
Inductance
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April 25th, 2024 is the 150th anniversary of the birth of Guglielmo Marconi (1874-2024).

Guglielmo Marconi (born April 25, 1874, Bologna, Italy—died July 20, 1937, Rome) was an Italian physicist and inventor of a successful wireless telegraph, or radio (1896). In 1909 he received the Nobel Prize for Physics, which he shared with German physicist Ferdinand Braun. He later worked on the development of shortwave wireless communication, which constitutes the basis of nearly all modern long-distance radio.

Read more here:
https://www.britannica.com/biography/Guglielmo-Marconi

Objectives

- On completion, you should be able to:
  - Define **Inductance** and **Inductive Reactance**;
  - Do **simple calculations** involving inductance; and
  - Explain the **role** of the inductor in a circuit.

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Inductance

- **Inductance** is the property of an electrical circuit that **opposes a change in current.**
- In a **DC circuit** inductance has **an effect only** when the **DC starts**, or when **attempts are made to stop it.**
- In an **AC circuit** though, the **voltage** is **constantly changing,** and **inductance** constantly **works to retard** the **change in current.**

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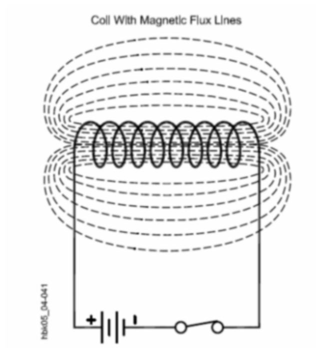
Inductance is the name given to the property of a component that opposes the change of current flowing through it. Even a straight piece of wire will have some inductance.

In electromagnetism and electronics, **inductance** is the tendency of an electrical conductor to oppose a change in the electric current flowing through it. The flow of electric current through a conductor creates a magnetic field around the conductor, whose strength depends on the magnitude of the current. A change in current causes a change in the magnetic field. From Faraday's law of induction, any change in magnetic field through a circuit induces an electromotive force (EMF) (voltage) in the conductors; this is known as electromagnetic induction. So the changing current induces a voltage in the conductor. This induced voltage is in a direction which tends to oppose the change in current (as stated by Lenz's law), so it is called a *back EMF*. Due to this back EMF, a conductor's inductance opposes any increase or decrease in electric current through it.

Current Through a Wire

- A **current** through a **wire** will generate a **magnetic field** around that wire, as can be demonstrated by bringing a **compass** near that wire.



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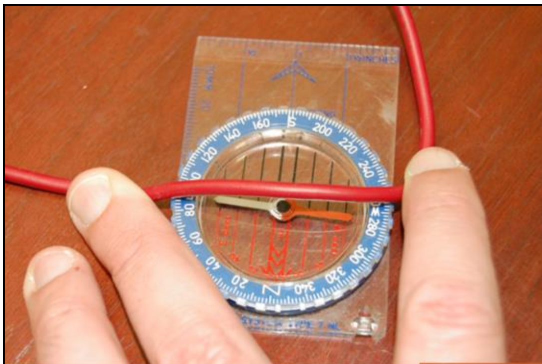
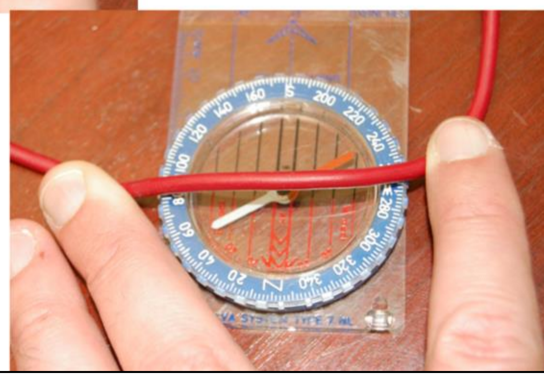


No Current



Current

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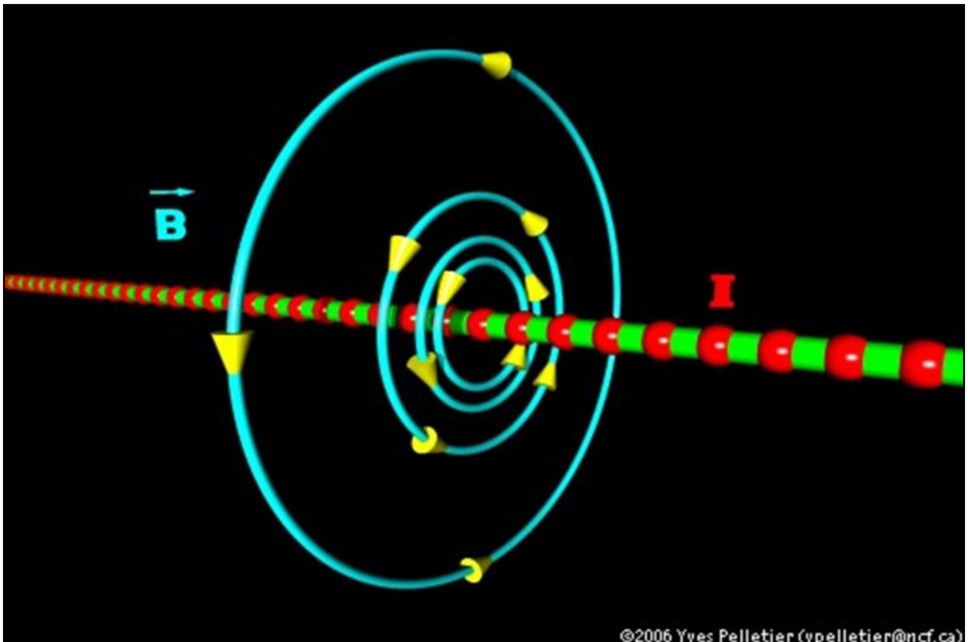

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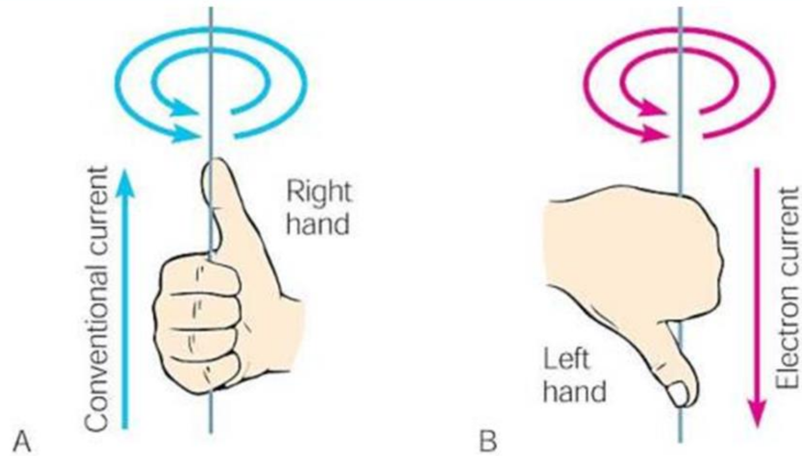
The magnetic field lines around a long wire which carries an electric current form concentric circles around the wire. The direction of the magnetic field is perpendicular to the wire and is in the direction the fingers of your right hand would curl if you wrapped them around the wire with your thumb in the direction of the current (CONVENTIONAL CURRENT, not electron flow). Change the direction of current flow, and the direction of the magnetic field will change.

If you use the direction of electron flow, use the left hand.

Conventional Current vs Electron Flow



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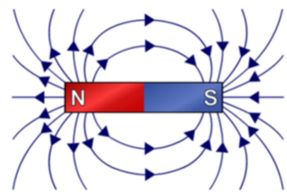
Magnetic Field Effects on a Wire

- Conversely, when magnetic **lines of flux cut** through a **wire,** a **current** will be **induced** to flow in that wire.
- This is the **basis for generators.**

Lines of flux – a way to visualize the magnetic field intensity and direction.



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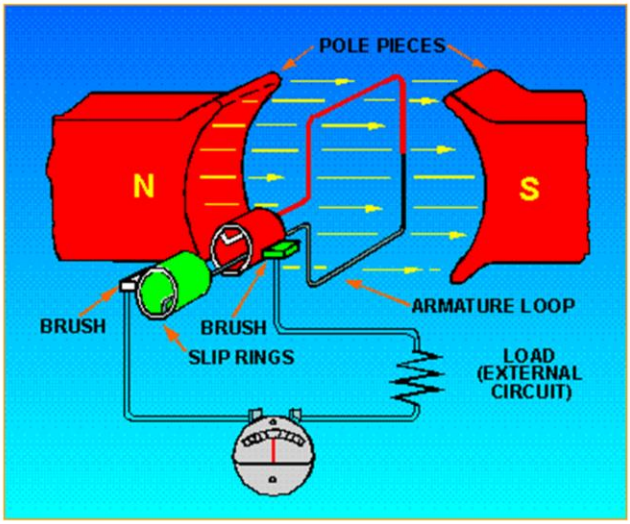
Lines of flux – a way to visualize the magnetic field intensity and direction.

Elementary Generator



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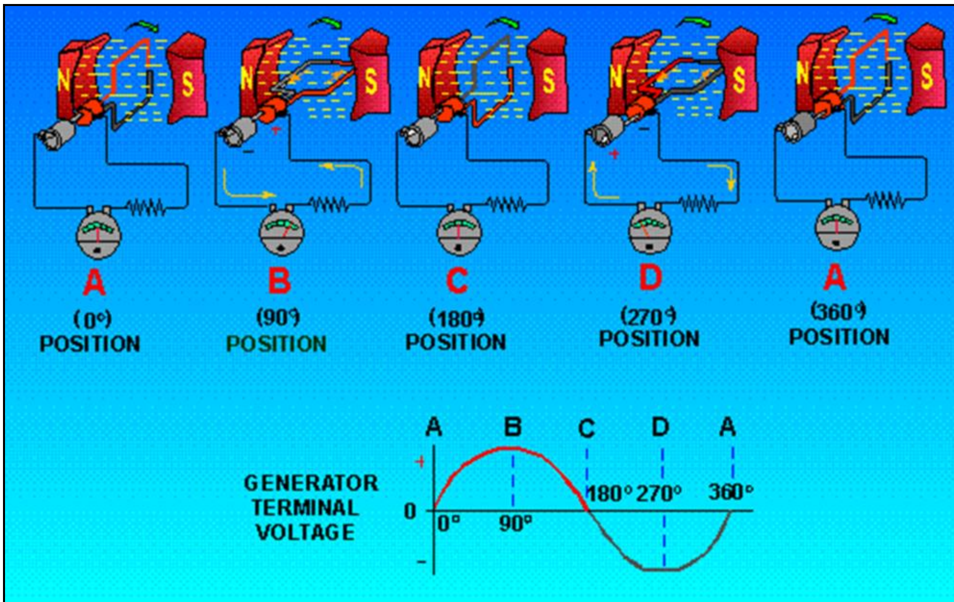
A basic design, called **elementary generator**, is to have a rectangular loop armature to cut the lines of force between the north and south poles. By cutting lines of force through rotation, it produces electric current. The current is sent out of the generator unit through two sets of slip rings and brushes, one of which is used for each end of the armature. In this two-pole design, as the armature rotates one revolution, it generates one cycle of single phase alternating current (AC). To generate an AC output, the armature is rotated at a constant speed having the number of rotations per second to match the desired frequency (in hertz) of the AC output.



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The relationship of armature rotation and the AC output can be seen in this series of pictures. Due to the circular motion of the armature against the straight lines of force, a variable number of lines of force will be cut even at a constant speed of the motion. At zero degrees, the rectangular arm of the armature does not cut any lines of force, giving zero voltage output. As the armature arm rotates at a constant speed toward the 90° position, more lines are cut. The lines of force are cut at most when the armature is at the 90° position, giving out the most current on one direction. As it turns toward the 180° position, lesser number of lines of force are cut, giving out lesser voltage until it becomes zero again at the 180° position. The voltage starts to increase again as the armature heads to the opposite pole at the 270° position. Toward this position, the current is generated on the opposite direction, giving out the maximum voltage on the opposite side. The voltage decrease again as it completes the full rotation. In one rotation, the AC output is produced with one complete cycle as represented in the sine wave.

The elementary generator produces a voltage in the following manner. The armature loop is rotated in a clockwise direction. The initial or starting point is shown at position A. (This will be considered the zero-degree position.)

At 0º the armature loop is perpendicular to the magnetic field. The black and white conductors of the loop are moving parallel to the field. The instant the conductors are moving parallel to the magnetic field, they do not cut any lines of flux. Therefore, no emf is induced in the conductors, and the meter at position A indicates zero. This position is called the NEUTRAL PLANE.

As the armature loop rotates from position A (0º) to position B (90º), the conductors cut through more and more lines of flux, at a continually increasing angle. At 90º they are cutting through a maximum number of lines of flux and at maximum angle. The result is that between 0º and 90º , the induced emf in the conductors builds up from zero to a maximum value. Observe that from 0º to 90º , the black conductor cuts DOWN through the field. At the same time the white conductor cuts UP through the field. The induced emfs in the conductors are series-adding. This means the resultant voltage across the brushes (the terminal voltage) is the sum of the two induced voltages. The meter at position B reads maximum value.

As the armature loop continues rotating from 90º (position B) to 180º (position C), the conductors which were cutting through a maximum number of lines of flux at position B now cut through fewer lines. They are again moving parallel to the magnetic field at position C. They no longer cut through any lines of flux. As the armature rotates from 90º to 180º , the induced voltage will decrease to zero in the same manner that it increased during the rotation from 0º to 90º . The meter again reads zero.

From 0º to 180º the conductors of the armature loop have been moving in the same direction through the magnetic field. Therefore, the polarity of the induced voltage has remained the same. This is shown by points A through C on the graph. As the loop rotates beyond 180º (position C), through 270º (position D), and back to the initial or starting point (position A), the direction of the cutting action of the conductors through the magnetic field reverses. Now the black conductor cuts UP through the field while the white conductor cuts DOWN through the field. As a result, the polarity of the induced voltage reverses.

Following the sequence shown by graph points C, D, and back to A, the voltage will be in the direction opposite to that 1-4 shown from points A, B, and C. The terminal voltage will be the same as it was from A to C except that the polarity is reversed (as shown by the meter deflection at position D). The voltage output waveform for the complete revolution of the loop is shown on the graph in the figure.

Counter EMF

- When a current **starts to flow** through a wire, it takes a **finite time** for the **magnetic field** to build up to its **final size.**
- As the magnetic field builds up, its **own lines of flux cut through the conductor.**
- This **induces** a **voltage** and **resulting current** in that wire.
- Because of Conservation of Energy reasons, that **induced current opposes the applied current.**
- This **opposing voltage** is called the **Counter** or **Back EMF (Electro Motive Force** – voltage).

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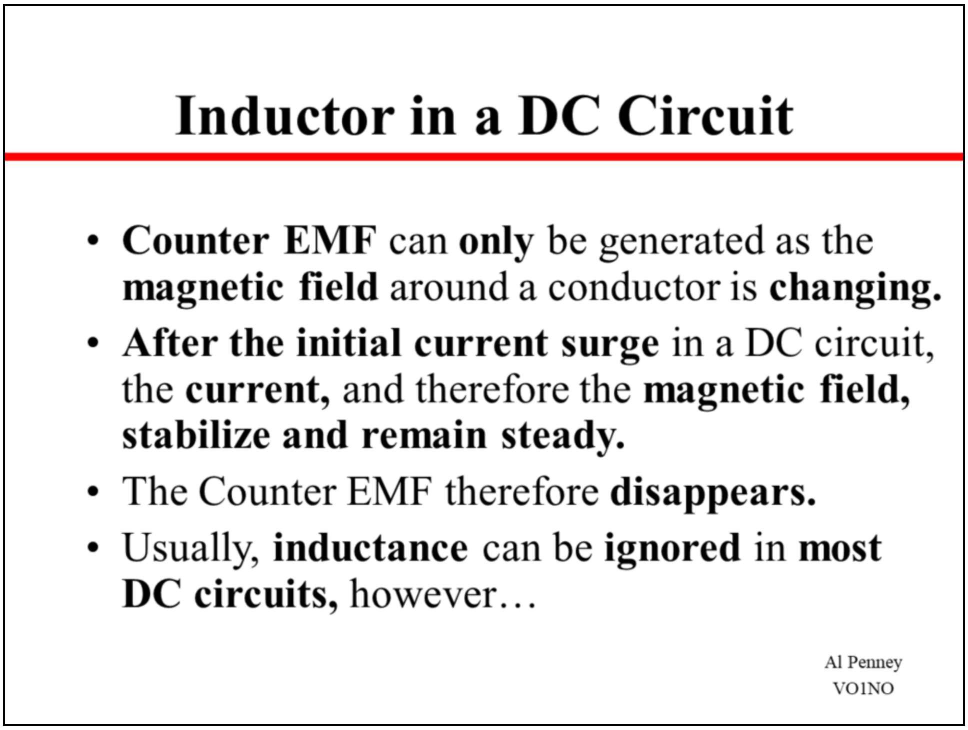
Inductors do this by generating a self-induced emf within itself as a result of their changing magnetic field. In an electrical circuit, when the emf is induced in the same circuit in which the current is changing this effect is called **Self-induction**, (L) but it is sometimes commonly called back-emf as its polarity is in the opposite direction to the applied voltage.

Back electromotive force (**back EMF**, BEMF) is a voltage that appears in the opposite direction to current flow as a result of the motor's coils moving relative to a magnetic field. It is this voltage that serves as the principle of operation for a generator.



When a current flows within a conductor, whether it be straight or in the form of a coil, a magnetic field builds up around it and this affects the way in which the current builds up after the circuit is made.

In terms of how inductance affects and electrical circuit, it helps to look at the way the circuit operates, first for a direct current, and then for an alternating current. Although they follow the same laws and the same effects result, it helps the explanation, the direct current example is simpler, and then this explanation can be used as the basis for the alternating current case.

•***Direct current:*** As the circuit is made the current starts to flow. It takes a finite period of time for the current to reach its maximum value, depending on the value of the inductance and resistance in the circuit. As the current increases to its steady value the magnetic field it produces builds up to its final shape. As this occurs, the magnetic field is changing, so this induces a voltage back into the coil itself, as would be expected according to Lenz's Law. Once the current reaches its maximum value, the magnetic field stabilizes and stops producing a counter-EMF. Once this happens, inductance plays no more part in the circuit until the power is turned off.

Counter EMF Backlash!

- In some devices such as **electric motors** and **relays**, the **Counter EMF** can **cause problems.**
- When the device is **turned off,** the **magnetic field collapses,** inducing a **strong Counter EMF.**
- This can be strong enough that it can cause an **arc in the switch** that controls the device.
- Sometimes it can even **weld the switch shut**, restarting the device and making it very difficult to stop.

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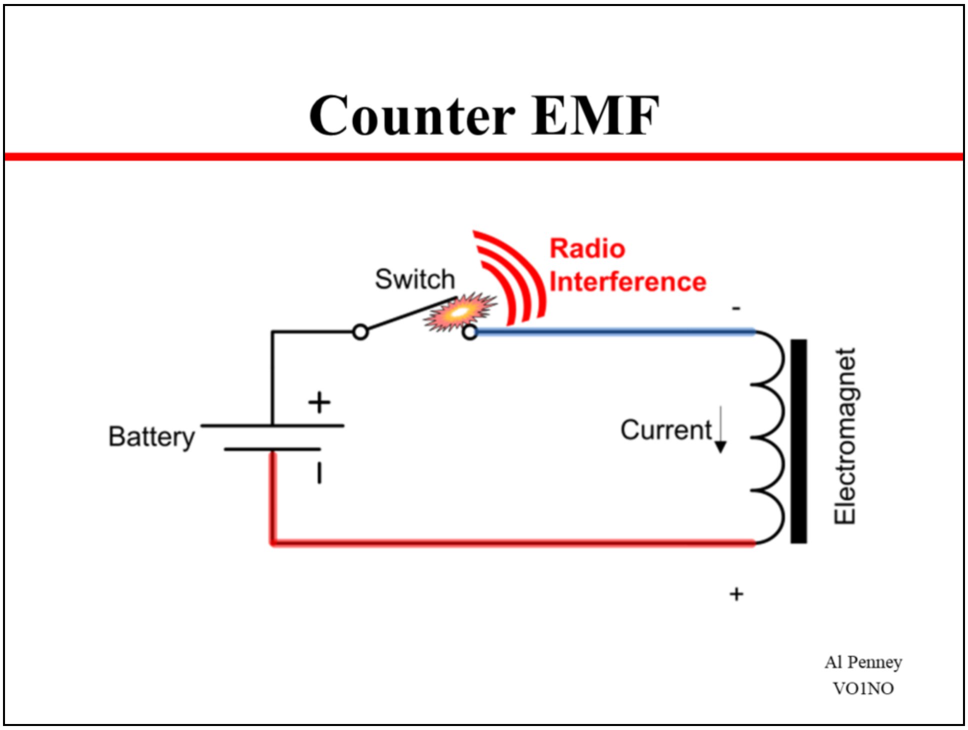
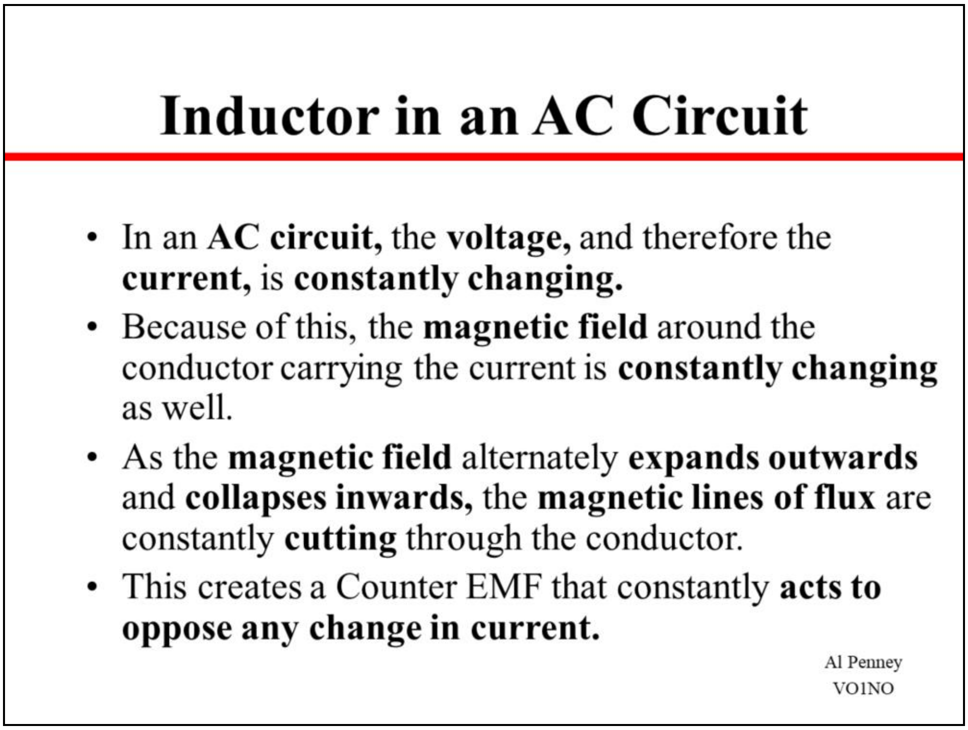
Back electromotive force (**back EMF**, BEMF) is a voltage that appears in the opposite direction to current flow as a result of the motor's coils moving relative to a magnetic field. It is this voltage that serves as the principle of operation for a generator.

Although Back EMF is a good and necessary phenomenon that makes running of motors possible, it assumes menacing proportions in the operation of relays and solenoids. A relay or a solenoid consists of a coil or a large number of turns of wire on an iron core. One of the properties of such an arrangement is the coil stores energy when current passes through it. This, by itself, is nothing to worry about, unless the current is suddenly stopped.

When the switch is opened, the current from the battery stops flowing instantly. However, the energy in the relay or solenoid “opposes the original change in magnetic flux”, which is now trying to collapse. The coil can do this only by keeping the current flowing across the gap in the switch. The only way it can do this is by creating a Back EMF high enough to generate an arc across the gap. The arc is sustained until the energy in the inductor dissipates.



When the current is switched off this means that effectively the resistance of the circuit rises suddenly to infinity. This means that the ratio L / R becomes very small and the magnetic field falls very rapidly. This represents a large change in magnetic field and accordingly the inductance tries to keep the current flowing and a back EMF is set up to oppose this arising from the energy stored in the magnetic field. The voltages mean that sparks can appear across the switch contact, especially just as the contact is broken. This leads to pitted contacts and wear on any mechanical switches. In electronic circuits this back EMF can destroy semiconductor devices and therefore ways of reducing this back EMF are often employed.

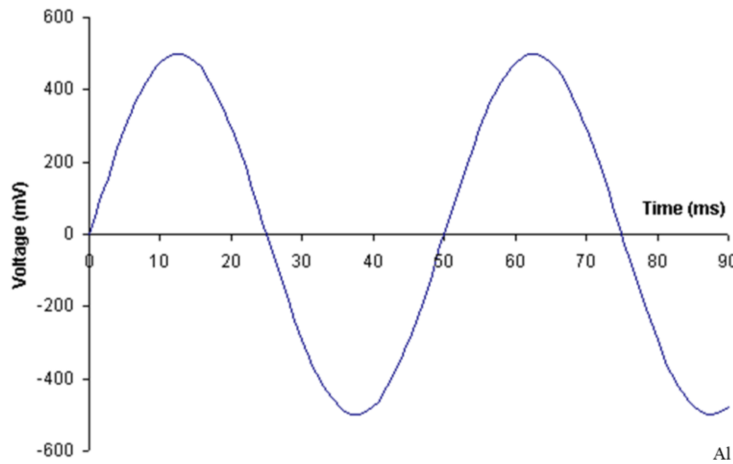


Alternating current: For the case of the alternating current passing through an inductor, the same basic principles are used, but as the waveform is repetitive, we tend to look at the way the inductor responds in a slightly different way as it is more convenient.

By its very nature, an alternating waveform is changing all of the time. This means that the resulting magnetic field will always be changing, and there will always be an induced back EMF produced. The result of this is that the inductor impedes the flow of the alternating current through it as a result of the inductance. This is in addition to the resistance caused but the Ohmic resistance of the wire.

It means that if the Ohmic resistance of the inductor is low, it will pass direct current, DC with little loss, but it can present a high impedance (AC resistance) to any high frequency signal. This characteristic of an inductor can be used in ensuring that any high frequency signals do not pass though the inductor.

AC Circuit



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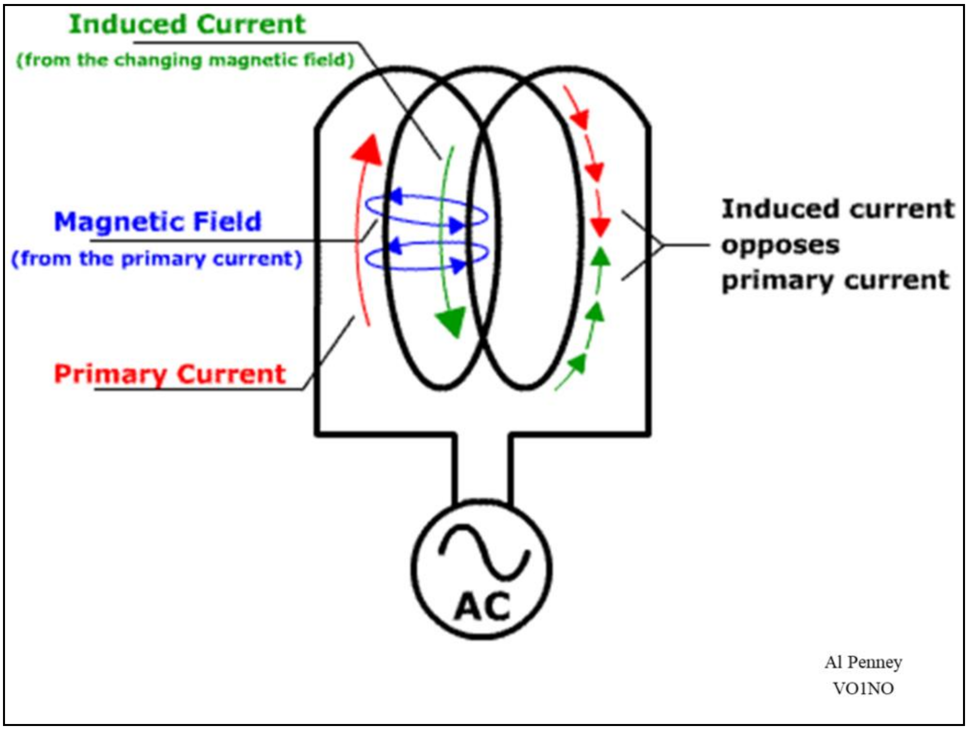
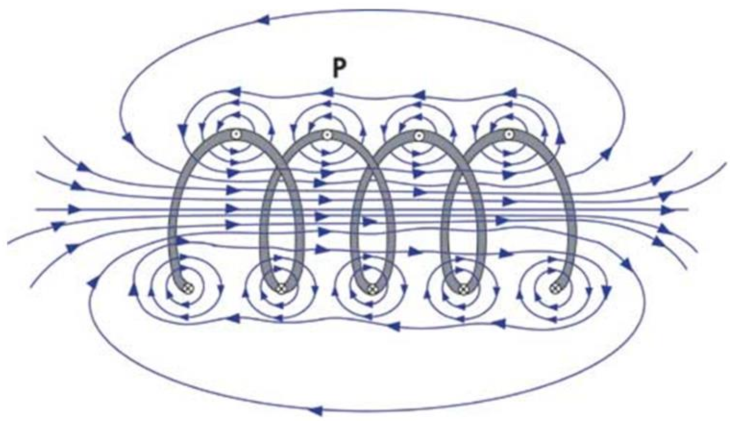


Next slide: Inductors are usually wound into a coil. There is a reason for that….

Magnetic Field Around a Coil



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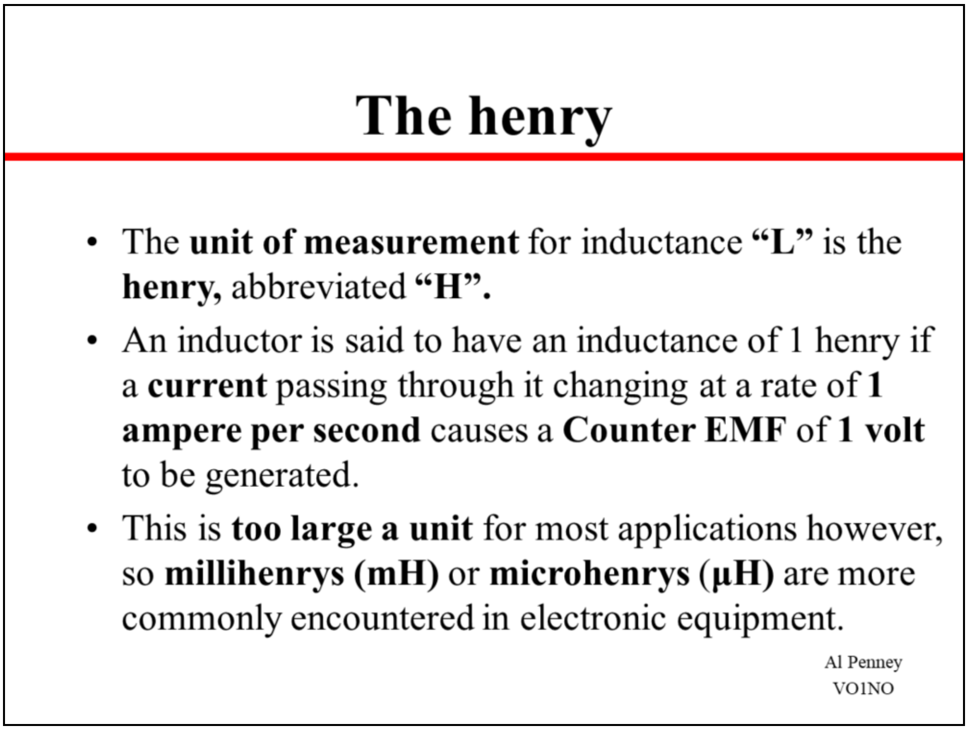
Winding a straight conductor into a coil concentrates the magnetic fields around the conductor, and therefore increases the ability of the magnetic lines of flux to "cut through" the conductor. This permits a greater counter-EMF to be produced when the current is changing. In other words, the amount of inductance has been increased.



Then we can accurately define **Inductance** as being: "a coil will have an inductance value of one Henry when an emf of one volt is induced in the coil were the current flowing through the said coil changes at a rate of one ampere/second".

Inductance, L is actually a measure of an inductors "resistance" to the change of the current flowing through the circuit and the larger is its value in Henries, the lower will be the rate of current change.

We know from the previous tutorial about the Inductor, that inductors are devices that can store their energy in the form of a magnetic field. Inductors are made from individual loops of wire combined to produce a coil and if the number of loops within the coil are increased, then for the same amount of current flowing through the coil, the magnetic flux will also increase.

So by increasing the number of loops or turns within a coil, increases the coils inductance.

The inductance of a coil depends on its size, the number of turns, and the permeability of the material within and surrounding the coil. Formulas can be used to calculate the inductance of many common arrangements of conductors, such as parallel wires, or a solenoid. A small air-core coil used for broadcast AM radio tuning might have an inductance of a few tens of microhenries. A large motor winding with many turns around an iron core may have an inductance of scores or hundreds of henries. The physical size of an inductance is also related to its current carrying and voltage withstand ratings.

Joseph Henry (December 17, 1797 – May 13, 1878) was an American scientist who served as the first Secretary of the Smithsonian Institution. He was the secretary for the National Institute for the Promotion of Science, a precursor of the Smithsonian Institution. He was highly regarded during his lifetime. While building electromagnets, Henry discovered the electromagnetic phenomenon of self-inductance. He also discovered mutual inductance independently of Michael Faraday, though Faraday was the first to make the discovery and publish his results. Henry developed the electromagnet into a practical device. He invented a precursor to the electric doorbell (specifically a bell that could be rung at a distance via an electric wire, 1831) and electric relay (1835). The SI unit of inductance, the Henry, is named in his honor. Henry's work on the electromagnetic relay was the basis of the practical electrical telegraph, invented by Samuel F. B. Morse and Sir Charles Wheatstone, separately.

Types of Inductors

Air Core

Variable

Magnetic or
Iron Core

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Roller Inductor

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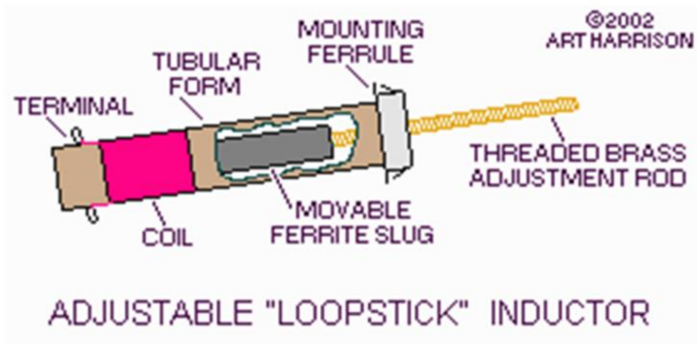
Loopstick Inductor



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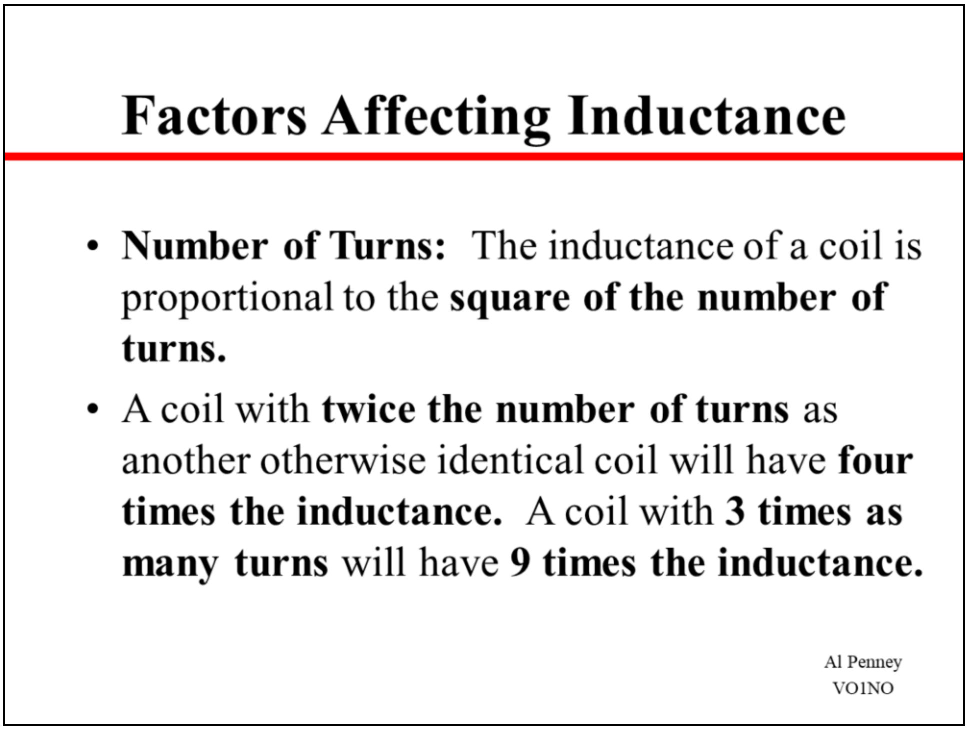
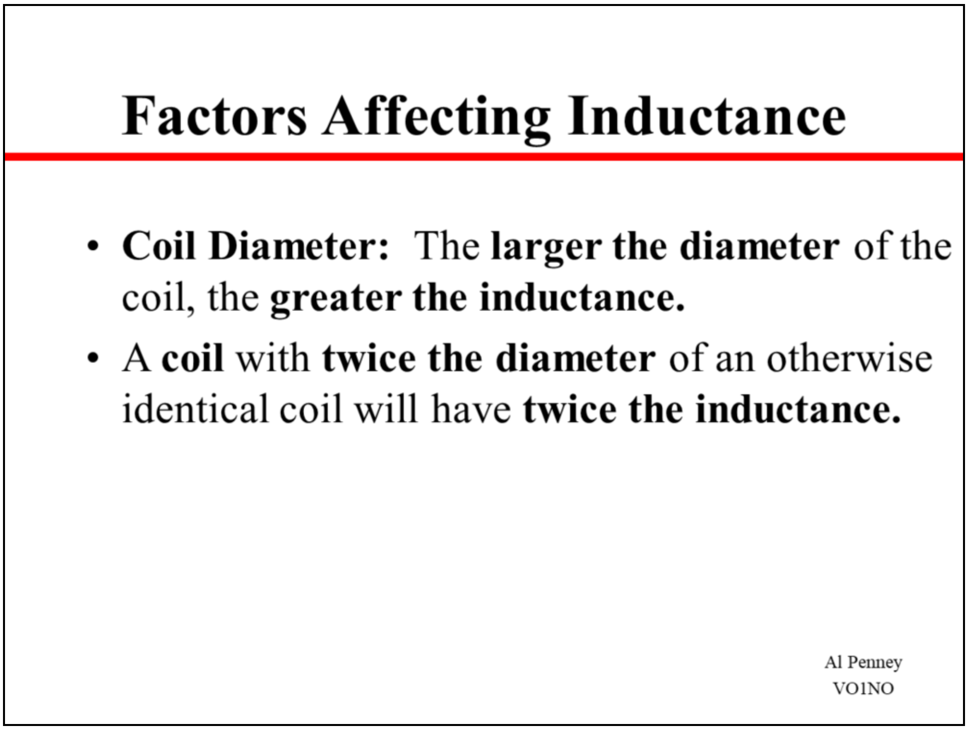


Number of Wire Wraps, or “Turns” in the Coil

All other factors being equal, a greater number of turns of wire in the coil results in greater inductance; fewer turns of wire in the coil results in less inductance.

Explanation: More turns of wire means that the coil will generate a greater amount of magnetic field force for a given amount of coil current.



Coil Area

All other factors being equal, greater coil area (as measured looking lengthwise through the coil, at the cross-section of the core) results in greater inductance; less coil area results in less inductance.

Explanation: Greater coil area presents less opposition to the formation of magnetic field flux, for a given amount of field force.

Factors Affecting Inductance

- **Changing the core:** Certain materials will **concentrate the lines of magnetic flux** better than others, and will therefore **increase the inductance** if used as a **core** for the coil.
- For example, a coil wound on an **iron core** will have much **more inductance** than one with an **air core.**

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Core Material

All other factors being equal, the greater the magnetic permeability of the core which the coil is wrapped around, the greater the inductance; the less the permeability of the core, the less the inductance.

Explanation: A core material with greater magnetic permeability results in greater magnetic field flux for any given amount of field force

Core Materials

Properties of Some High-Permeability Materials

Material	*Approximate Percent Composition*					*Maximum Permeability*
	Fe	Ni	Co	Mo	Other	
Iron	99.91	—	—	—	—	5000
Purified Iron	99.95	—	—	—	—	180000
4% silicon-iron	96	—	—	—	4 Si	7000
45 Permalloy	54.7	45	—	—	0.3 Mn	25000
Hipernik	50	50	—	—	—	70000
78 Permalloy	21.2	78.5	—	—	0.3 Mn	100000
4-79 Permalloy	16.7	79	—	—	0.3 Mn	100000
Supermalloy	15.7	79	—	5	0.3 Mn	800000
Permendur	49.7	—	50	—	0.3 Mn	5000
2V Permendur	49	—	49	—	2 V	4500
Hiperco	64	—	34	—	2 Cr	10000
2-81 Permalloy*	17	81	—	2	—	130
Carbonyl iron*	99.9	—	—	—	—	132
Ferroxcube III**	($MnFe_2O_4$ + $ZnFe_2O_4$)				1500	

Note: all materials in sheet form except * (insulated powder) and ** (sintered powder).
(Reference: L. Ridenour, ed., *Modern Physics for the Engineer*, p 119.)

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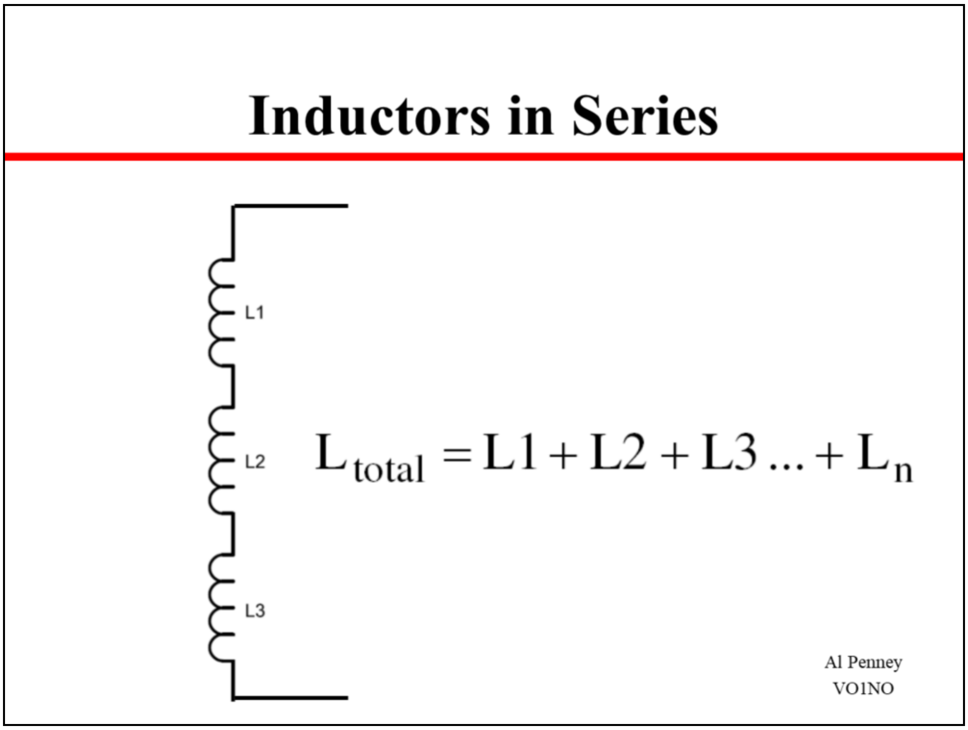
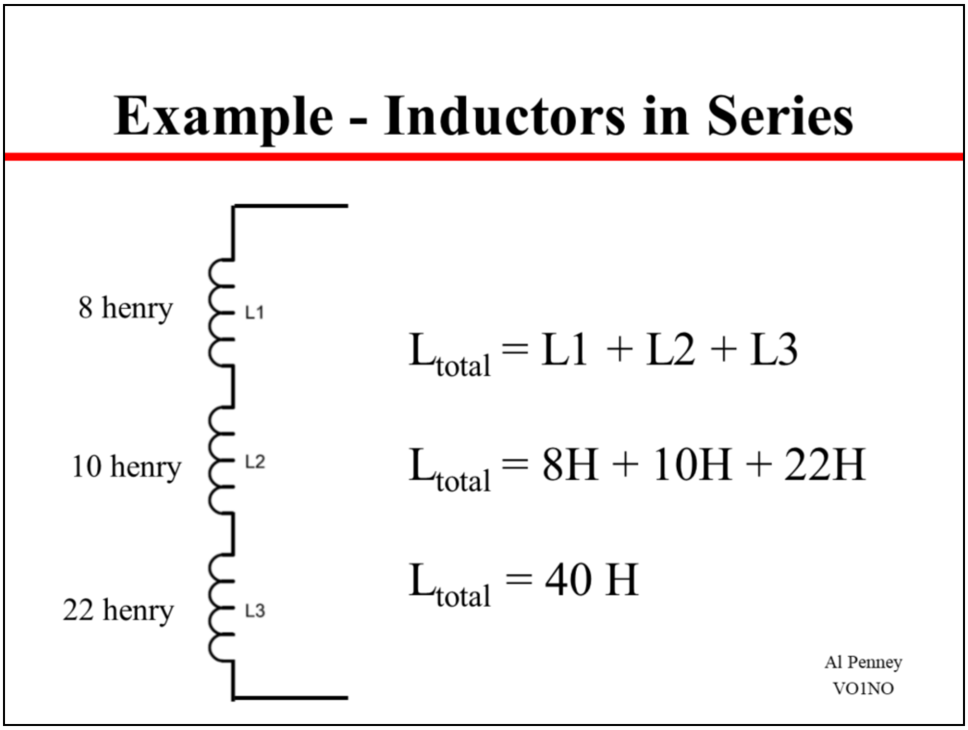


Inductors can be connected together in a series connection when they are daisy chained together sharing a common electrical current.

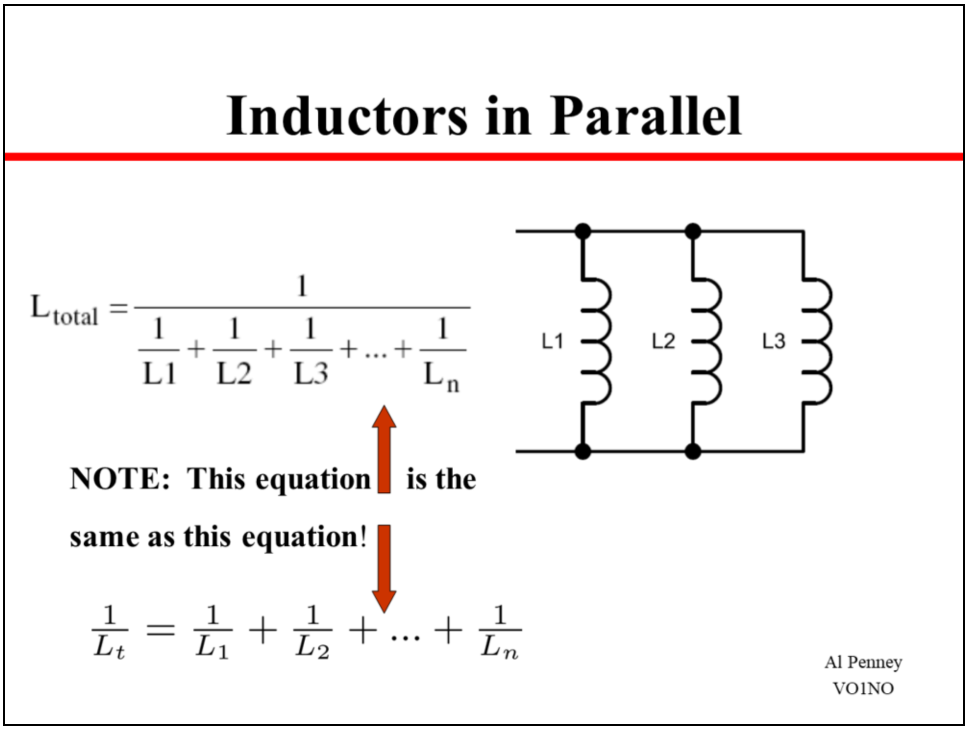
Inductors are said to be connected in “Series” when they are daisy chained together in a straight line, end to end. In the Resistors in Series lesson we saw that the different values of the resistances connected together in series just “add” together and this is also true of inductance. Inductors in series are simply “added together” because the number of coil turns is effectively increased, with the total circuit inductance L_T being equal to the sum of all the individual inductances added together.



Mutually Connected Inductors in Series

When inductors are connected together in series so that the magnetic field of one links with the other, the effect of mutual inductance either increases or decreases the total inductance depending upon the amount of magnetic coupling. The effect of this mutual inductance depends upon the distance apart of the coils and their orientation to each other.

Mutually connected series inductors can be classed as either “Aiding” or “Opposing” the total inductance. If the magnetic flux produced by the current flows through the coils in the same direction then the coils are said to be **Cumulatively Coupled**. If the current flows through the coils in opposite directions then the coils are said to be **Differentially Coupled**

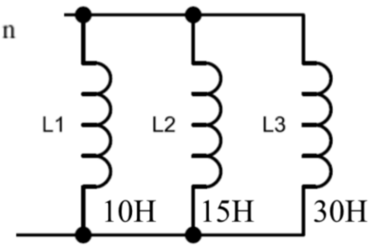


Inductors are said to be connected together in Parallel when both of their terminals are respectively connected to each terminal of another inductor or inductors.

Here, like the calculations for parallel resistors, the reciprocal (1/Ln) value of the individual inductances are all added together instead of the inductances themselves. But again as with series connected inductances, the above equation only holds true when there is "NO" mutual inductance or magnetic coupling between two or more of the inductors, (they are magnetically isolated from each other). Where there is coupling between coils, the total inductance is also affected by the amount of coupling.

Example - Inductors in Parallel

$$L_{total} = \frac{1}{\frac{1}{L1} + \frac{1}{L2} + \frac{1}{L3} + \ldots + \frac{1}{L_n}}$$



$$L_{total} = \frac{1}{\frac{1}{10} + \frac{1}{15} + \frac{1}{30}}$$

$$L_{total} = \frac{1}{\frac{3}{30} + \frac{2}{30} + \frac{1}{30}} = \frac{1}{6/30} = 5H$$

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Reactance

- **Reactance** is the **opposition** to the **flow of Alternating Current (AC)** caused by **inductance** or **capacitance.**
- **Reactance** has **no effect** on the flow of **Direct Current (DC).**

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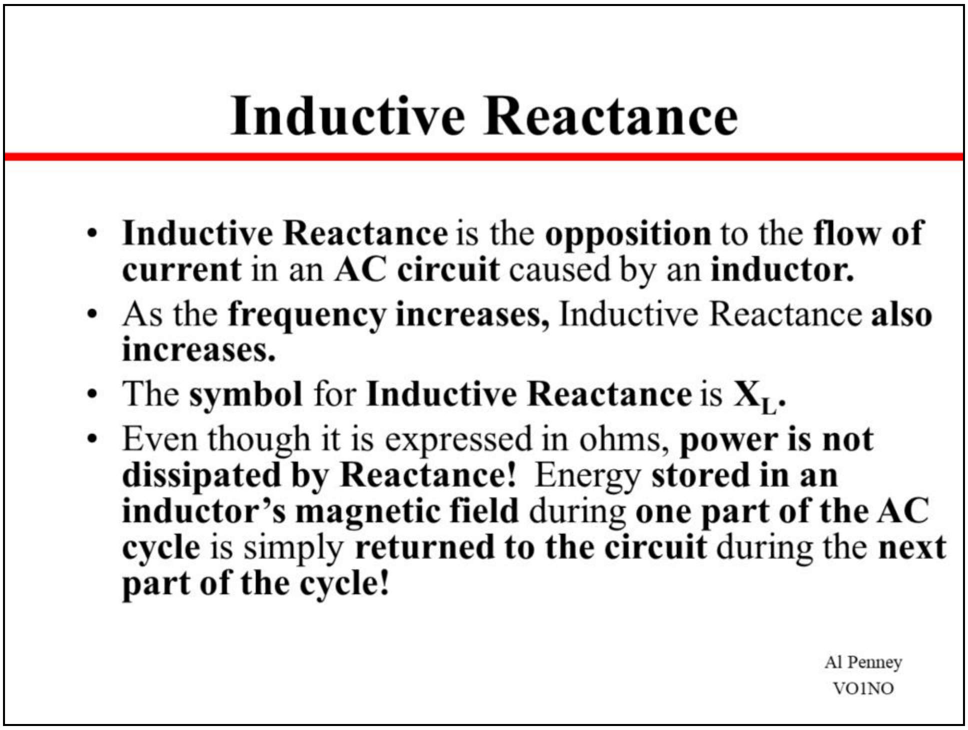
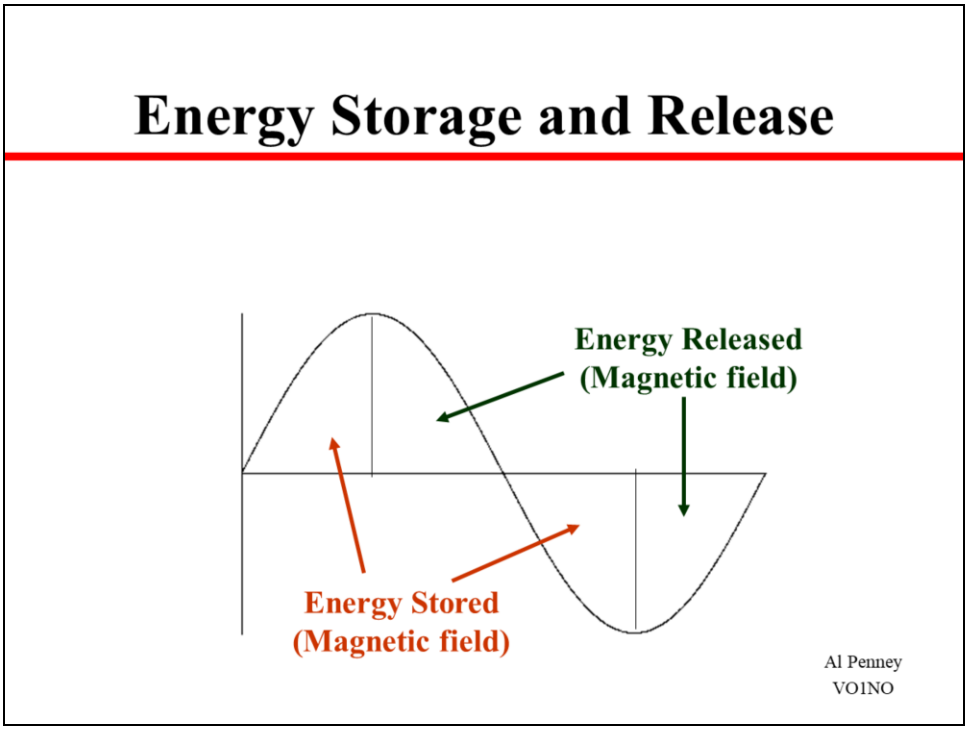
In electric and electronic systems, **reactance** is the opposition of a circuit element to the flow of current due to that element's inductance or capacitance. Larger reactance leads to smaller currents for the same voltage applied. Reactance is similar to electric resistance, but it differs in several respects.



Inductive Reactance of a coil depends on the frequency of the applied voltage as reactance is directly proportional to frequency.

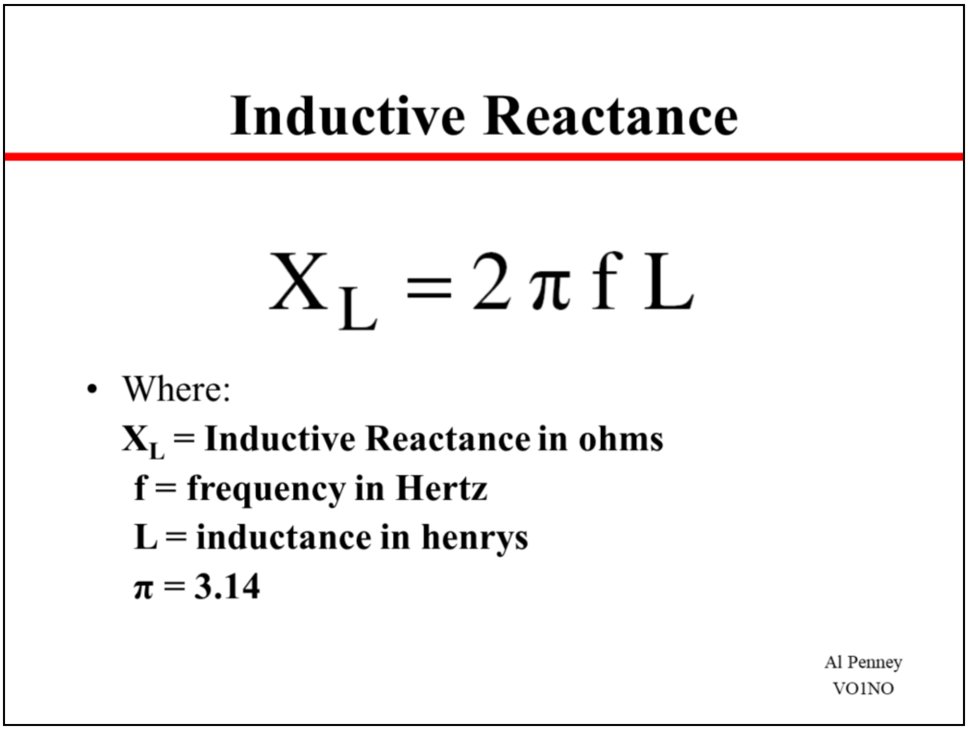


Energy stored in an inductor

One intuitive explanation as to why a potential difference is induced on a change of current in an inductor goes as follows:

When there is a change in current through an inductor there is a change in the strength of the magnetic field. For example, if the current is increased, the magnetic field increases. This, however, does not come without a price. The magnetic field contains potential energy, and increasing the field strength requires more energy to be stored in the field. This energy comes from the electric current through the inductor. The increase in the magnetic potential energy of the field is provided by a corresponding drop in the electric potential energy of the charges flowing through the windings. This appears as a voltage drop across the windings as long as the current increases. Once the current is no longer increased and is held constant, the energy in the magnetic field is constant and no additional energy must be supplied, so the voltage drop across the windings disappears.

Similarly, if the current through the inductor decreases, the magnetic field strength decreases, and the energy in the magnetic field decreases. This energy is returned to the circuit in the form of an increase in the electrical potential energy of the moving charges, causing a voltage rise across the windings.

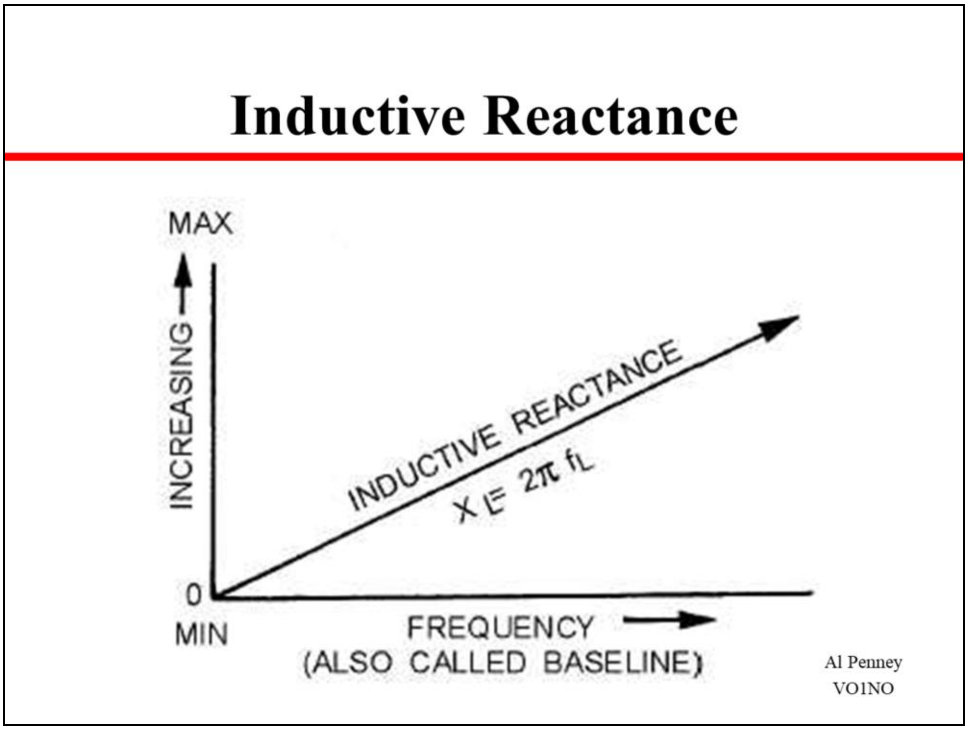


Inductive Reactance which is given the symbol X_L, is the property in an AC circuit which opposes the change in the current. In our tutorials about Capacitors in AC Circuits, we saw that in a purely capacitive circuit, the current I_C "LEADS" the voltage by 90°. In a purely inductive AC circuit the exact opposite is true, the current I_L "LAGS" the applied voltage by 90°, or (π/2 rads).

From the above equation for inductive reactance, if either the **Frequency** or the **Inductance** is increased the overall inductive reactance value of the inductor would also increase. As the frequency approaches infinity the inductors reactance would also increase towards infinity with the circuit element acting like an open circuit.

However, as the frequency approaches zero or DC, the inductors reactance would decrease to zero, causing the opposite effect acting like a short circuit. This means then that inductive reactance is "**Proportional**" to frequency and is small at low frequencies and high at higher frequencies and this demonstrated in the following curve:

The graph of inductive reactance against frequency is a straight line linear curve. The inductive reactance value of an inductor increases linearly as the frequency across it increases. Therefore, inductive reactance is positive and is directly proportional to frequency ($X_L \propto f$)



When an alternating or AC voltage is applied across an inductor the flow of current through it behaves very differently to that of an applied DC voltage. The effect of a sinusoidal supply produces a phase difference between the voltage and the current waveforms. Now in an AC circuit, the opposition to current flow through the coils windings not only depends upon the inductance of the coil but also the frequency of the AC waveform.

The opposition to current flowing through a coil in an AC circuit is determined by the AC resistance, more commonly known as **Impedance** (Z), of the circuit. But resistance is always associated with DC circuits so to distinguish DC resistance from AC resistance the term **Reactance** is generally used.

Just like resistance, the value of reactance is also measured in Ohm's but is given the symbol X, (uppercase letter "X"), to distinguish it from a purely resistive value.

As the component we are interested in is an inductor, the reactance of an inductor is therefore called "Inductive Reactance". In other words, an inductors electrical resistance when used in an AC circuit is called **Inductive Reactance**.

Inductive Reactance Example 1

- What is the reactance of a coil having an inductance of 8.00 henrys at a frequency of 120 Hertz?

$$X_L = 2 \pi f L$$

$$\mathbf{X_L = 2 \times 3.14 \times 120\ Hertz \times 8.00H}$$

$$\mathbf{X_L = 6030\ Ohms}$$

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Inductive Reactance Example 2

- What is the reactance of that same coil having an inductance of 8.00 henrys at a frequency of 2 kHz?

$$X_L = 2\pi f L$$

Remember that **2 kHz = 2000 Hz**

X_L = 2 x 3.14 x 2000 Hertz x 8.00H

X_L = 100,480 Ohms

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Inductive Reactance Examples

- Note that as the **frequency increased** from 120 Hz to 2000 Hz, the **Inductive Reactance increased** from 6030 ohms to 100,480 ohms.
- **Remember:**
  - **Inductors allow DC to pass, but hinder AC;**
  - Inductors **store energy** as a magnetic field; and
  - As the **frequency increases, inductive reactance increases (and vice versa!).**

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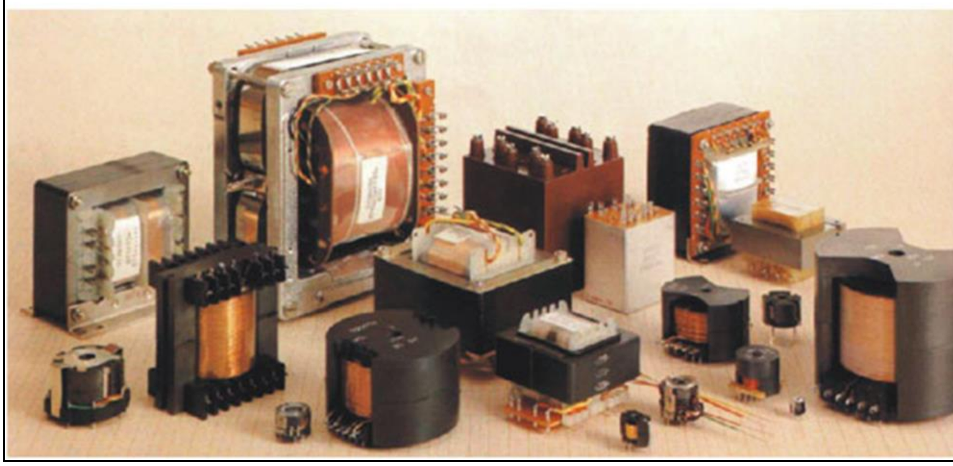
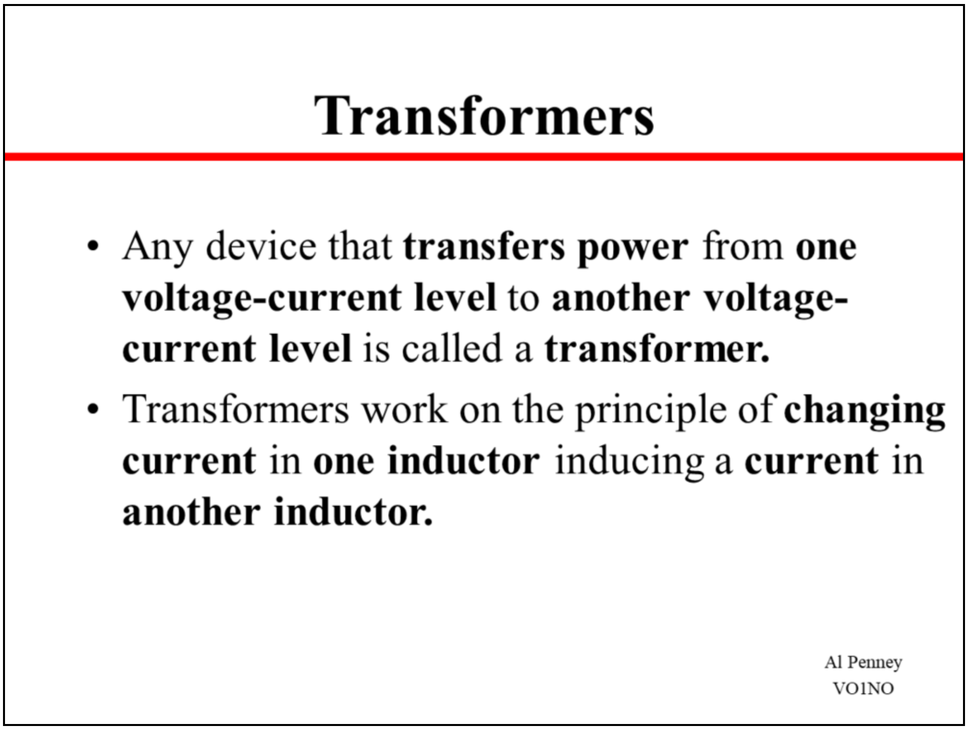
Transformers

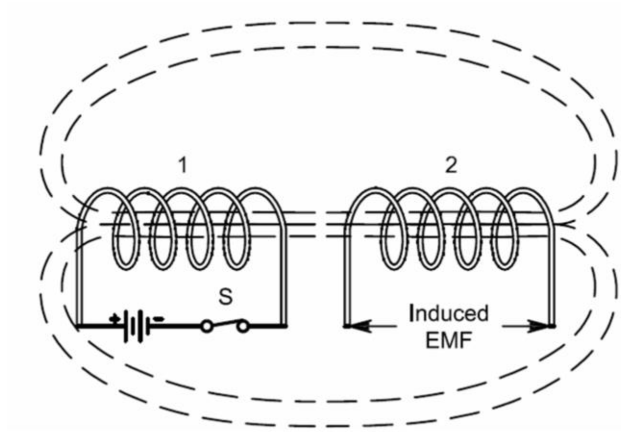




A **transformer** is a passive electrical device that transfers electrical energy from one electrical circuit to another, or multiple circuits. A varying current in any one coil of the transformer produces a varying magnetic flux in the transformer's core, which induces a varying electromotive force across any other coils wound around the same core. Electrical energy can be transferred between separate coils without a metallic (conductive) connection between the two circuits. Faraday's law of induction, discovered in 1831, describes the induced voltage effect in any coil due to a changing magnetic flux encircled by the coil.

Transformers are most commonly used for increasing low AC voltages at high current (a step-up transformer) or decreasing high AC voltages at low current (a step-down transformer) in electric power applications, and for coupling the stages of signal processing circuits. Transformers can also be used for isolation, where the voltage in equals the voltage out, with separate coils not electrically bonded to one another.

Induced EMF



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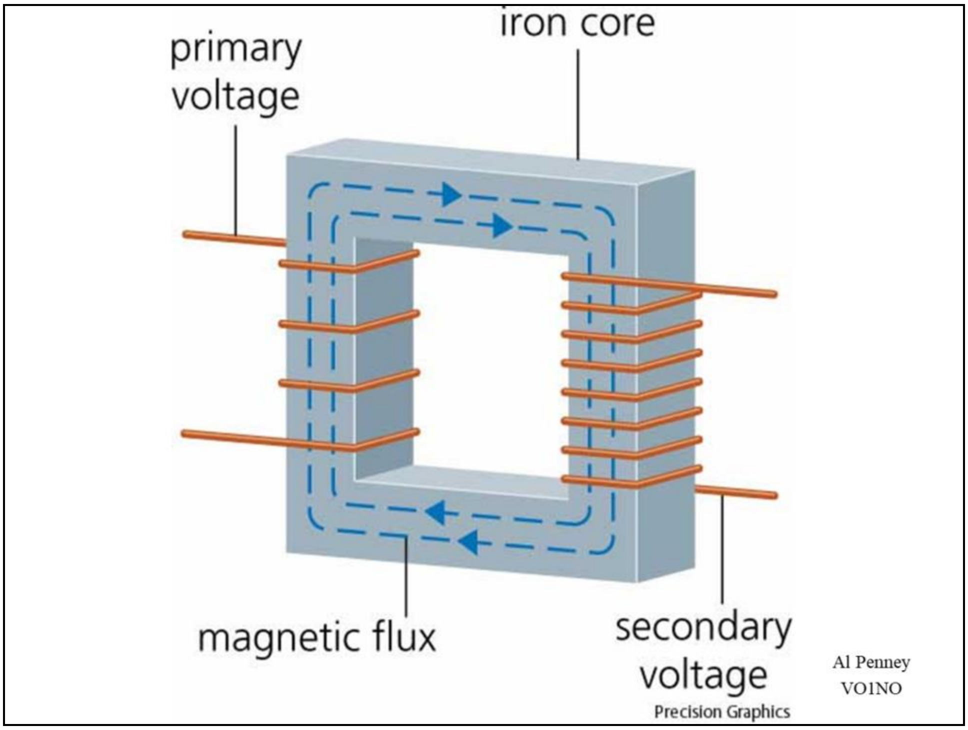
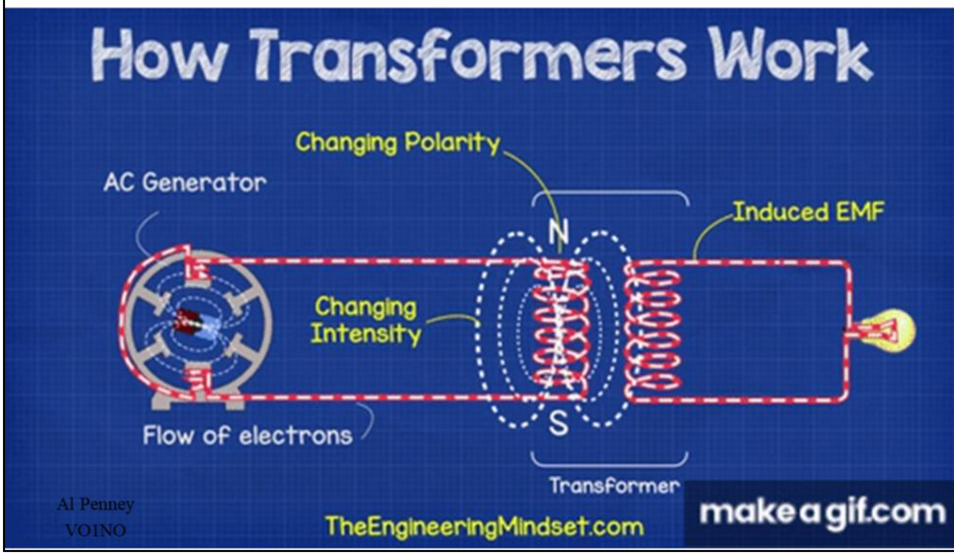


Also please note that as transformers require an alternating magnetic flux to operate correctly, transformers cannot therefore be used to transform or supply DC voltages or currents, since the magnetic field must be changing to induce a voltage in the secondary winding. In other words, **transformers DO NOT operate on steady state DC voltages**, only alternating or pulsating voltages.

Transformers



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Transformer Applications

- Transformers have **3 primary applications:**
  - **Isolating** one part of a circuit from another (**magnetic** linkage only, versus **conductive** linkage);
  - **Stepping voltages up or down**; and
  - **Impedance matching.**

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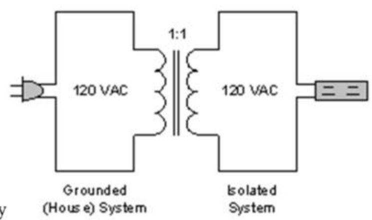
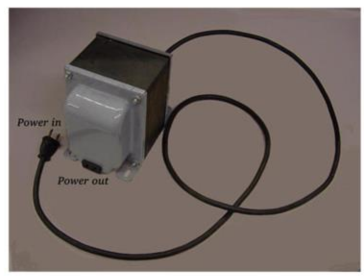
Isolation Transformer

- Many uses for isolation transformers in electronic circuits.
- Also used in power circuits, using transformers that have a 1:1 turns ratio.





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An **isolation transformer** is a transformer used to transfer electrical power from a source of alternating current (AC) power to some equipment or device while isolating the powered device from the power source, usually for safety reasons. Isolation transformers provide galvanic isolation and are used to protect against electric shock, to suppress electrical noise in sensitive devices, or to transfer power between two circuits which must not be connected. A transformer sold for isolation is often built with special insulation between primary and secondary, and is specified to withstand a high voltage between windings.

Isolation transformers block transmission of the DC component in signals from one circuit to the other, but allow AC components in signals to pass. Transformers that have a ratio of 1 to 1 between the primary and secondary windings are often used to protect secondary circuits and individuals from electrical shocks between energized conductors and earth ground. Suitably designed isolation transformers block interference caused by ground loops. Isolation transformers with electrostatic shields are used for power supplies for sensitive equipment such as computers, medical devices, or laboratory instruments.

Changing the Voltage

- A **transformer** can be used to **step the voltage up or down.**
- The **ratio of turns** in the primary and secondary windings determine the **amount of voltage change:**

$$\frac{\text{Primary Voltage}}{\text{Secondary Voltage}} = \frac{\text{\# Turns Primary winding}}{\text{\# Turns Secondary winding}}$$

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The difference in voltage between the primary and the secondary windings is achieved by changing the number of coil turns in the primary winding (N_P) compared to the number of coil turns on the secondary winding (N_S).

As the transformer is basically a linear device, a ratio now exists between the number of turns of the primary coil divided by the number of turns of the secondary coil. This ratio, called the ratio of transformation, more commonly known as a transformers “turns ratio”, (TR). This turns ratio value dictates the operation of the transformer and the corresponding voltage available on the secondary winding.

It is necessary to know the ratio of the number of turns of wire on the primary winding compared to the secondary winding. The turns ratio, which has no units, compares the two windings in order and is written with a colon, such as 3:1 (3-to-1). This means in this example, that if there are 3 volts on the primary winding there will be 1 volt on the secondary winding, 3 volts-to-1 volt. Then we can see that if the ratio between the number of turns changes the resulting voltages must also change by the same ratio, and this is true.

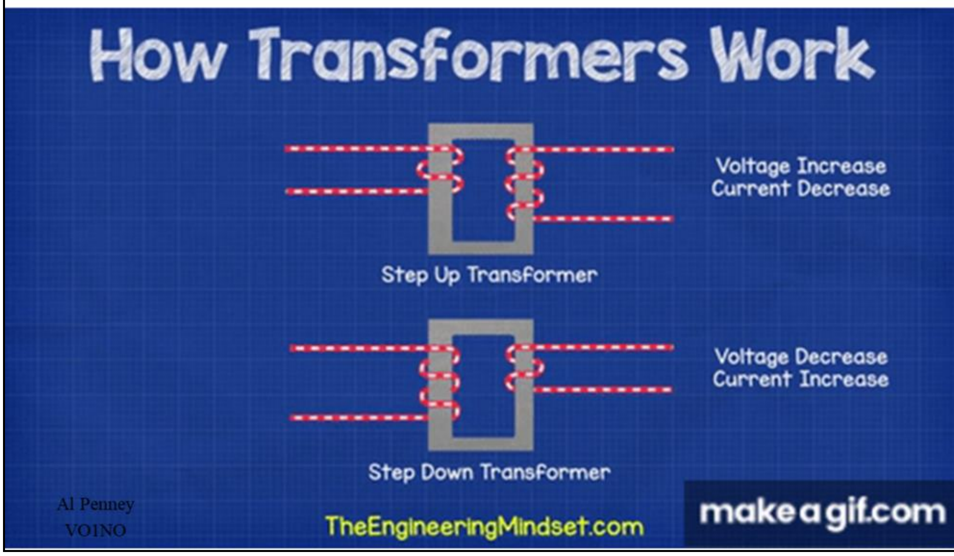
Transformers are all about “ratios”. The ratio of the primary to the secondary, the ratio of the input to the output, and the turns ratio of any given transformer will be the same as its voltage ratio. In other words for a transformer: “turns ratio = voltage ratio”. The actual number of turns of wire on any winding is generally not important, just the turns ratio and this relationship is given as:

Np/Ns = Tp/Ts = turns ratio

Assuming an ideal transformer and the phase angles: $\Phi_P \equiv \Phi_S$

Note that the order of the numbers when expressing a transformers *turns ratio* value is very important as the turns ratio 3:1 expresses a very different transformer relationship and output voltage than one in which the turns ratio is given as: 1:3.

Step Up vs Step Down



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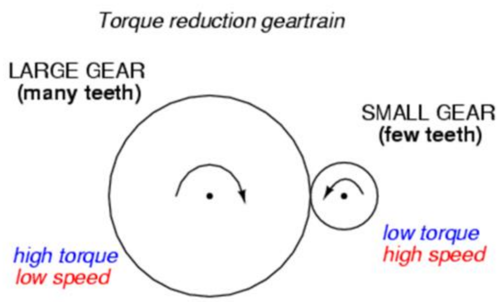
Transformer Mechanical Equivalent



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Example

- *Input voltage is 120 VAC. You require an output voltage of 24 VAC. The Primary winding has 240 turns. How many turns does the Secondary winding need?*

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Example (2)

$$\frac{\text{Primary Voltage}}{\text{Secondary Voltage}} = \frac{\text{\# Turns Primary winding}}{\text{\# Turns Secondary winding}}$$

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Example (3)

$$\frac{\text{Primary Voltage}}{\text{Secondary Voltage}} = \frac{\text{\# Turns Primary winding}}{\text{\# Turns Secondary winding}}$$

- $120 / 24 = 240 / T_{sec}$
- $T_{sec} =$

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Example (4)

$$\frac{\text{Primary Voltage}}{\text{Secondary Voltage}} = \frac{\text{\# Turns Primary winding}}{\text{\# Turns Secondary winding}}$$

- $120 / 24 = 240 / T_{sec}$
- $T_{sec} = 240 \times 24 / 120$

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Example (5)

$$\frac{\text{Primary Voltage}}{\text{Secondary Voltage}} = \frac{\text{\# Turns Primary winding}}{\text{\# Turns Secondary winding}}$$

- $120 / 24 = 240 / T_{sec}$
- $T_{sec} = 240 \times 24 / 120$
- $T_{sec} =$

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Example (6)

$$\frac{\text{Primary Voltage}}{\text{Secondary Voltage}} = \frac{\text{\# Turns Primary winding}}{\text{\# Turns Secondary winding}}$$

- $120 / 24 = 240 / T_{sec}$
- $T_{sec} = 240 \times 24 / 120$
- $T_{sec} = 48$ turns

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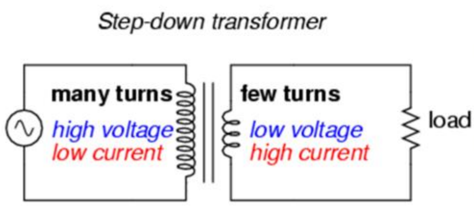
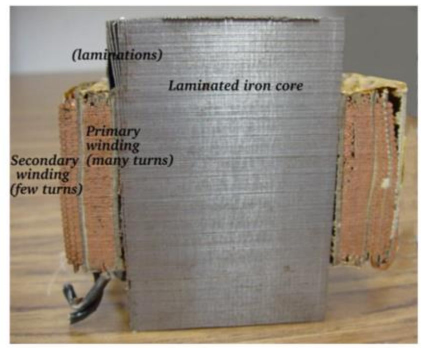
Step Down Transformer





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Impedance Matching

- Many electronic devices and circuits (speakers, microphones, antennas, transmission lines, amplifiers etc.) have their own **characteristic impedance.**
- When interconnecting these devices and circuits, **maximum power transfer** will take place if the various **impedances are matched.**

In electronics, **impedance matching** is the practice of designing the input impedance of an electrical load or the output impedance of its corresponding signal source to maximize the power transfer or minimize signal reflection from the load.

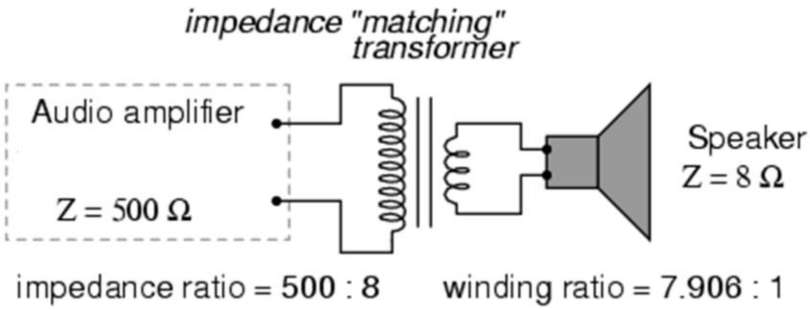
Matching with Transformers

- **Transformers** are often used to **match impedances** which are primarily **resistive.**
- This is especially true for **antenna and transmission line systems.**
- The **turns ratio** determines the **degree of impedance change.**
- **Turns Ratio** = Square Root (Source Z / Load Z).
- Take the matching transformer **(Balun – BALanced to UNbalanced)** used to match 300 Ohms to 75 Ohms in TV systems.

Transformers are sometimes used to match the impedances of circuits. A transformer converts alternating current at one voltage to the same waveform at another voltage. The power input to the transformer and output from the transformer is the same (except for conversion losses). The side with the lower voltage is at low impedance (because this has the lower number of turns), and the side with the higher voltage is at a higher impedance (as it has more turns in its coil).

One example of this method involves a television balun transformer. This transformer converts a balanced signal from the antenna (via 300-ohm twin-lead) into an unbalanced signal (75-ohm coaxial cable such as RG-6). To match the impedances of both devices, both cables must be connected to a matching transformer with a turns ratio of 2 (such as a 2:1 transformer). In this example, the 75-ohm cable is connected to the transformer side with fewer turns; the 300-ohm line is connected to the transformer side with more turns.

Audio Impedance Matching



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To obtain an impedance transformation ratio of 500:8, we would need a winding ratio equal to the square root of 500:8 (the square root of 62.5:1, or 7.906:1). With such a transformer in place, the speaker will load the amplifier to just the right degree, drawing power at the correct voltage and current levels to satisfy the Maximum Power Transfer Theorem and make for the most efficient power delivery to the load. The use of a transformer in this capacity is called *impedance matching*.

Anyone who has ridden a multi-speed bicycle can intuitively understand the principle of impedance matching. A human's legs will produce maximum power when spinning the bicycle crank at a particular speed (about 60 to 90 revolution per minute). Above or below that rotational speed, human leg muscles are less efficient at generating power. The purpose of the bicycle's "gears" is to impedance-match the rider's legs to the riding conditions so that they always spin the crank at the optimum speed.

If the rider attempts to start moving while the bicycle is shifted into its "top" gear, he or she will find it very difficult to get moving. Is it because the rider is weak? No, it's because the high step-up ratio of the bicycle's chain and sprockets in that top gear presents a mismatch between the conditions (lots of inertia to overcome)

and their legs (needing to spin at 60-90 RPM for maximum power output). On the other hand, selecting a gear that is too low will enable the rider to get moving immediately, but limit the top speed they will be able to attain. Again, is the lack of speed an indication of weakness in the bicyclist's legs? No, it's because the lower speed ratio of the selected gear creates another type of mismatch between the conditions (low load) and the rider's legs (losing power if spinning faster than 90 RPM). It is much the same with electric power sources and loads: there must be an impedance match for maximum system efficiency. In AC circuits, transformers perform the same matching function as the sprockets and chain ("gears") on a bicycle to match otherwise mismatched sources and loads.

Antenna Impedance Matching

- Transformers are often used to **match impedances** in **antenna systems.**
- The most frequently encountered are **1:1** and **4:1,** but other impedance transformations are available.

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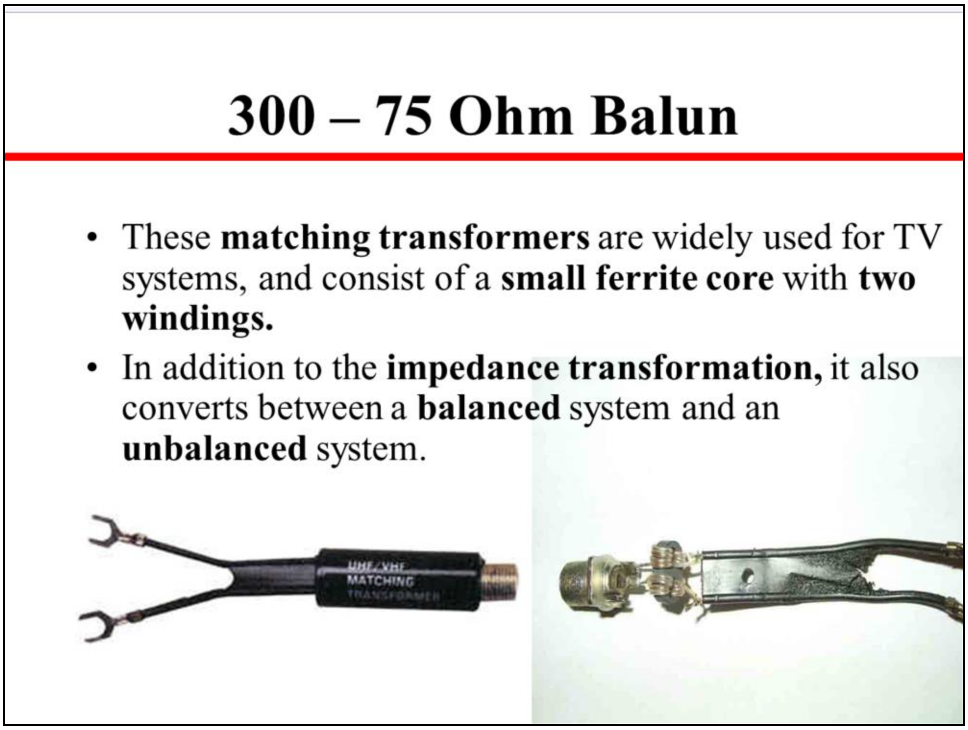

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Power Rating of the Transformer

- Determined by the **size of the core** and the **diameter of the wire.**
- Power rating usually **stamped on the side** of the transformer, and is **expressed in Volt-Amperes** (abbreviated **VA**).
- **Power = Voltage x Current**
- Calculate power requirements of the equipment using the transformer and compare it with the Power rating of the transformer.

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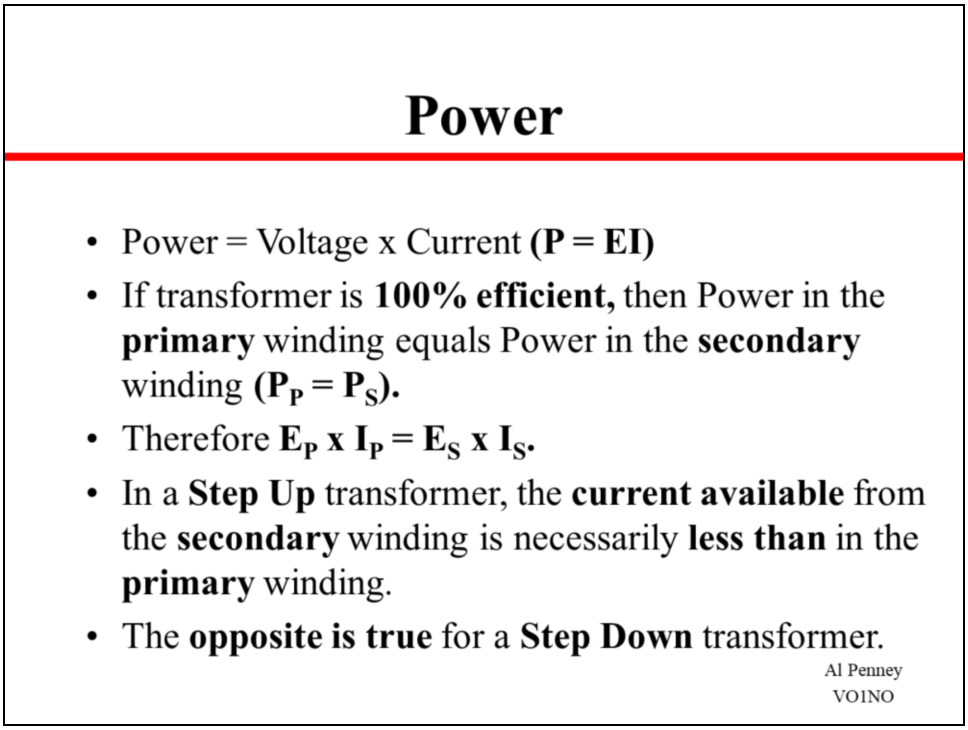
Transformer Ratings

Respecting these limitations, transformers are rated for certain levels of primary and secondary winding voltage and current, though the current rating is usually derived from a volt-amp (VA) rating assigned to the transformer.

Sometimes windings will bear current ratings in amps, but this is typically seen on small transformers. Large transformers are almost always rated in terms of winding voltage and VA or kVA.



Electrical Power in a Transformer

Another one of the transformer basics parameters is its power rating. The power rating of a transformer is obtained by simply multiplying the current by the voltage to obtain a rating in **Volt-amperes**, (VA). Small single phase transformers may be rated in volt-amperes only, but much larger power transformers are rated in units of **Kilo volt-amperes**, (kVA) where 1 kilo volt-ampere is equal to 1,000 volt-amperes, and units of **Mega volt-amperes**, (MVA) where 1 mega volt-ampere is equal to 1 million volt-amperes.

In an ideal transformer (ignoring any losses), the power available in the secondary winding will be the same as the power in the primary winding, they are constant wattage devices and do not change the power only the voltage to current ratio. Thus, in an ideal transformer the **Power Ratio** is equal to one (unity) as the voltage, V multiplied by the current, I will remain constant.

That is the electric power at one voltage/current level on the primary is “transformed” into electric power, at the same frequency, to the same voltage/current level on the secondary side. Although the transformer can step-up (or step-down) voltage, it cannot step-up power. Thus, when a transformer steps-up a voltage, it steps-down the current and vice-versa, so that the output power is always at the same value as the input power. Then we can say that primary power equals secondary power, ($P_P = P_S$).

Power

- **Step Up Transformer** (Voltage increases, so available current is less)

$$E_P \times I_P = E_S \times I_S$$

- **Step Down Transformer** (Voltage decreases, so available current is greater)

$$E_P \times I_P = E_S \times I_S$$

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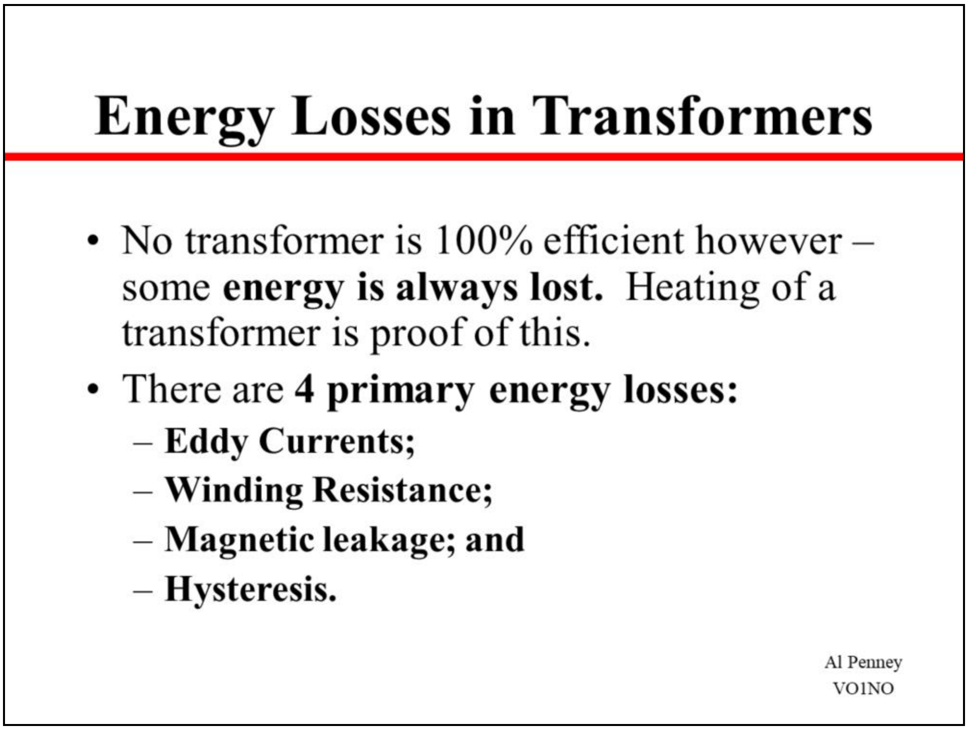

Transformer Basics – Efficiency

A transformer does not require any moving parts to transfer energy. This means that there are no friction or windage losses associated with other electrical machines. However, transformers do suffer from other types of losses called "copper losses" and "iron losses" but generally these are quite small.

Copper losses, also known as I^2R loss is the electrical power which is lost in heat as a result of circulating the currents around the transformers copper windings, hence the name. Copper losses represents the greatest loss in the operation of a transformer. The actual watts of power lost can be determined (in each winding) by squaring the amperes and multiplying by the resistance in ohms of the winding (I^2R).

Iron losses, also known as hysteresis is the lagging of the magnetic molecules within the core, in response to the alternating magnetic flux. This lagging (or out-of-phase) condition is due to the fact that it requires power to reverse magnetic molecules; they do not reverse until the flux has attained sufficient force to reverse them.

Their reversal results in friction, and friction produces heat in the core which is a form of power loss. Hysteresis within the transformer can be reduced by making the core from special steel alloys.

The intensity of power loss in a transformer determines its efficiency. The efficiency of a transformer is reflected in power (wattage) loss between the primary (input) and secondary (output) windings. Then the resulting efficiency of a transformer is equal to the ratio of the power output of the secondary winding, P_S to the power input of the primary winding, P_P and is therefore high.

An ideal transformer is 100% efficient because it delivers all the energy it receives. Real transformers on the other hand are not 100% efficient and at full load, the efficiency of a transformer is between 94% to 96% which is quite good. For a transformer operating with a constant voltage and frequency with a very high capacity, the efficiency may be as high as 98%.

Eddy Currents

- The changing **magnetic fields generate electric current** called **Eddy Currents** in the **core** of the transformer.
- These currents **divert energy** away from the transformer's actual purpose.
- To prevent eddy currents, we use **thin layers of insulated metal** to make up the core, instead of a solid piece of metal.
- At higher frequencies (RF) **powdered metal** with a **ceramic** or **plastic filler** is used instead.

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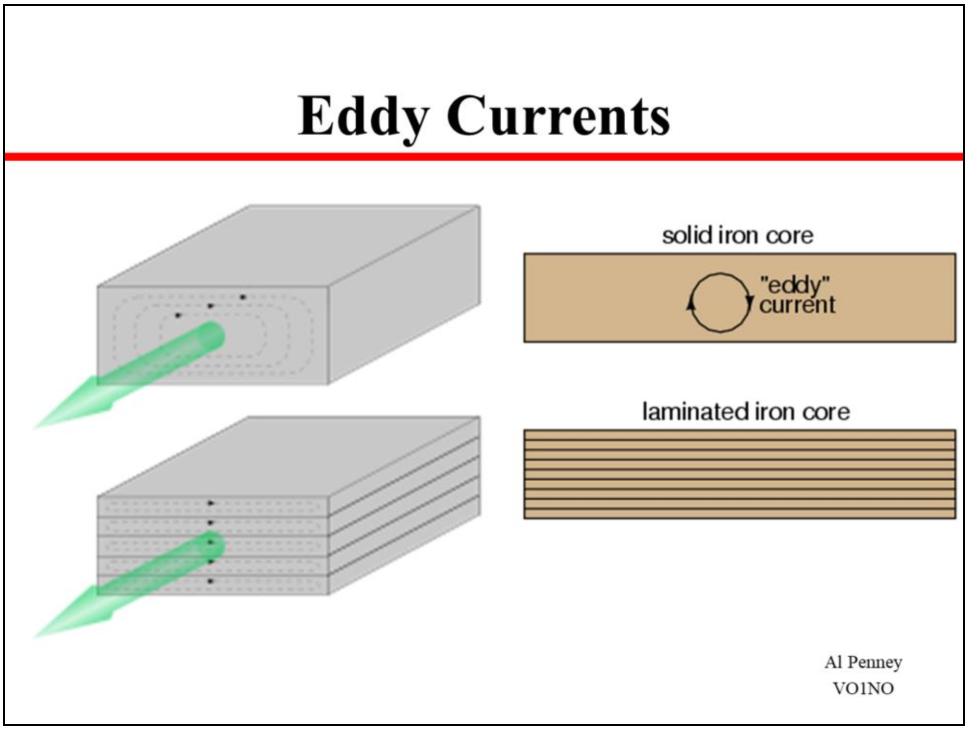

Resistive losses aside, the bulk of transformer power loss is due to magnetic effects in the core. Perhaps the most significant of these "core losses" is *eddy-current loss*, which is resistive power dissipation due to the passage of induced currents through the iron of the core. Because iron is a conductor of electricity as well as being an excellent "conductor" of magnetic flux, there will be currents induced in the iron just as there are currents induced in the secondary windings from the alternating magnetic field. These induced currents -- as described by the perpendicularity clause of Faraday's Law -- tend to circulate through the cross-section of the core perpendicularly to the primary winding turns. Their circular motion gives them their unusual name: like eddies in a stream of water that circulate rather than move in straight lines.

Iron is a fair conductor of electricity, but not as good as the copper or aluminum from which wire windings are typically made. Consequently, these "eddy currents" must overcome significant electrical resistance as they circulate through the core. In overcoming the resistance offered by the iron, they dissipate power in the form of heat. Hence, we have a source of inefficiency in the transformer that is difficult to eliminate.

The main strategy in mitigating these wasteful eddy currents in transformer cores is to form the iron core in sheets, each sheet covered with an insulating varnish so that the core is divided up into thin slices. The result is very little width in the core for eddy currents to circulate in:

Laminated **cores like the one shown here are standard in almost all low-frequency transformers. Recall from the photograph of the transformer cut in half that the iron core was composed of many thin sheets rather than one solid piece. Eddy current losses increase with frequency, so transformers designed to run on higher-frequency power (such as 400 Hz, used in many military and aircraft applications) must use thinner laminations to keep the losses down to a respectable minimum. This has the undesirable effect of increasing the manufacturing cost of the transformer.**

Another, similar technique for minimizing eddy current losses which works better for high-frequency applications is to make the core out of iron powder instead of thin iron sheets. Like the lamination sheets, these granules of iron are individually coated in an electrically insulating material, which makes the core nonconductive except for within the width of each granule. Powdered iron cores are often found in transformers handling radio-frequency currents.

Winding Resistance

- There is always some **loss** caused by the **resistance of the wire** in the windings.
- This loss appears as **heating of the transformer.**
- It is sometimes called **Copper Loss.**
- Transformers that must carry large currents use **larger wire.**

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When transformers transfer power, they do so with a minimum of loss. As it was stated earlier, modern power transformer designs typically exceed 95% efficiency. It is good to know where some of this lost power goes, however, and what causes it to be lost.

There is, of course, power loss due to the resistance of the wire windings. Unless superconducting wires are used, there will always be power dissipated in the form of heat through the resistance of current-carrying conductors. Because transformers require such long lengths of wire, this loss can be a significant factor.

Increasing the gauge of the winding wire is one way to minimize this loss, but only with substantial increases in cost, size, and weight.

Magnetic Leakage

- **Not every magnetic flux line** produced by the primary winding **can cut through** the secondary winding.
- This inefficiency is called **Magnetic Leakage.**
- **Proper core design** can minimize these losses.

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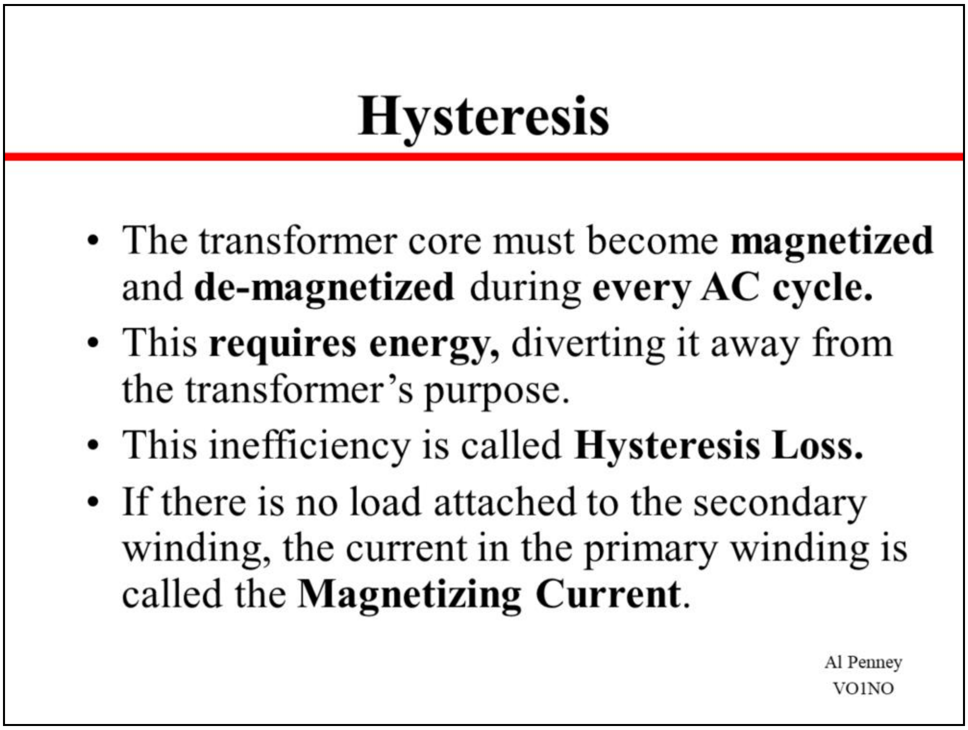
Flux containment (making sure a transformer's magnetic flux doesn't escape so as to interfere with another device, and making sure other devices' magnetic flux is shielded from the transformer core) is another concern shared both by inductors and transformers.

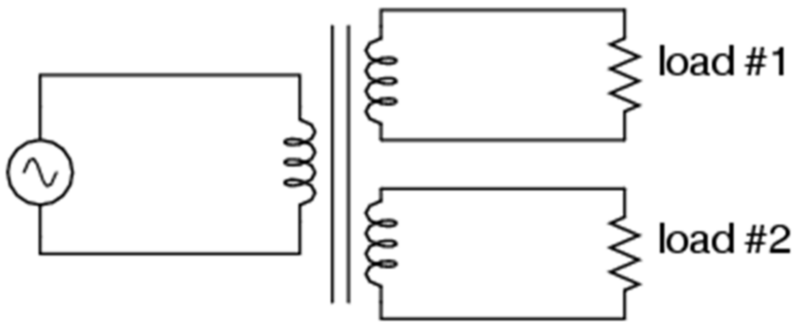


Another "core loss" is that of magnetic *hysteresis*. All ferromagnetic materials tend to retain some degree of magnetization after exposure to an external magnetic field.

This tendency to stay magnetized is called "hysteresis," and it takes a certain investment in energy to overcome this opposition to change every time the magnetic field produced by the primary winding changes polarity (twice per AC cycle).

This type of loss can be mitigated through good core material selection (choosing a core alloy with low hysteresis, as evidenced by a "thin" B/H hysteresis curve), and designing the core for minimum flux density (large cross-sectional area).

Multiple Windings



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Multiple Windings

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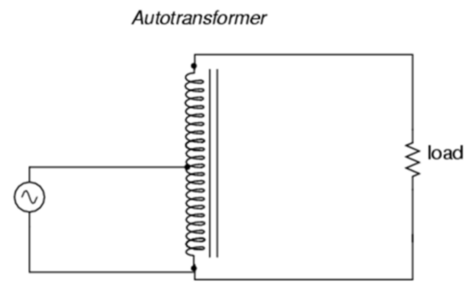
Auto Transformer

- Transformer that utilizes a **single winding.**
- Often used to **adjust** a line voltage that is consistently **too low or high.**
- **WARNING – No isolation in an auto-transformer or Variac!**



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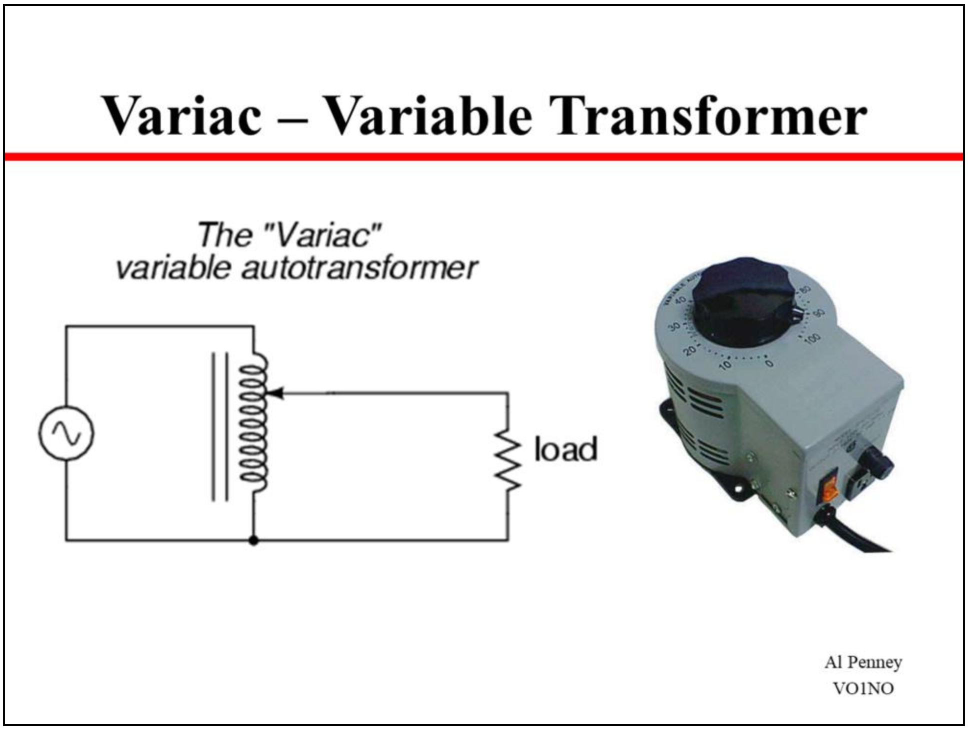
An **autotransformer** is an electrical transformer with only one winding. The "auto" (Greek for "self") prefix refers to the single coil acting alone, not to any kind of automatic mechanism. In an autotransformer, portions of the same winding act as both the primary winding and secondary winding sides of the transformer. In contrast, an ordinary transformer has separate primary and secondary windings which are not connected to each other.

The autotransformer winding has at least three taps where electrical connections are made. Since part of the winding does "double duty", autotransformers have the advantages of often being smaller, lighter, and cheaper than typical dual-winding transformers, but the disadvantage of not providing electrical isolation between primary and secondary circuits. Other advantages of autotransformers include lower leakage reactance, lower losses, lower excitation current, and increased VA rating for a given size and mass.

An example of an application of an autotransformer is one style of traveler's voltage converter, that allows 230-volt devices to be used on 120 volt supply circuits, or the reverse. An autotransformer with multiple taps may be applied to adjust the voltage at the end of a long distribution circuit to correct for excess voltage drop; when automatically controlled, this is one example of a voltage regulator.

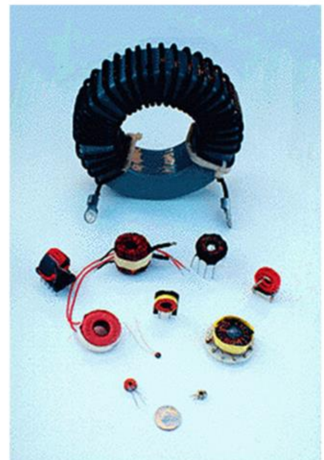


By exposing part of the winding coils and making the secondary connection through a sliding brush, a continuously variable turns ratio can be obtained, allowing for very smooth control of output voltage.

Variac transformers are AC voltage controls that provide a variable AC voltage. Variac is a generic trade name for a variable autotransformer.

Toroids

- **Doughnut-shaped cores** (usually) made of a ferrite material used to wind transformers and inductors.
- **Entire magnetic field** is contained **within** the toroid.



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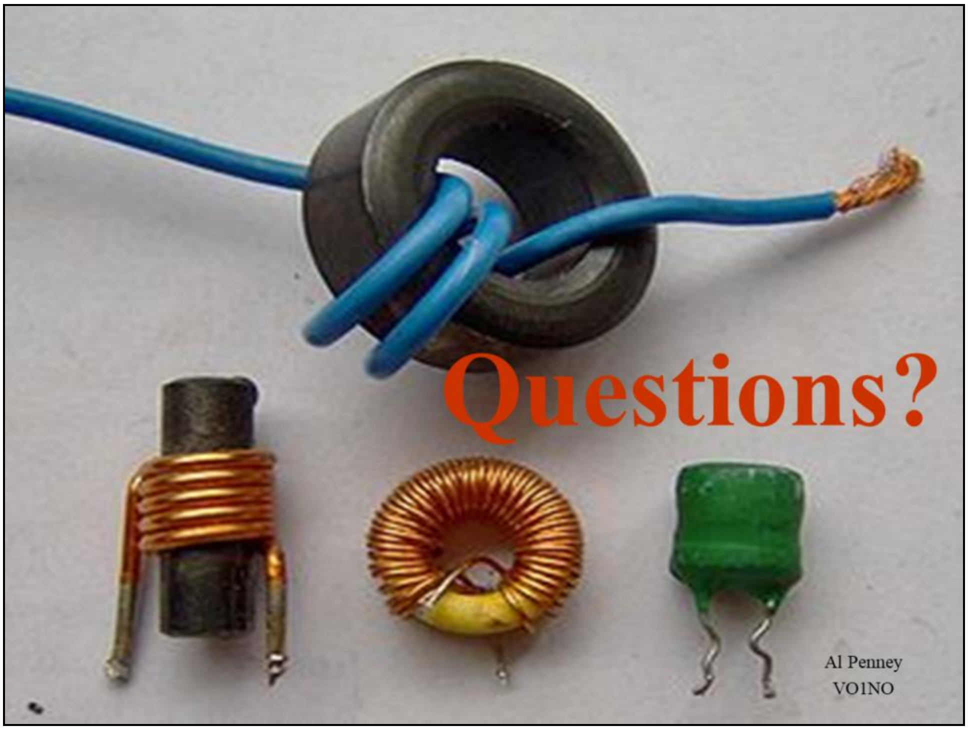
Toroidal inductors and transformers are inductors and transformers which use magnetic cores with a toroidal (ring or donut) shape. They are passive electronic components, consisting of a circular ring or donut shaped magnetic core of ferromagnetic material such as laminated iron, iron powder, or ferrite, around which wire is wound.

Although in the past, closed-core inductors and transformers often used cores with a square shape, the use of toroidal-shaped cores has increased greatly because of their superior electrical performance. The advantage of the toroidal shape is that, due to its symmetry, the amount of magnetic flux that escapes outside the core (leakage flux) is low, therefore it is more efficient and thus radiates less electromagnetic interference (EMI).

Toroidal inductors and transformers are used in a wide range of electronic circuits: power supplies, inverters, and amplifiers, which in turn are used in the vast majority of electrical equipment: TVs, radios, computers, and audio systems.


Questions?
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Review Question 1

If two equal-value inductors are connected in series, what is their total inductance?

- Twice the value of one inductor
- Half the value of one inductor
- The same as the value of either inductor
- The value of one inductor times the value of the other

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< Twice the value of one inductor >

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Review Question 2

If two equal-value inductors are connected in parallel, what is their total inductance?

- Twice the value of one inductor
- The same as the value of either inductor
- The value of one inductor times the value of the other
- Half the value of one inductor

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If two equal-value inductors are connected in parallel, what is their total inductance?

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< Half the value of one inductor >

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Review Question 3

What determines the inductance of a coil?

• The core material, the core diameter, the length of the coil and the number of turns of wire used to wind the coil

• The core material, the number of turns used to wind the core and the frequency of the current through the coil

• The core diameter, the number of turns of wire used to wind the coil and the type of metal used for the wire

• The core material, the core diameter, the length of the coil and whether the coil is mounted horizontally or vertically

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< The core material, the core diameter, the length of the coil and the number of turns of wire used to wind the coil >

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Review Question 4

Inductive reactance may be increased by:

- an increase in the applied voltage
- an increase in the applied frequency
- a decrease in the applied frequency
- a decrease in the supplied current

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< an increase in the applied frequency >

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Review Question 5

How does a coil react to AC?

• As the amplitude of the applied AC increases, the reactance decreases

• As the amplitude of the applied AC increases, the reactance increases

• As the frequency of the applied AC increases, the reactance decreases

• As the frequency of the applied AC increases, the reactance increases

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Review Question 5

How does a coil react to AC?

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• As the amplitude of the applied AC increases, the reactance increases

• As the frequency of the applied AC increases, the reactance decreases

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< As the frequency of the applied AC increases, the reactance increases >

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Review Question 6

Inductive reactance may be increased by:

- an increase in the applied voltage
- an increase in the applied frequency
- a decrease in the applied frequency
- a decrease in the supplied current

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Review Question 6

Inductive reactance may be increased by:

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- a decrease in the applied frequency
- a decrease in the supplied current

< an increase in the applied frequency >

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Review Question 7

What property allows a coil wound on a ferrite core to mitigate the effects of an offending radio signal?

- Low reactance at audio frequencies
- High reactance at audio frequencies
- High reactance at radio frequencies
- Low reactance at radio frequencies

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Review Question 7

What property allows a coil wound on a ferrite core to mitigate the effects of an offending radio signal?

- Low reactance at audio frequencies
- High reactance at audio frequencies
- High reactance at radio frequencies
- Low reactance at radio frequencies

< High reactance at radio frequencies >

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Review Question 8

If no load is attached to the secondary winding of a transformer, what is current in the primary winding called?

- Magnetizing current
- Direct current
- Latent current
- Stabilizing current

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Review Question 8

If no load is attached to the secondary winding of a transformer, what is current in the primary

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< Magnetizing current >

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Review Question 9

A transformer operates a 6.3 volt 2 ampere light bulb from its secondary winding. The input power to the primary winding is approximately:

- 3 watts
- 13 watts
- 6 watts
- 8 watts

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Review Question 9

A transformer operates a 6.3 volt 2 ampere light bulb from its secondary winding. The input power to the primary winding is approximately:

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Review Question 10

A transformer has a 240 volt primary that draws a current of 250 milliamperes from the mains supply. Assuming no losses and only one secondary, what current would be available from the 12 volt secondary?

- 50 amperes
- 5 amperes
- 215 amperes
- 25 amperes

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< 5 amperes >

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Review Question 11

In a mains power transformer, the primary winding has 250 turns, and the secondary has 500. If the input voltage is 120 volts, the likely secondary voltage is:

- 480 V
- 610 V
- 26 V
- 240 V

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Review Question 11

In a mains power transformer, the primary winding has 250 turns, and the secondary has 500. If the input voltage is 120 volts, the likely secondary voltage is:

- 480 V
- 610 V
- 26 V
- 240 V

< 240 V >

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Review Question 12

Maximum induced voltage in a coil occurs when:

- current is going through its least rate of change
- the magnetic field around the coil is not changing
- current is going through its greatest rate of change
- the current through the coil is of a DC nature

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Review Question 12

Maximum induced voltage in a coil occurs when:

• current is going through its least rate of change

• the magnetic field around the coil is not changing

• current is going through its greatest rate of change

• the current through the coil is of a DC nature

< current is going through its greatest rate of change >

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Review Question 13

A 100% efficient transformer has a turns ratio of 1/5. If the secondary current is 50 milliamperes, the primary current is:

- 0.25 A
- 2 500 mA
- 0.01 A
- 0.25 mA

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Review Question 13

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< 0.25 A >

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Review Question 14

When will a power source deliver maximum output to the load?

• When the impedance of the load is equal to the impedance of the source

• When air wound transformers are used instead of iron-core transformers

• When the power-supply fuse rating equals the primary winding current

• When the load resistance is infinite

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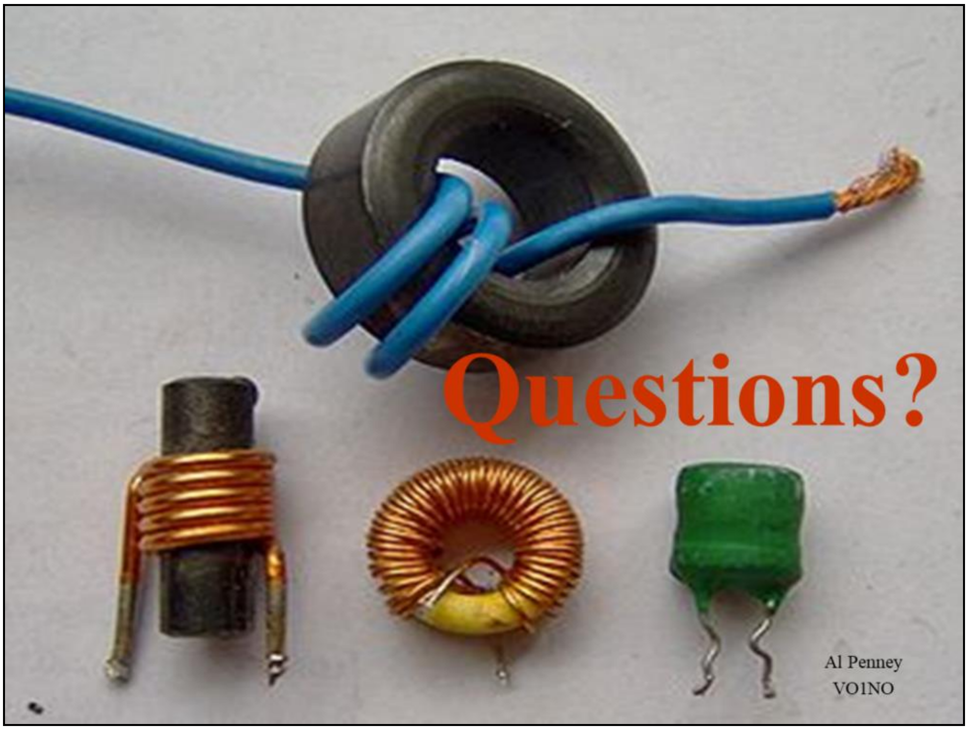
For Next Class:

- Review Chapter 4 of Basic Study Guide; and
- Read RIC-1: https://www.ic.gc.ca/eic/site/smt-gst.nsf/eng/sf01007.html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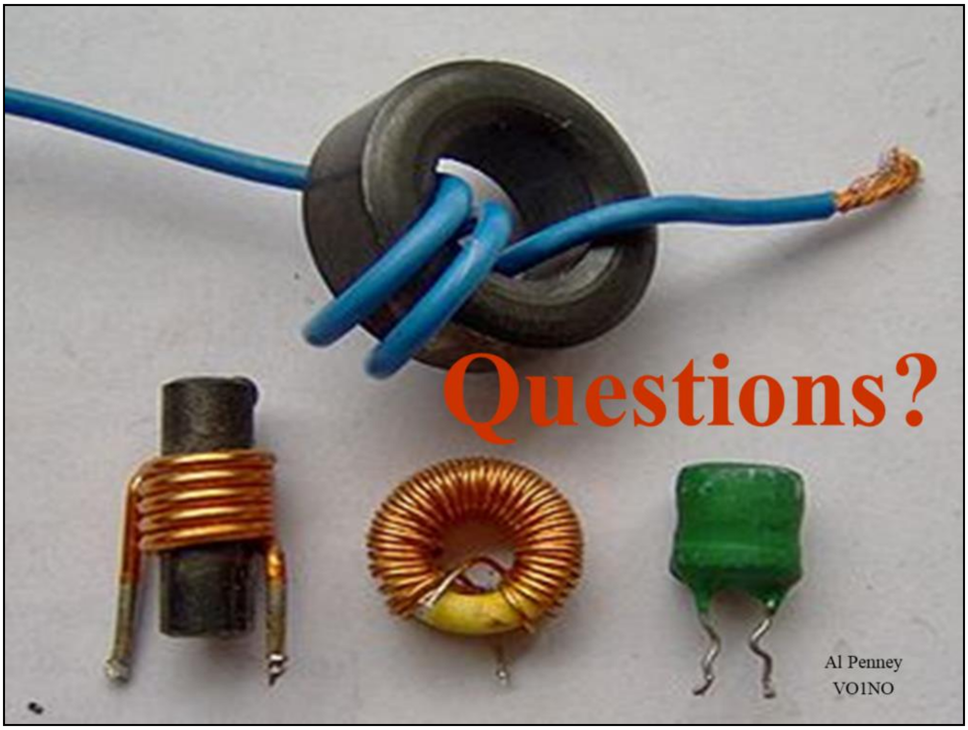
Grand Pre National Historic Site


Tim
WIN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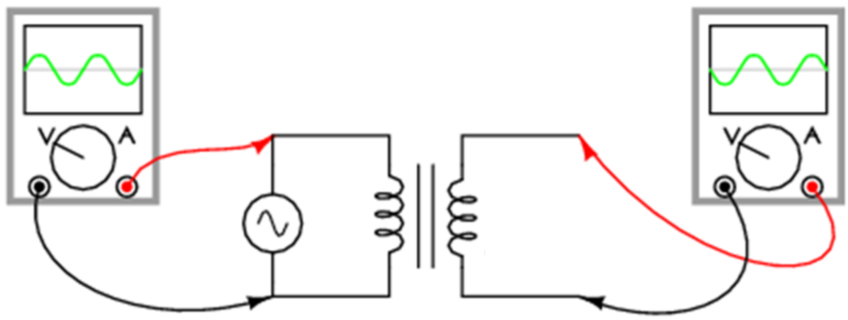
Phase Relationship



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