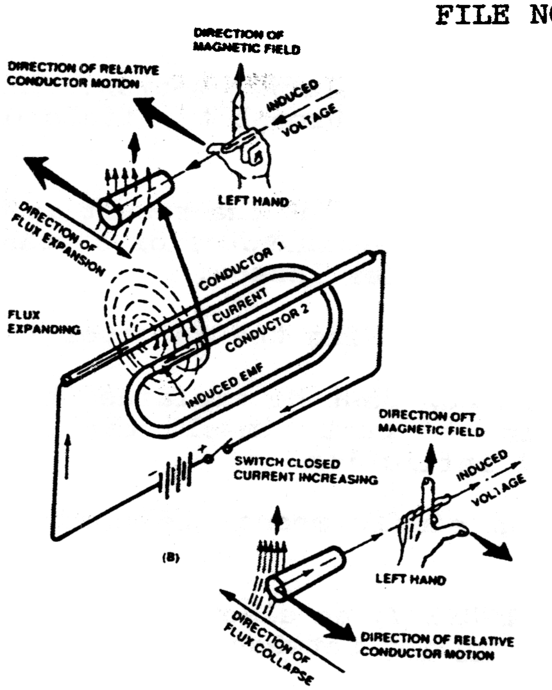


FIGURE 8

Although the expanding field of flux originates at the same time in both conductors, it is considered as originating in conductor 1 and its effect on conductor 2 will be explained. With increasing current, the flux field expands outward from conductor 1, cutting across a portion of conductor 2. This results in an induced EMF in conductor 2 as shown by the dashed arrow. Note that the induced EMF is in the opposite direction to (in OPPOSITION to) the battery current and voltage.

The direction of this induced voltage may be determined by applying the LEFT-HAND RULE FOR GENERATORS. This rule is applied to a portion of conductor 2 that is "lifted" and enlarged for this purpose in FIGURE 8(A). This rule states that if you point the thumb of your left hand in the direction of relative motion of the conductor and your index finger in the direction of the magnetic field, your middle finger, extended as shown, will now indicated the direction of the induced current which will generate the induced voltage counter EMF as shown.

In FIGURE 8 (B), the same section of conductor 2 is shown after the switch has been opened. The flux field is collapsing. Applying the left-hand rule in this case shows that the reversal of flux MOVEMENT has caused a reversal in the direction of the induced voltage. The induced voltage is now in the same direction as the battery voltage. The most important thing for you to note is that the self-induced voltage opposes BOTH changes in current. That is, when the switch is closed, this voltage delays the initial buildup of current by opposing the battery voltage. When the switch is opened, it keeps the current flowing in the same direction by aiding the battery voltage.

Thus, from the above explanation, you can see that when a current is building up, it produces a growing magnetic field. This field induces and EMF in the direction opposite to the actual flow of current. This induced EMF opposes the growth of the current and the growth of the magnetic field. If the increasing current had not set up a magnetic field there would have been no opposition to its growth. The whole reaction, or opposition, is caused by the building up and collapse of the magnetic field, the lines of which, as they expand or contract, cut across the conductor and develop the counter emf.

Since all circuits have conductors in them, you can assume that all circuits have inductance. However, inductance has its greatest effect only when there is a change in current. Inductance does NOT oppose current, only a CHANGE in current. Where current is constantly changing as in an A.C. circuit, inductance has more effect.

From FIGURE 8, we see the result of self induction in one turn (N) of the conductor. Increasing the number of turns will increase the amount of self induction, thus increasing the inductance (L).

Because the inductor opposes a change in current flow, or reacts in opposition to a change in current, this opposition was and is called REACTANCE.

REACTANCE, whose letter symbol is X, and designated INDUCTIVE REACTANCE or (X_L), is measured in OHMS like the resistance of the resistor. The Greek letter OMEGA (Ω) is used for ohms.

We know from Kirchhoff's Law that the sum of the voltage drops around a closed loop is zero or the applied voltage around a closed circuit is equal to the sum of the voltage drops.

From the current shown in FIGURE 9, we may see that the voltage drops in the circuit are equal to zero. $E_A = E_L$ or $E_A - E_L = 0$.

Note, for the student interested and having had enough math, the demonstration of the formula for X_L is shown in APPENDIX A, at the end of this lesson.

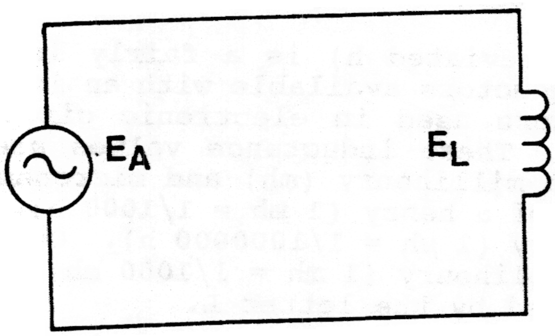


FIGURE 9

Inductor action can best be explained by the circuits shown in FIGURE 10.

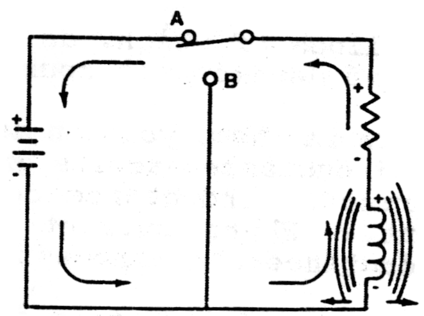


FIGURE 10

When the switch is placed in position A, current flows through the circuit and coil as shown.

When the switch is placed in position B, the battery current does not flow, but the magnetic field collapses, keeping current flowing in the circuit.

An inductor opposes any change in current and <u>stores</u> energy in an electromagnetic field.

Inductors are sometimes referred to as coils or chokes.

The unit of electrical inductance is the henry. One henry is defined as the amount of inductance that a coil has if the current, changing at the rate of one ampere per second, produces one volt of induced voltage. Inductance is a measure of how much counter EMF is generated in an inductor for a specific amount of change in the current through that inductor.

The henry (abbreviated h) is a fairly large unit of inductance. While there are inductors available with an inductance of one henry or more, most inductors used in electronic circuits have a much lower inductance value. These inductance values are expressed in smaller units known as the millihenry (mh) and microhenry (h). One millihenry is one thousandth of a henry (1 mh = 1/1000 h). One microhenry is one millionth of a henry (1 μh = 1/1000000 h). One microhenry is also one thousandth of a millihenry (1 mh = 1/1000 mh). The unit of inductance is usually expressed by the letter L.

An inductor has a certain amount of resistance since it is made up of a number of turns of wire.

The amount of resistance in many types of inductors is so small that it can be neglected.

When two or more coils are connected in series, and there is no mutual inductance between them, the total inductance is equal to the sum of the individual inductances (assuming pure inductance). Mutual inductance would exist only if the inductors were close to each other.

This is expressed by the formula $L_T = L_1 + L_2 + L_3 + L_4 +$ etc Inductance in series is computed as resitors in series.

L_T is the total inductance in henries and L_1, L_2, L_3, and L_4 are the individual inductances in henries as shown in FIGURE 11.

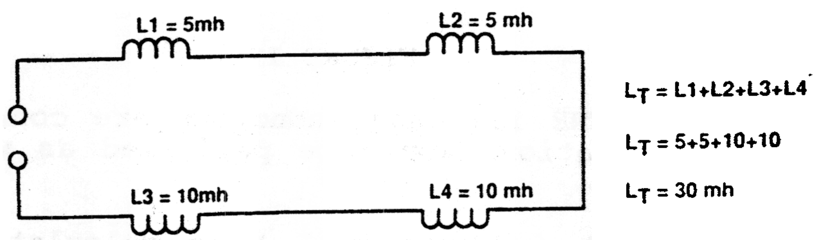


FIGURE 11

Inductors in series are calculated like resistors in series.

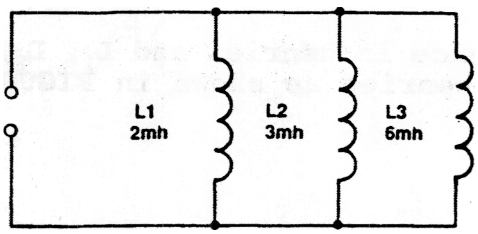
As shown in FIGURE 12, when inductors are connected in parallel and there is no mutual inductance between them, the total inductance is found by taking the reciprocal of the sum of the reciprocals (the same method that is used for finding the total resistance of two or more resistors connected in parallel). (Assume all are purely inductive).

This is expressed by the formula

$$L_T = \frac{1}{\frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3}}$$

Inductors in parallel are computed as resistors in parallel.

L_T is the total inductance and L_1, L_2, and L_3 are the individual inductances.



$$L_T = \frac{1}{\frac{1}{L1} + \frac{1}{L2} + \frac{1}{L3}}$$

$$L_T = \frac{1}{\frac{1}{2X10^{-3}} \quad \frac{1}{3X10^{-3}} \quad \frac{1}{6X10^{-3}}}$$

$$L_T = \frac{1}{500 + 333 + 167}$$

$$L_T = \frac{1}{1000}$$

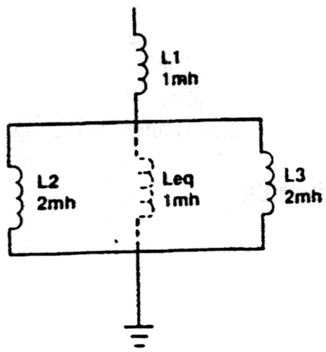
$$L_T = 1mh$$

FIGURE 12

As shown in FIGURE 13, when inductors are connected in series-parallel, the calculations would be performed as with resistors in series-parallel.

First, equivalent inductance (L_{eq}) is calculated as a parallel branch.

Second, total inductance (L_T) will be calculated by adding the series inductors.



$$Leq = \frac{1}{\frac{1}{L2} + \frac{1}{L3}}$$

$$Leq = \frac{1}{\frac{1}{2x10^{-3}} + \frac{1}{2x10^{-3}}}$$

$$Leq = \frac{1}{500 + 500}$$

$$Leq = \frac{1}{1000}$$

$$Leq = 1mh$$

FIGURE 13

L_{eq} for L_2 and L_3 can now be placed in series with L_1. Inductor L_1 and L_{eq} is treated as a series circuit to obtain L_T.

$$L_T = L_1 + L_{eq}$$

$$L_T = 1 + 1$$

$$L_T = 2 \text{ mh}$$

Inductive reactance is the oppostion of an inductor or coil to the flow of alternating current.

Letter symbol X_L.

Unit of measure = ohm.

NOTE: The formula $X_L = 2\ \pi fl$ is used to show the following relationships.

If frequency is decreased, inductive reactance decreases.

$2\ \pi fl)$

If frequency is increased, inductive reactance increases.

$= 2\ \pi fl)$

Inductance changes affect inductive reactance.

If inductance decreases, inductive reactance decreases

$= 2\ \pi fl)$

If inductance increases, inductive reactance increases.

$(X_L = 2\ \pi fl)$

Current Calculations in inductor circuits.

When the inductive reactance is known, the current flowing through the coil can be calculated by using Ohm's law.

$$I_L = \frac{E}{X_L}.$$

EXAMPLE: Using FIGURE 14, solve for I_L by using the formula:

$$I = \frac{E}{X_L}$$

$$I_L = \frac{E}{X_L}$$

$$\frac{110}{1256}$$

.087 Amps or 87mA

Since inductive reactance is opposition to current flow, it can be substituted for "R" in Ohm's Law.

The amount of inductive reactance of the coil depends upon the inductance of the coil, the frequency of the alternating current, and a constant value of 2π which is equal to 6.28 (approx.).

Stated as a formula: $X_L = 2\pi fl$.

X_L is the inductive reactance in ohms.

f is the frequency of the applied alternating current and the unit of measurement is the Hertz.

L is the inductance of the coil in henries.

Greek letter π equals 3.1416.

NOTE: When an ohmmeter is placed across an inductor, it measures the (DC) (wiring) resistance of the inductor.

In FIGURE 14, the required circuit parameters are given to allow us to calculate inductive reactance.

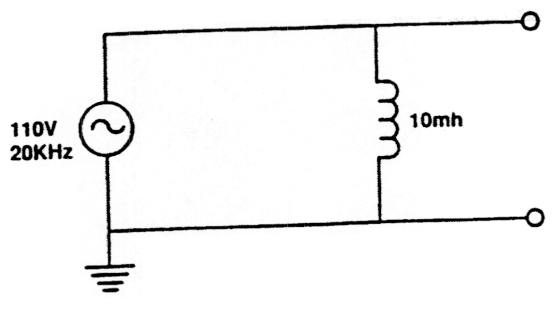


FIGURE 14

SOLUTION: $X_L = 2\pi fl$

$= 6.28\ (20 \times 10^3)\ (10 \times 10^{-3})$

$= 1256$

$1.256K\Omega$

Frequency changes affect inductive reactance.

The student has been taught in previous discussions that the current lags the voltage in an inductor. This was true because the counter electromotive force (CEMF) generated by self induction showed that current is simply not allowed to flow at the instant voltage is applied.

FIGURE 15, shows as inductor (L) in series with a resistor (R) and an AC voltage source.

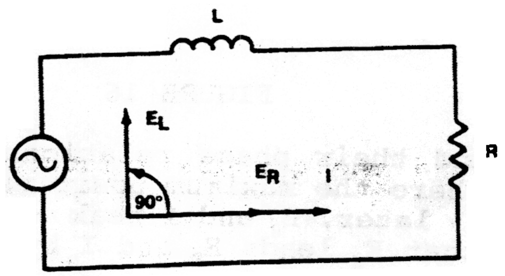


FIGURE 15

Earlier in this lesson we saw how Ohm's Law was used, as in series resistor circuits, to calculate the voltage drops. The same method is used to calculate voltage drops across the inductor (E_L) and across the resistor (E_R).

We know that the current in a series circuit is the same through out the circuit. We also know that the current and voltage are in phase through the resistor. We further know that the voltage across the inductor leads the current through the inductor by 90°. This is shown by the vector diagram in FIGURE 15.

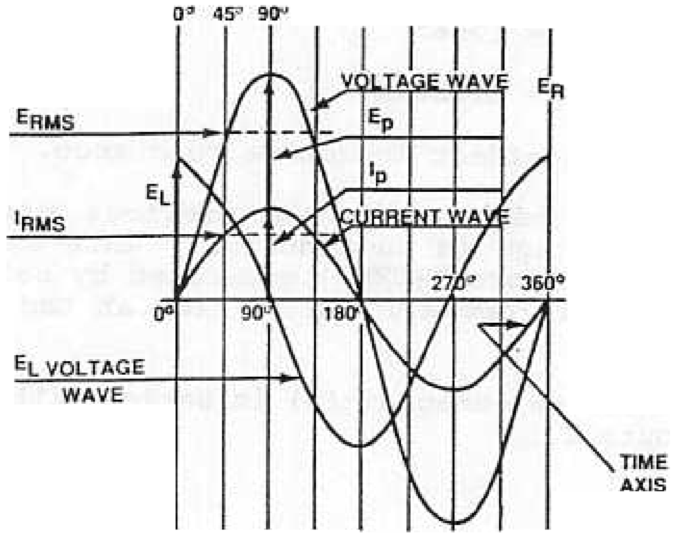


FIGURE 16

The waveforms and their phase relationships are demonstrated in FIGURE 16. Notice where the maximum positive voltages occur, E_L peaks first at 0°, then 90° later, E_R and I peak at 90°. On the basis of the diagram we can see that E_L leads E_R and I by 90°.

The solution to problems involving resistors and inductors take a new approach <u>because of the phase shift</u>. Thus we may say, due to phase difference between current and voltage across the inductive component, the total impedance of the circuit is not equal to the arithmetic sum of the ohmic values, but can be found by the formula

$Z = \sqrt{R^2 + X_L^2}$.

Since the phase difference is always at 90°, we may use what is known as vector addition to calculate the resultant voltage or E_A, as shown in FIGURE 17.

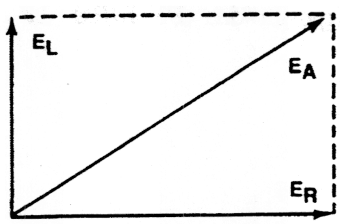


FIGURE 17

E_R represents resistor voltage.

E_L represents inductor voltage.

E_A represents applied voltage.

Vector represents formula

$E_A = \sqrt{E_R^{\,2} + E_L^{\,2}}$.

The formula called the Pythagorean Theorem states that the length of the hypotenuse (E_A) is equal to the square root of the sum of the squares of the other two sides (E_R and E_L).

The student will notice that the voltage across the inductor and resistor if added directly will be greater than the applied voltage, E_A.

Using the procedures discussed above, calculate the impedance (Z) and the applied voltage (E_A) using the values shown in FIGURE 18.

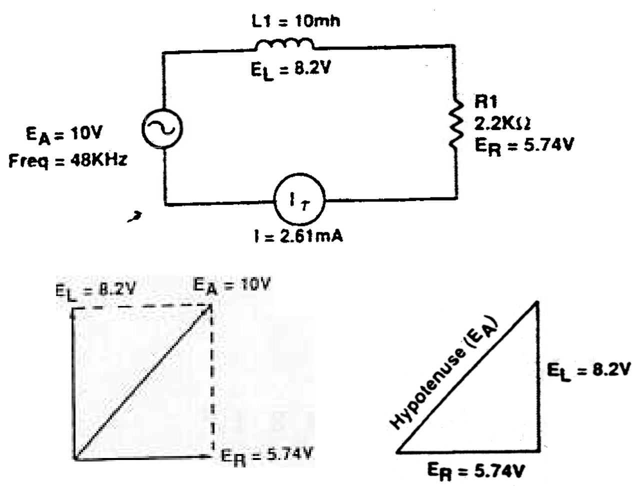


FIGURE 18

X_L $\pi f L$

X_L 0^3 X

X_L X

X_L .4 KΩ

$\sqrt{R^2 + X_L{}^2}$

$\sqrt{(2\ 2 \times 10^3)^2 + (3.014 \times 10^3)^2}$

$\sqrt{4.84 \times 10^6 + 9.084 \times 10^6}$

0^6

KΩ

Current $\frac{E_A}{}$ Ohm La

$\frac{10V}{3\ 73 \times 10^3}$

mA

V $I_{T1} \times R_1$

E_{R1} X 2

X X_L

E_L X

E_L 2V

Applied voltage:

$$E_A = \sqrt{E_{R1}^{\ 2} + E_{L1}^{\ 2}}$$

$$E_A = \sqrt{(5.742)^2 + (8.2)^2}$$

$$E_A = \sqrt{32.95 + 67.24}$$

$$E_A = \sqrt{100.19}$$

$$E_A = 10.009V$$

The three major steps in troubleshooting are in most cases employed for malfunctioning circuits.

Sectionalize.
Localize.
Isolate.

Isolate is the only step necessary in troubleshooting the inductive circuits we are working with.

Isolation - Isolate to the defective component.

Visual check - Visual inspection of the circuit for any possible external defects.

Visual check is used in conjunction with every major troubleshooting step.

Voltage check - This is one of the most valuable single means of locating a trouble in a circuit.

To summarize, during this conference you were introduced to inductors. Inductors are constructed by turns of wire around a core, and as current flows through the coil, a magnetic field develops. When current flow ceases through the coil, the field collapses, thus keeping current flowing in the circuit. It is by this process that an inductor stores energy. Inductors oppose any change in current. Inductors also cause a phase difference between current and voltage, and the voltage across an inductor leads the current by 90°. Due to this phase difference, the voltage of an inductive-resistive circuit must be computed vectorially, or by using the Pythagorean Theorem.

APPENDIX A:

$E_A = E_L$ or $E_A = E_L = 0$
When voltage is first applied to the inductor the induced (E_I) or counter electromotive force (CEMF) is equal to and opposite to the applied voltage, which completely stops current flow through the inductor.

Since the induced voltage (E_I) is equal to the voltage across the inductor and they are opposite in polarity, this equality can be expressed mathematically as follows;

$$L = \frac{I}{t}$$

$E_L = L \frac{I}{t}$ or a change in current (I) divided by a change in time (t), times the inductance, (L), is equal to the self induced voltage (E_I).

The following example may be used to show how inductive reactance (X_L) may be determined mathematically.

$$E_I = L \frac{di}{dt}$$

$$L = \frac{di}{dt}$$

i = the instantaneous value of AC
i = I sin wt
where (w) = $2\pi f$
di = a change in current
dt = a change in time

It must be remembered that the sine wave is changing faster as it passes through zero (0). This means the slope of the sine wave is maximum here. Also, at the peak of the sine wave the slope is minimum or zero.

To find the slope of the sine wave at zero and 90°, we must substitute in the above formula and integrate if from 0° to 90°.

$$E_L = L \frac{d\,(I \sin wt\,)}{dt} = L \qquad I_M \sin wt\, dt$$

$$E_L = wLI_M\,[\cos wt] \qquad = -wLI_M\,(\text{Cos } 90° - \text{Cos } 0°$$

$$E_L = wLI_M\,(0-1 \qquad\qquad \text{Cos } 90° = 0 \quad \text{Cos } 0° = 1$$

$$E_L = wLI_M = 2\pi FL\,(I) \qquad\qquad w = 2\pi f \quad X_L = 2\pi FL$$

$E_L = IX_L$, which is OHM's Law for AC inductors.
X_L= Inductive reactance in OHMS.