Electron AC vs DC

A. AC vs. DC - Make sure pictures are numbered correctly

1. Alternating Current

   a. Alternating current (AC) is a flow of electricity, as measured by voltage and current, which reaches a maximum in one direction, decreases to zero, then reverses and reaches a maximum in the opposite direction.

2. Comparison to Direct Current

   a. Direct current was the first type to be widely used because it was the first to be produced and understood. When electrical powered machinery was first applied to practical use, it was thought that DC could be more easily used than AC.

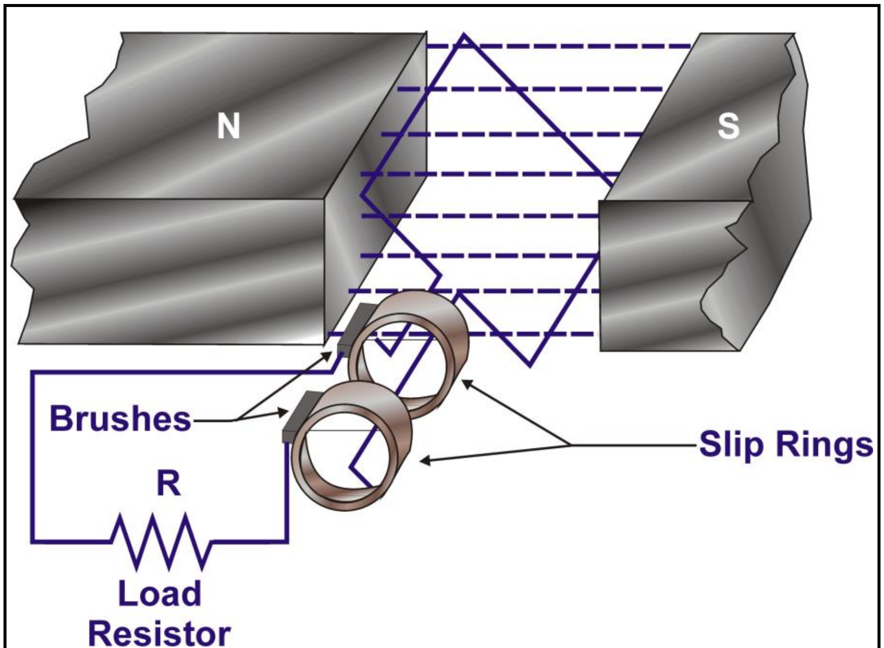
   b. It was soon apparent that DC had certain disadvantages. One of these was that DC cannot be transmitted over long distances without a considerable loss of power in the transmission lives. This is because DC voltages are low and the currents are higher for the same power transmitted (P = E x I). Resistance of the wire between the two points causes the loss of much DC power (in the form of heat loss), before it reaches its destination.

   c. AC power, on the other hand, can be transmitted for great distances without an appreciable loss of power. Due to its nature, AC power can be converted to a high-voltage low-current signal (power remains the same) prior to transmission. This is performed by a device called a transformer. The AC is transmitted on the familiar high-tension cross-country lines as a relatively low current at a high voltage. Because current flowing through the wires is low, power lost in transmission is considerably reduced. At the destination, the low- current high-voltage power is easily transformed into the proper voltage required.

B. Analysis of a Voltage Sine Wave

1. Simple AC Generator Construction

   a. In a simple two-pole AC generator (Picture 1), a loop of wire, called an armature coil, is mounted so it can be rotated on a shaft between the poles of a magnet. An armature may have one or more coils on it. The ends of the loop (s) are connected to slip rings which allow the loop to rotate while connected electrically to an external circuit. The external circuit, a load resistor (R), is connected to the slip rings by sliding contacts called brushes. A magnetic field, excitation, is set up so the loop is subjected to a magnetic flux. The generator coil rotates at a constant speed inside the magnetic field. This sets up a relative motion between the conductor and magnetic field, resulting in an induced voltage.



Picture 1, Simple AC Generator

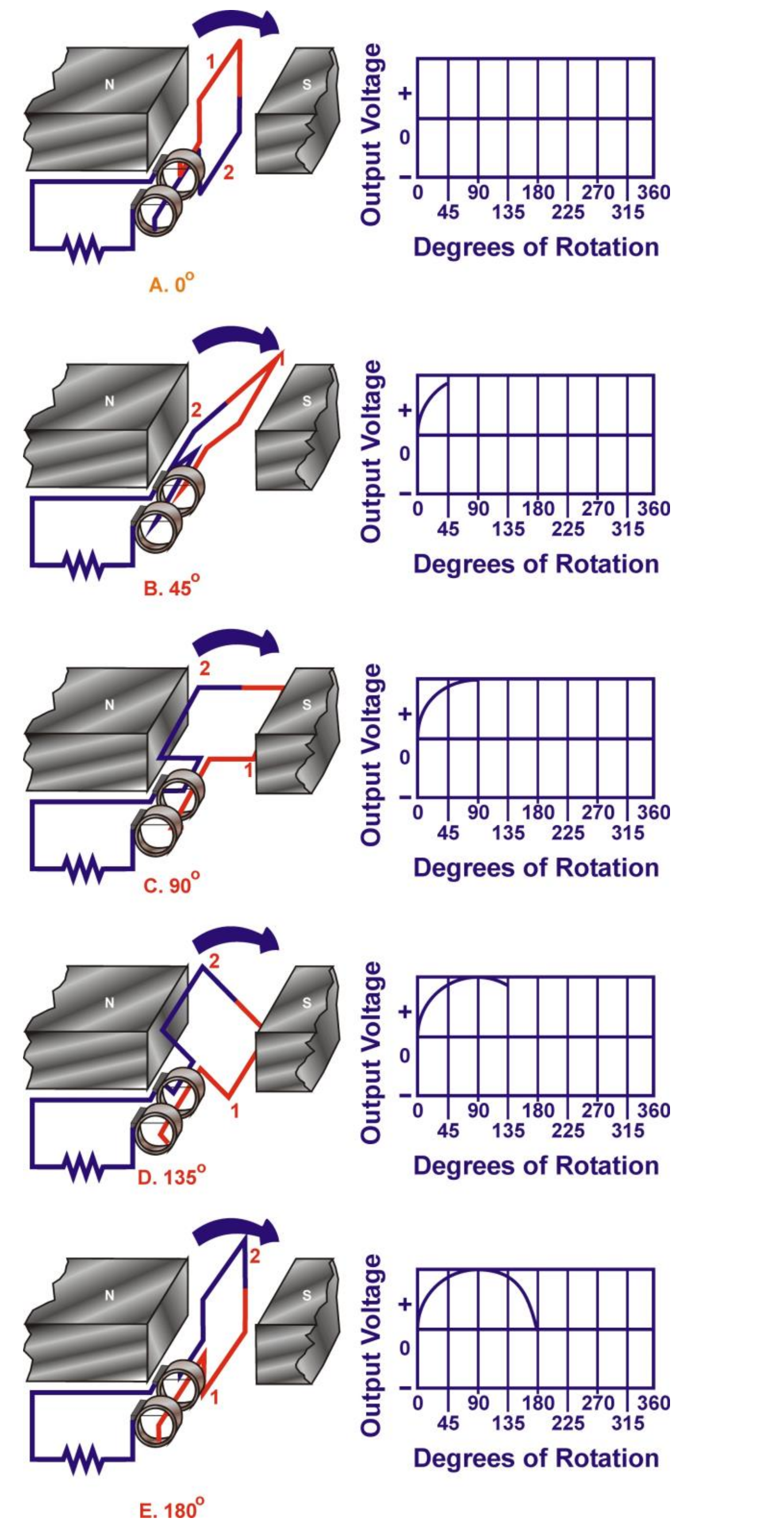
2. Cycle

   a. Two pole generator coils make a complete revolution 60 times every second. One revolution of the generator rotor produces one electrical cycle. Picture 2 (A thru I) represents one cycle. To simplify explanation, the loop sides are numbered (1 and 2). Chapter 4 listed three variables for the magnitude of induced voltage: 1) strength of the magnetic field, 2) number of conductors cutting the magnetic field, and 3) speed at which those conductors cut the magnetic field. Since rotation speed, number of conductors, and magnetic field strength are constant, only the angle of the conductor motion with respect to the magnetic field affects induced voltage strength and polarity. As the loop of wire rotates through the magnetic field, the angle between the conductor motion (electron) and magnetic flux vectors change, resulting in a change in force. The force can be related to voltage.

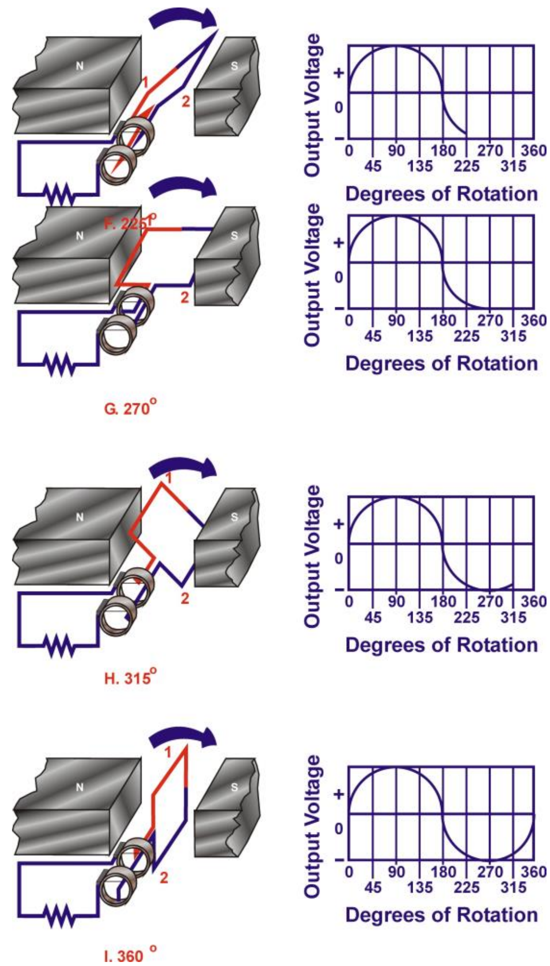
b. Another way to explain the output voltage is the amount of voltage induced in the loop depends on the number of flux lines cut in a unit of time.

c. At position A of Picture 2, side 2 is moving parallel to the lines of force. Consequently, it is cutting no lines of flux. The same is true of the side 1, moving in the opposite direction. Since conductors are cutting no lines of flux, no emf is induced. As the loop rotates, it cuts more and more lines of flux per second because it is cutting more directly across the magnetic field as it approaches position C. At position C, induced voltage is greatest because the conductor is cutting directly across the field, hence the most lines of flux per second. As the loop continues to be rotated toward position E, it cuts fewer and fewer lines of flux per second. Induced voltage decreases from its peak value. Eventually, the loop reaches point E and is once again moving in a plane parallel to the magnetic field, and no voltage is induced.

d. The next quarter-turn of the loop moves it to position G, where it cuts across the flux again for maximum induced voltage. Note, however, that now the side 2 conductor is moving up through the field. This motion is reversed from the previous direction. Because of reversed direction of motion during the second half of the revolution, induced voltage has opposite polarity, causing the current flow to reverse. This effect will be discussed in more detail when the left-hand rule for generator action is covered in Chapter 6. When the loop completes the last quarter-turn in the cycle, induced voltage returns to zero as the loop returns to its original parallel position. This cycle of induced voltage is repeated as the loop continues to rotate, with one complete cycle of voltage, for each cycle of revolution.



Picture 2-A, Production of a Sine Wave

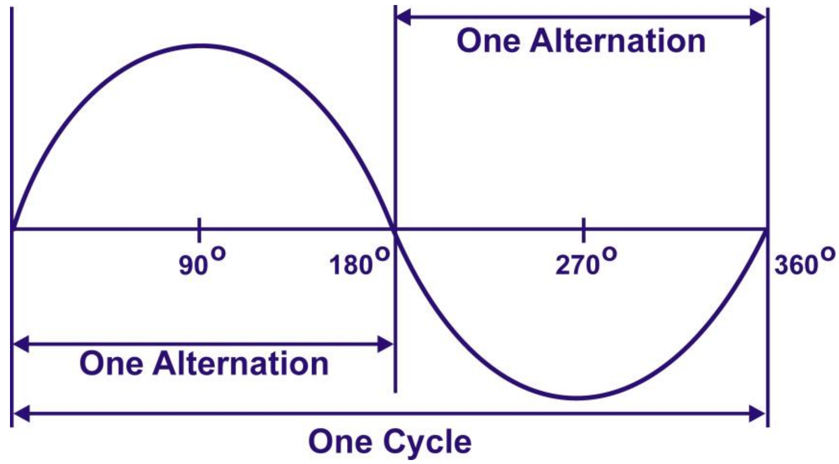


Picture 2-B, Production of a Sine Wave

e. If the loop is rotated at a steady rate, the strength of the magnetic field remains constant, the number of cycles per second and voltage will remain constant. Continuous rotation will produce a series of sine-wave voltage cycles, or, in other words, AC voltage.

3. Alternation

a. An alternation is defined as one-half of a cycle. The part of a sine curve above the horizontal axis is called the positive alternation or the positive half cycle. Conversely, the part below is called the negative alternation or the negative half cycle. Picture 3 shows the alternations in one cycle.



Picture 3, Comparison of Cycle and Alternation

4. Frequency

   a. The number of complete cycles generated each second is called the frequency (f). Frequency is measured in cycles per second (cps), called hertz (Hz).

   b. The simple generator used in Picture 2 has one pair of magnetic poles (N and S). For every revolution of the loop, a single cycle is produced. Therefore, if the loop is rotated 60 times per second, 60 cycles would be produced every second (60 cps or 60 Hz).

   c. If an AC generator has four pole pieces (2 pairs of magnetic poles), voltage at the slip rings will reverse direction four times during each revolution. In other words, two cycles are generated for each mechanical revolution. If each revolution lasts one second, the output frequency would be 2 Hz (2cps).

   d. Frequency of an AC generator can be calculated if the speed of rotation and the number of poles is known.

$$f = \frac{PS}{120}$$

Where: f = frequency of the generated AC voltage in cycles per second

P = number of magnetic poles in the generator

S = revolutions per minute of the coil in the magnetic field

120 = constant to convert minutes to seconds

e. Example: An electrical stations main generator has four poles and turns at 1800 revolutions per minute. What is the output frequency?

f. Answer:

$$f = \frac{4 \text{ x} 1800}{120} = 60\text{Hz}$$

5. Period

a. A period (τ) of AC voltage or current is the time for one complete cycle, or 1/f.

b. Example: What is the period of a 50 Hz sine wave?

c. Answer: $\tau = \frac{1}{50} = 0.02 \text{ seconds/cycle}$

6. Voltage and Current Values

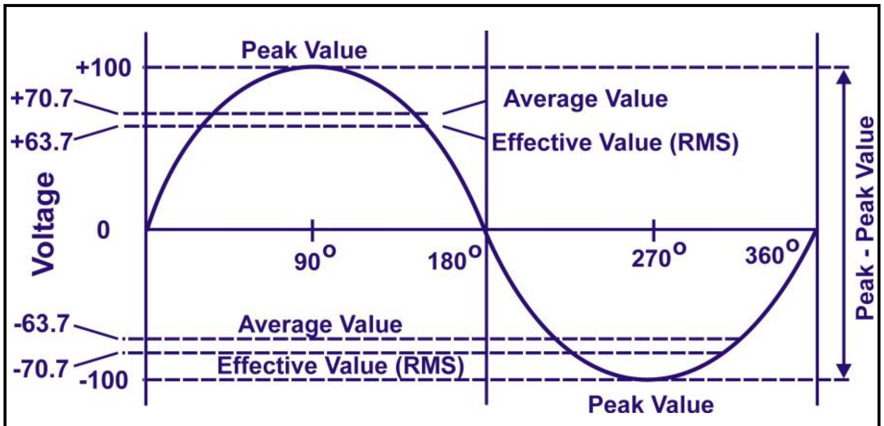
a. Because the value of AC voltage and current is constantly changing it is important to understand that:

1) Voltage and current have different types of values

2) These types of values have names, definitions, and precise methods of determining their amounts

3) The operator must understand the meanings of these values to communicate intelligently about AC voltage and current

b. Values for voltage can be seen on Picture 4.



Picture 4, Types of Voltage Values

7. Peak Value

   a. The maximum value of voltage (or current) attained during coil rotation is the peak value. There are positive and negative peak values. Peak values are represented by $E_{;k}\,(\mathrm{or}\,I_{pk})$. In Picture 4, peak values are +100v and –100v.

   b. The peak-to-peak value is the absolute difference between peak values. In Picture 4, the peak-to-peak voltage is 200v.

8. Instantaneous Value

   a. The value at any one instant during armature rotation is the instantaneous value. It could be the peak value, zero, or any value in between.

9. Average Value

   a. The average of all instantaneous values during one alternation is the average value. The average over a complete cycle would be zero as one half of the cycle is positive and one half negative. For a pure sine wave, (Picture 4), average value is 0.637 times the peak value.

$$E_{avg} = E_{pk}\ x\, 0.637$$

10. Effective (RMS) Value

a. The most useful voltage value is the effective or root mean square value (rms). It is the AC voltage required to produce the same amount of heat (power) in a circuit as is produced by DC when the circuit contains only resistance. 2 amps of effective (rms) AC passing through a given load will produce as much heat as 2 amps of DC passing through the same load. For a pure sine wave, Picture 4, rms value is 0.707 times peak current.

$$E_{eff} = E_{pk} \text{ x } 0.707$$

b. This is the value used in AC voltage calculations Most AC voltage and current measuring devices read out in rms.

c. Example: What value of peak voltage would be required to produce the same amount of heat in a 2 ohm load as when a 10 volt DC battery is connected to it?

d. Answer:

1) Solve for the direct current

$$I_{dc} = \frac{E_{dc}}{R_L} = \frac{10\,v}{2\,\Omega} = 5\,\text{DC amps}$$

2) Effective AC amps produce the same heat as 5 DC amps. Therefore, solve for the AC voltage required to produce that equivalent current (rms)

$$\begin{aligned} E_{rms} &= I_{rms} \text{ x } R_L \\ &= 5\,\text{amps x } 2\,\text{ohms} \\ &= 10\,v_{rms} \end{aligned}$$

3) Solve for E_{pk} using the following equation.

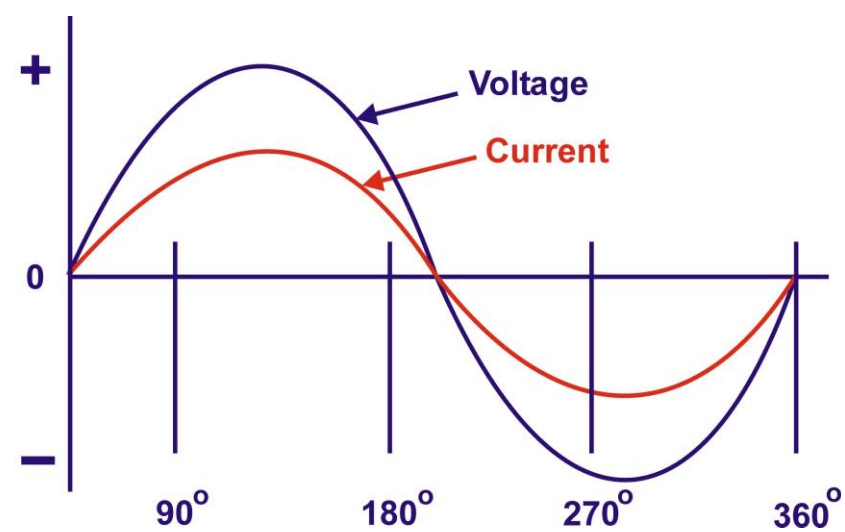
$$E_{pk} = \frac{E_{eff}}{0.707} = \frac{10\,v}{.770} = 14.14 \text{ volts peak}$$

e. It takes a higher peak AC voltage to produce the same amount of power for a given load as DC voltage.

C. Characteristics of Alternating Current

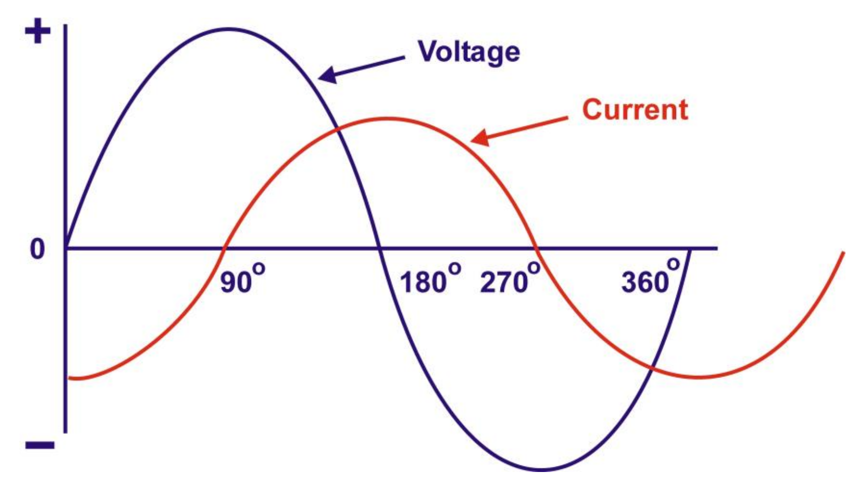
1. Phase

a. When voltage and current rise and fall together (Picture 5), they are said to be in phase. Under certain conditions, even though voltage is induced in the circuit, current does not start flowing immediately. (An explanation occurs later in this chapter.)

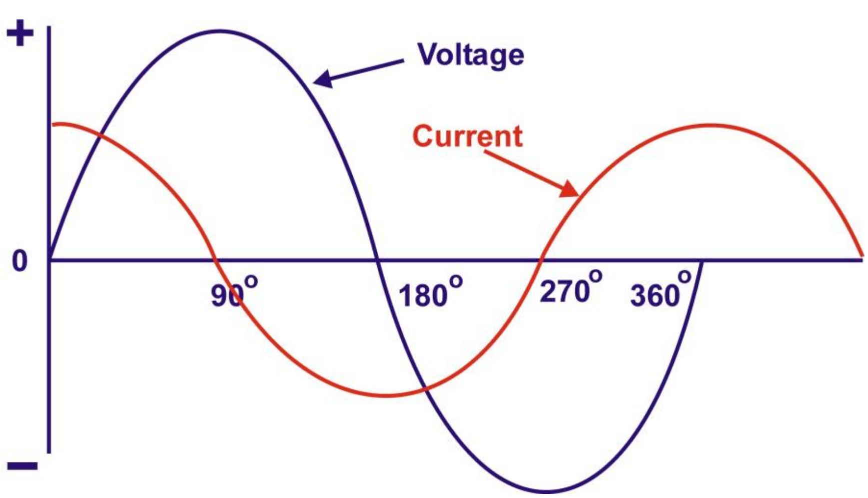


Picture 3, Voltage and Current In Phase

b. When not in phase, current will either be “lagging” or “leading” voltage. A condition showing current lagging 90° behind voltage is shown in Picture 6. Notice that current does not pass through zero until 90° after the voltage does. Picture 7 shows current leading voltage by 90°.



Picture 4, Current Lagging Voltage by 90˚



Picture 5, Current Leading Voltage by 90˚

2. Phase Angle

   a. Phase difference existing between two AC voltages, two AC currents, or between an AC voltage and its current is called the phase angle and is measured in degrees. The symbol is the Greek letter theta (θ).

   b.

   c. Example: What is the phase angle between a voltage (A) that peaks at 90˚ and another voltage (B) of the same frequency that peaks at 45˚?

d. Answer:

$\theta = 90^\circ - 45^\circ = 45^\circ$

e. Therefore, voltage B is leading voltage A by 45° or voltage A is lagging voltage B by 45°.

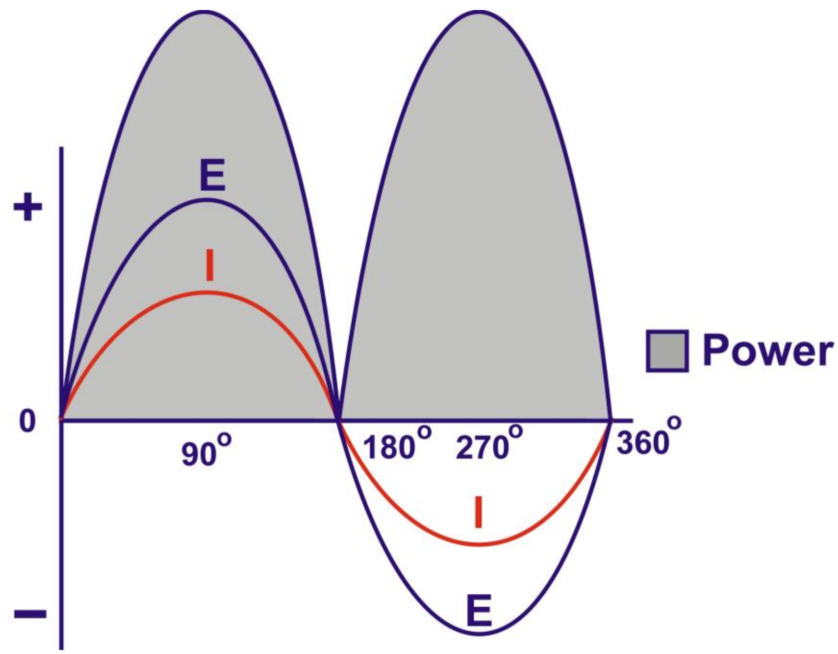
D. Factors Affecting Alternating Current

1. Alternating current produces different effects than direct current. In AC circuits two factors other than resistance oppose current. These factors are inductance and capacitance.

2. Resistance

   a. Fortunately, the average resistor handles either direct or alternating current, except at high frequencies above many thousands of cycles per second. Thus, if a resistor of a given value is connected to either a DC or AC voltage, the current immediately flows at a value determined by Ohm's law. For AC systems the effective, or rms, value of voltage and current are used.

   b. A plot of the relationship between sine-wave AC voltage applied to a resistor, and the resulting current, is illustrated in Picture 8. Voltage and current are in phase, going through their respective maximum and minimum together, and the ratio of voltage to current at any point is equal to resistance. The phase angle in a purely resistive AC circuit is zero.



Picture 6, Waveforms of Current, Voltage, and Power

c. Power in a purely resistive AC circuit is the product of the rms values of voltage and current, or the square of the rms current times the resistance, or the square of the rms voltage divided by the resistance, just as for DC. Notice that the power in a purely AC resistive circuit is always positive. This indicates an AC resistive circuit always uses power except when both voltage and current pass through zero.

d. Example: An ammeter indicates a current of 2 amps through a resistor connected to 120 volts DC (vdc). The resistor is then connected to an AC voltage with peak value of 170 volts. What is the AC (rms) through the resistor and the power consumed in the resistance?

e. Anser:

   1) Find the resistor's value in the DC circuit.

$$R = E/I = 120 \div 2 = 60\Omega$$

Since the value will be the same in an AC circuit, the AC resistance will be 60 Ω.

2) Find the rms (effective) value of AC voltage.

$$E_{rms} = 0.707 \text{x} E_{pk} = 0.707 \text{x} 170 = 120 \text{v}.$$

3) Find the rms current.

$$I = E/R = 120\text{v}/60\Omega = 2 \text{amps}.$$

4) Find the power consumed.

$$P = IE = 120 \text{x} 2 = 240 \text{watts}$$

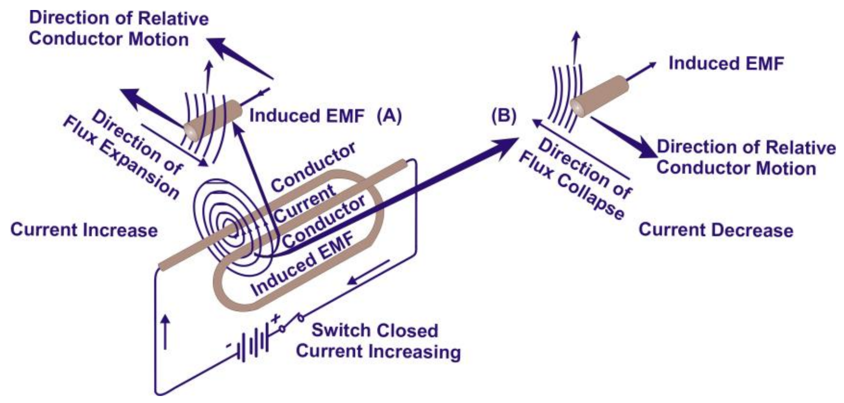
or $P = I^2R = (2)^2 \text{x} 60 = 4 \text{x} 60 = 240 \text{watts};$

or $P = E^2/R = (120)^2 / 60 = 14{,}000/60 = 240 \text{watts}$

f. Current and power consumed for a resistor supplied by a DC voltage is identical to current and power consumed by the resistor with the same numerical value of rms voltage.

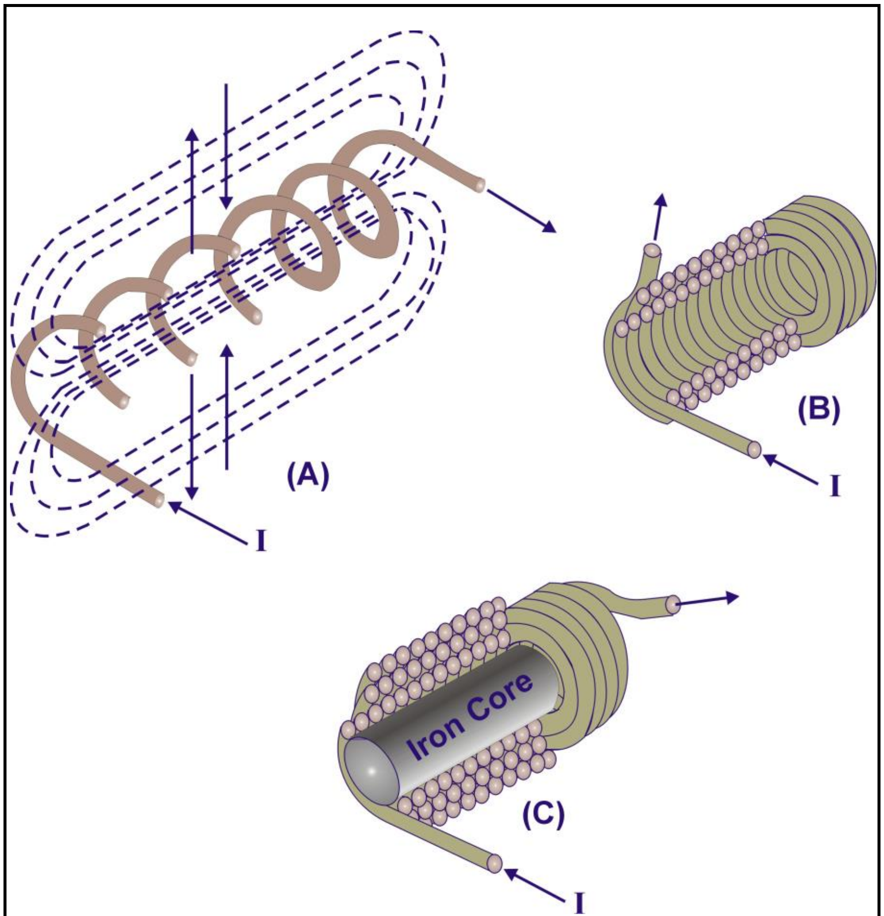
3. Inductance

a. Inductance opposes an instantaneous change in current in a circuit. When current increases or decreases, a self induced voltage, in opposition to the change in applied voltage is developed in parallel conductors, Picture 9. The voltage is developed in conductor 2 because the magnetic field around conductor 1 is expanding, or collapsing through conductor 2. The requirements to generate a voltage are met only when the current in the conductor is changing. Recall, the requirements are: a current carrying conductor, a magnetic field, and relative motion between the two.



Picture 7, Self-inductance

b. Amount of self-induced voltage can be increased by adding more conductor turns, Picture 10A. This is because a longer length of conductor is interacting with the changing magnetic field. Winding the coils closer together, Picture 10B, will increase self-induced voltage because of better flux linkage between the turns. A core of appropriate material will increase the magnetic flux strength and, thus, increase the self induced voltage.



Picture 8, Various Coils

c. Anytime AC is applied to an inductor, a counter electromotive force (cemf) is developed. This produces a restriction (inductive reactance, discussed later) to AC much the same as resistance in a DC circuit.

d. The unit of inductance (L) is the Henry (h). When the self-induced counter-emf is 1 volt while current is changing at 1 amp per second, the inductor has 1 henry of inductance. Mathematically, the relationship between self-induced voltage, inductance and rate of change of current is:

$$E = -L\frac{\Delta I}{\Delta t}$$

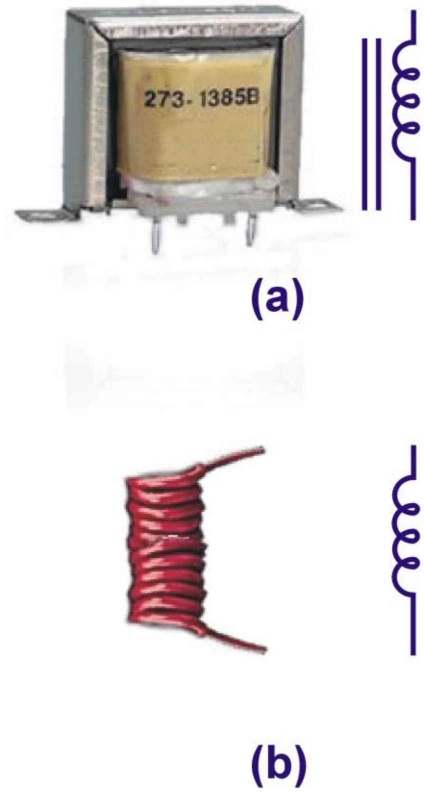
e. Where E is the self-induced voltage, L is inductance (in henrys), ΔI is the change in current (in amperes), and Δt is the change in time (in seconds).

f. The minus sign indicates that the induced voltage opposes the applied voltage.

g. The self-induced voltage can be very large if the current changes very rapidly. This happens when a switch is opened to a solenoid (coil of wire) and can cause arcs across the switch. Many solenoids have a resistor in parallel to dissipate this energy and protect the switch.

4. Self Inductance

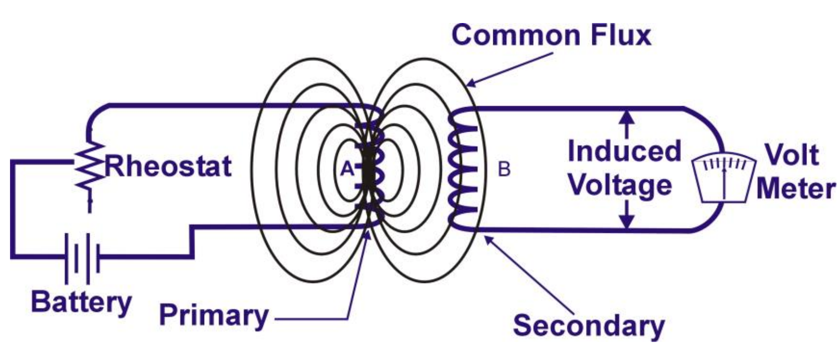
a. A conductor produces a magnetic field surrounding itself as a consequence of current flow. If the applied emf is changed this magnetic field will attempt to maintain the original current flow. Therefore, even a perfectly straight length of conductor, such as a transmission line, has some inductance. The amount of inductance in a straight conductor is small because flux lines cut the conductor at only one point. Self-inductance is increased by shaping a conductor so that the electromagnetic field around each portion of the conductor cuts across some other portion of the same conductor. Construction of an inductor (also called a choke or coil) depends on the planned application. A distinction is made between iron core inductors (Picture 11a), used for power and filtering applications at low frequencies such as 60 Hz, and air-core inductors (Picture 11b), used in electronic applications at high frequencies. Major self-inductive loads on the grid are transmission lines themselves and the windings of motors.



Picture 9, Typical Inductors with Their Schematic Symbols

5. Mutual inductance

   a. When two conductors or coils are located so the flux from one coil cuts the turns of the other, Picture 12, a change of flux in one coil (primary) will cause an emf to be induced in the other (secondary) coil.



Picture 10, Mutual Inductance between coils

b. The magnitude of voltage induced in a secondary by a primary coil is given by the equation:

$$\text{Induced emf } (E) = -M \frac{\Delta I}{\Delta t}$$

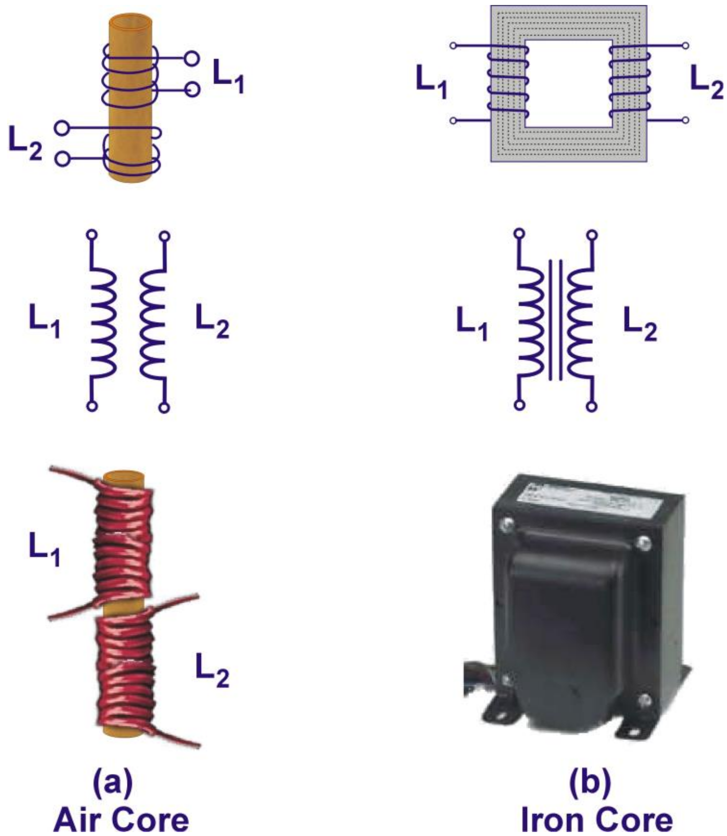
c. Where ΔI is primary current change (in amperes), Δt is time (in seconds), M is mutual inductance (in henrys), and E is voltage induced in secondary.

d. When a current change of 1 ampere per second results in 1 volt induced in the other coil, mutual inductance is 1 henry. The negative sign indicates that induced voltage is opposite the change in primary current.

e. Mutual inductance is affected by the:

1) physical dimensions of the two coils
2) number of turns in each coil
3) distance between the two coils
4) relative position of the axes of the two coils
5) permeability of the cores.

f. Mutual inductance is the basis behind transformer coupling and will be used in Chapter 8 to discuss transformers. The schematic symbol for two coils with mutual inductance is shown in Picture 13a for an air core, Picture 13b for an iron core. Iron increases mutual inductance, since it concentrates magnetic flux. The permeability of iron is much greater than air. As with chokes, the iron core is normally used for low frequency power transformation and the air core is used for much higher (radio) frequencies.

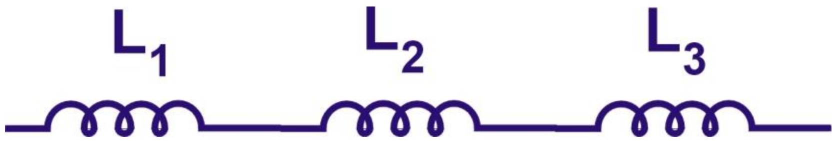


Picture 11, Typical Transformers With Their Schematic Symbols

6. Inductors in Series

   a. Inductors spaced sufficiently far apart to not interact with each other combine like resistors when connected together. Thus, total inductance, LT, of a number of inductors connected in series, Picture 14, is simply the sum of individual inductances.

$$L_T = L_1 + L_2 + L_3 + L_n$$



Picture 12, Inductors in Series

b. Example: A 5-henry and a 12-henry inductor are connected in series and far apart. What is their total inductance?

c. Answer:

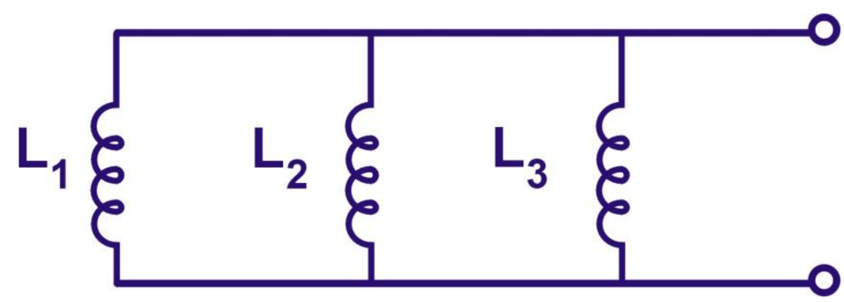
1) The inductance of two uncoupled coils in series is:

$L_T = L_1 + L_2 = 5 + 12 = 17$ henrys

7. Inductors in Parallel

a. Inductors in parallel circuits sufficiently far apart that mutual inductance can be ignored follow the same rules as resistors. The total inductance of a number of coils in parallel is equal to the reciprocal of the sum of the reciprocals of individual inductances, Picture 15. Expressed as a formula,

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



Picture 13, Several Inductors in Parallel

c. If the inductance of each coil is the same, the following can be used to solve for total inductance.

$$L_T = \frac{L}{N}$$

d. Where: L is the value of one of the inductors, and N is the number of inductors in parallel.

e. Example: What is the total inductance of five inductors connected in parallel and each having an inductance equal to 20 henrys?

f. Answer:

g. The total inductance of equal inductors in parallel is:

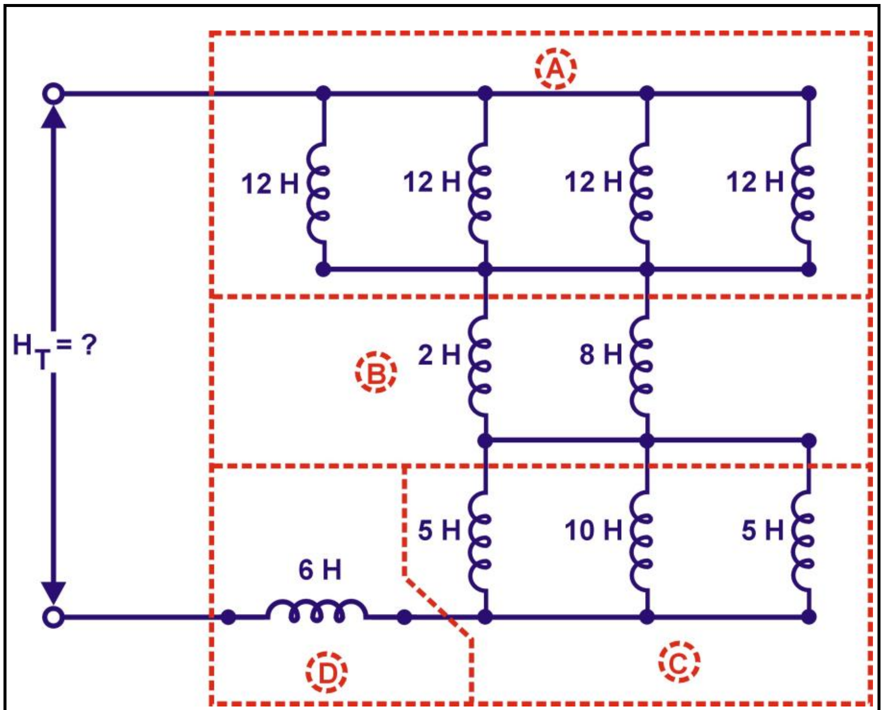
$$L_T = \frac{L}{N} = 4\,\text{henrys}$$

h. If two inductors are connected in parallel, the form of equation is,

$$L_T = \frac{L_1 \, x \, L_2}{L_1 + L_2}$$

i. Recall from ohms law, to solve for resistors in series-parallel (complex) arrangement a circuit is first reduced (simplified) to a series network. The same form is used for inductors in series-parallel combinations.

j. Example: A number of inductors are connected together into the inductance network shown. What is the total circuit inductance?



Example: Complex Inductive Circuit

k. Answer:

1) Solve for the equivalent inductance of Group A.

$$L_T = \frac{L}{N} = \frac{12}{4} = 3\,h$$

2) Solve for the equivalent inductance of Group B.

$$L_T = \frac{L_1 x L_2}{L_1 + L_2} = \frac{8 x 2}{8 + 2} = \frac{16}{10} = 1.6h$$

3) Solve for the equivalent inductance of Group C.

$$L_T = \frac{1}{\frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3}} = \frac{1}{\frac{1}{5} + \frac{1}{10} + \frac{1}{5}} = \frac{1}{\frac{5}{10}} = 2$$

$$L_T = 2h$$

4) Solve for the series of Groups A thru D.

$$L_T = L_1 + L_2 + L_3 + L_4 = 3 + 1.6 + 2 + 6 = 12.6 \text{ henrys}$$

l. Recall Ohm's law: I = E/R. As resistance increases in a circuit, less current flows. Inductance opposes any change in the magnitude of current flowing through it. Since alternating current is changing continuously, inductance has a constant opposition to that current. If inductance increases and applied voltage stays the same, current decreases. The term used to describe opposition to current flow caused by inductance of a circuit is inductive reactance (XL). Inductive reactance is measured in ohms, as is resistance. In a purely inductive AC circuit (no resistance or capacitance, discussed later) inductive reactance replaces resistance in Ohm's law and acts as resistances in series and parallel when added together.

m. Since Ohm's law can be used in a purely inductive circuit, then

$$E = X_L \times I$$

n. The voltage across an inductor is self-induced, therefore

$$E = -L \times \frac{\Delta I}{\Delta t}$$

o. The rate of change of AC with respect to time is proportional to frequency. With this fact and elementary calculus:

$$E = \omega L I_{peak} \cos \omega t$$

p. ω is the angular velocity in radians per second and is equal to 2π x frequency. There are 2π radians per cycle. Substituting gives an equation for inductive reactance (X_L).

$$X_L = \omega L = 2\pi f L$$

X_L is Inductive reactance in ohms

f is frequencyin hertz

L is Inductivein henrys

8. Inductors in DC circuits

   a. It should be noted that inductive reactance is directly proportional to frequency, that is if frequency decreases X_L decreases. As the frequency approaches zero hertz, as in DC, the inductive reactance approaches 0Ω. In pure DC, the inductor presents no reactive resistance, and the coil of wire only provides a small value of natural resistance to the circuit. A field still exists around the coil, but as long as the current through the coil is not changing, there is no X_L to impede current flow.

   b. When first energized, a DC circuit containing inductors will provide current flow to generate the electromagnetic field around the inductor. During this period, while the field is building, the inductor appears to the circuit as a very high resistance, all of the energy is being employed in generating the field. As the field builds, the inductor will require less of the total energy until eventually, with the field fully generated, the inductor requires no energy from the circuit and its resistance to current flow (X_L) is zero. The amount of time required to generate the field around the indicator is known as it's charge time. The charge time on an inductor is equal to five to six times the value of the time constant associated with the circuit components. The time constant for an inductive circuit is determined by dividing the value of induction (in henrys) by the total resistance through which the inductor must change.

$$TC = L/R$$

Where: TC is the inductor Time Constant (in secs)

L is Total value of induction

R is Total Value of resistance in Change Path

c. With a time constant of 5 microseconds, the inductor would be fully changed in 25 to 30 microseconds. Although this time period is very short, and may seem relatively unimportant, it is the basis for understanding why an inductor presents a higher circuit impedance as the frequency of the applied voltage increases. The inductor simply does not have time to fully charge at high frequencies.

d. Example: Which has a greater opposition to a 60 hertz current, an 1884 ohm resistor or 5 henry inductor

e. Answer:

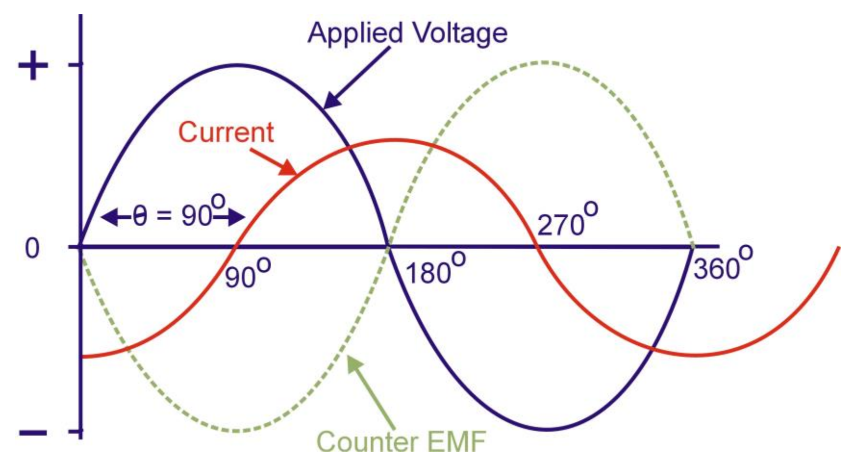
1) Solve for X_L of the inductor

$X_L = 2\pi\ f_L$

XL = 2 x 3.14 x 60 x 5 = 1884 Ω

2) They offer the same opposition

f. Inductance opposes an instantaneous change in current. With alternating current flowing through an inductance, counter emf is greatest when current is changing at the faster rate. Counter emf reaches a maximum negative value when the current is increasing most rapidly in the positive direction, the opposite is true for maximum positive emf (Picture 16).

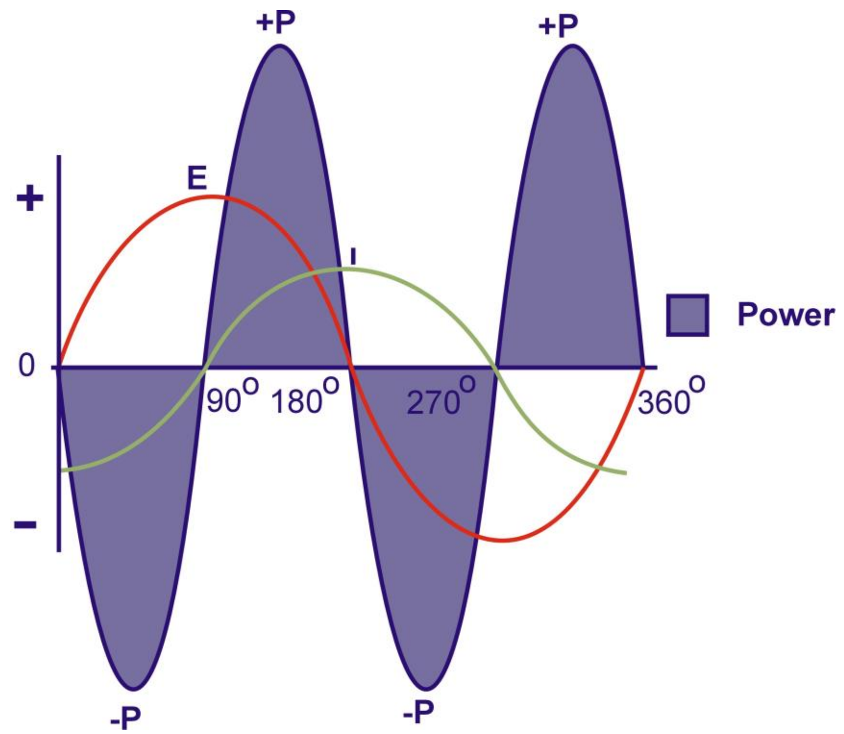


Picture 16, Graph of Applied Voltage, CEMF, and Current in a Purely Inductive Circuit

g. Counter emf is always opposed to the applied voltage. That is, counter emf is 180˚ out of phase with applied voltage. It can be seen from the position of waves along the axis that current in pure inductance lags the applied voltage by 90˚. Therefore, the phase angle (of a purely inductive circuit would be 90□ in the lagging direction or +90˚ from reference zero.

h. A memory aid (MNEMONIC) that can be used to remember the relationship between current and voltage in a reactive circuit (in this case inductive) is "ELI the ICE man". The ELI portion of the mnemonic describes the relationship between voltage (E) and current (I) in an inductive (L) circuit. ELI means that voltage leads the current in an inductive circuit. The ICE man portion will be covered later when capacitors (another reactive type component) are discussed.

i. To obtain the power in a purely inductive circuit, multiply instantaneous rms values of applied voltage and current, as for resistance in an AC circuit. The resulting power curve is shown in Picture 17.



Picture 17, Graph of Power in a Pure Inductance

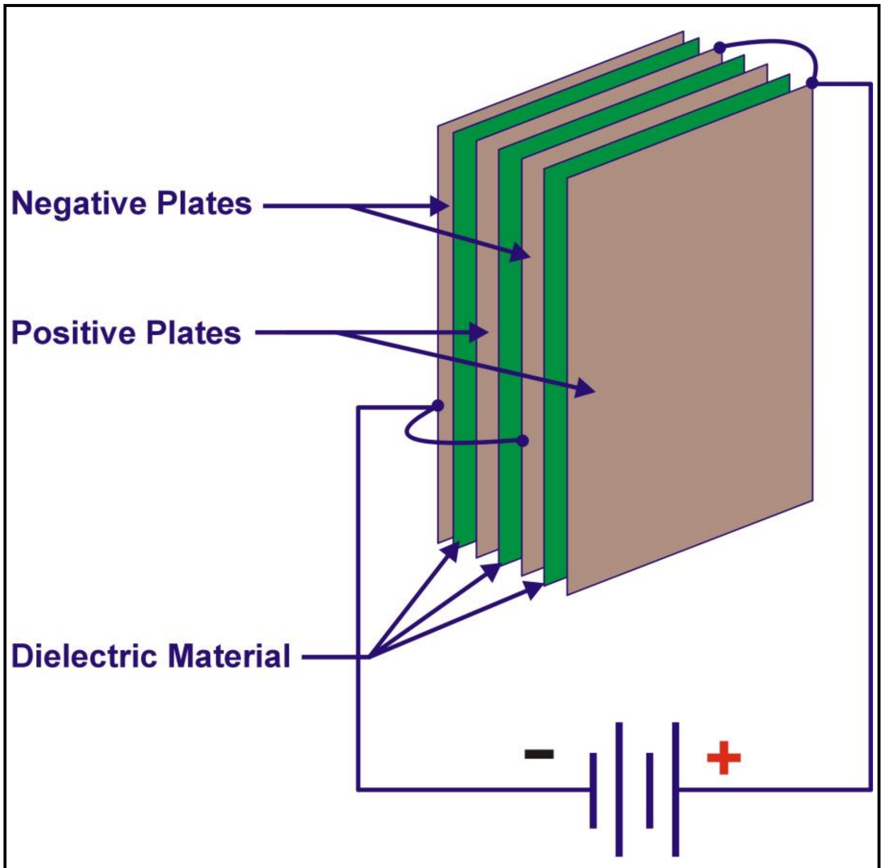
j. This power curve has two positive and two negative loops during one complete cycle of applied voltage. Positive power means power consumed or absorbed by the circuit and negative power indicates power returned from the circuit. No net, or real, power is consumed by a purely inductive circuit. This does not mean that the generator doesn't have to produce power.

k. During one quarter of the cycle, energy is supplied to the inductor and in the next quarter, the same amount of energy is returned by the inductor. This means energy in the magnetic field, built up by current flow, is returned by the collapsing magnetic field when the current flow decreases. Although a pure inductance does not absorb any power, all inductive loads have some resistance and always absorb some power.

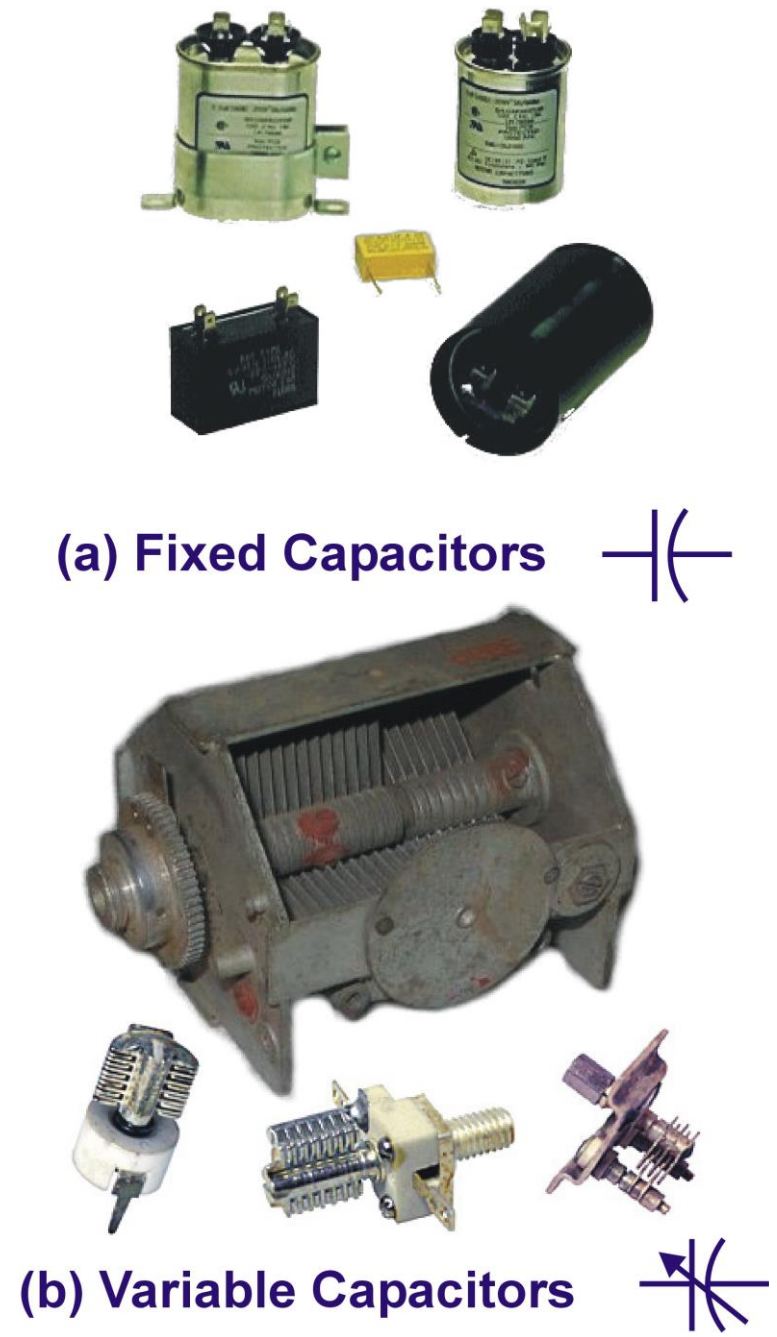
9. Capacitance

   a. Capacitance opposes an instantaneous change of voltage in a circuit. If applied voltage is increased, capacitance opposes the change and delays the voltage increase across the circuit. If applied voltage is decreased, capacitance maintains higher original voltage across the circuit, thus delaying the voltage decrease. Consequently, the most noticeable effect of capacitance in a circuit is that voltage in a capacitive circuit can neither increase nor decrease as fast as in a noncapacitive circuit. Capacitive energy is stored in an electrostatic field. This is different from inductance, which stores energy in a magnetic field.

   b. A capacitor, also called a condenser, in its simplest form consists of two metal plates separated by a thin layer of insulating material called a dielectric (Picture 18). Common types of capacitors are shown with their schematic symbol for a fixed value in Picture 19a and for a variable value in Picture 19b.



Picture 18, Simple Capacitor



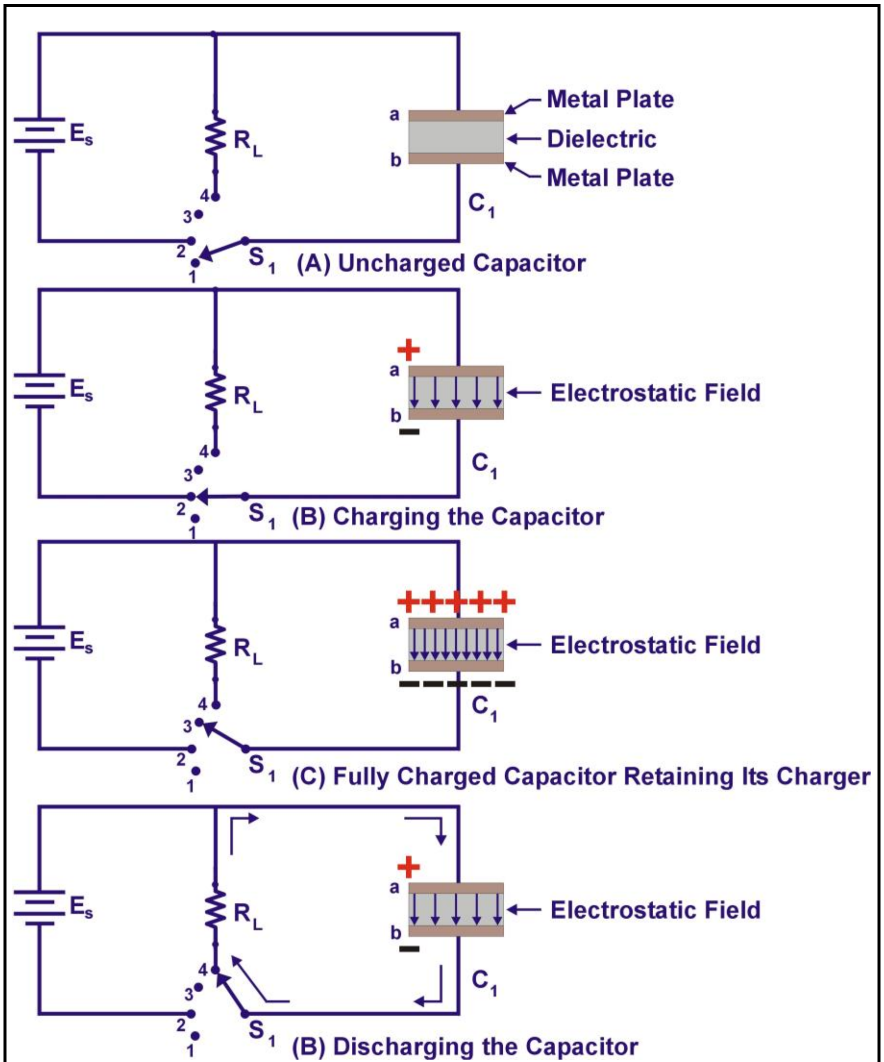
Picture 19, Types of Capacitors and Their Schematic Symbols

c. In an uncharged capacitor the plates are neutral in charge (Picture 20a). When the switch is moved to position 2 (Picture 20b), electrons rush out of the negative battery terminal and flow through the wire into plate “b”.

Electrons cannot pass through the dielectric because dielectric material is insulating material. Therefore, plate "b" acquires an excess of electrons and becomes negatively charged. At the same time, the influence of the positive battery terminal attracts electrons away from plate "a". Plate "a" acquires a deficiency of electrons and becomes positively charged. As the electrons build up on the capacitor plate, a voltage in opposition to applied voltage develops. This reduces circuit current flow. When emf equals battery voltage, the capacitor is said to be fully charged, no difference of potential remains to cause current flow), and current is reduced to zero. Thus a capacitor, always charges itself to the voltage of the source if enough time is allotted. In this condition, the capacitor is a source of potential energy similar to a charged battery. The dielectric must have sufficient insulating qualities to withstand potential differences. If it does not, the dielectric breaks down, allowing current to flow through the dielectric. Under these conditions, the capacitor has shorted.

d. If the switch is moved to position 3, the circuit is open (Picture 20c). The capacitor remains charged nearly indefinitely. The charge will eventually leak through the dielectric and dissipate, but this may take several months in a well-constructed capacitor. With the switch at position 4 (Picture 20d), the circuit is closed but the source voltage is out of circuit. Negative electrons on capacitor plate "b" will flow to the opposite plate via load resistance to equalize charges. The value of current at any time is dependent upon the voltage of the capacitor and the total resistance encountered by the current. This neutralizes the positive charge on capacitor plate "a". When current flows in this direction the process is called discharging.

e. The voltage across a charged capacitor is equal to the charge on the plates divided by the capacitance.



Picture 20, Capacitor Charge and Discharge

f. Four facts should be noted in connection with Picture 20:

1) After a momentary surge of electrons, direct current is completely stopped by the capacitor.

2) Free electrons (current) do not pass from one plate to the other through the dielectric because the dielectric is a nonconductor.

3) Electrons are distributed on the negative plate and held there by the mutual attraction of corresponding positive charges on the positive

plate. The presence of the two polarities (plus and minus) establishes an electric field through the dielectric.

4) The electric lines of force (flux) originate on a positively charged plate and terminate on a negatively charged plate. The lines of force would be present even if the plates were enclosed in a perfect vacuum. Electric lines of force cannot exist in a metallic conductor to any great extent, because equalizing currents are free to flow within the metal. If the force is to exist, two dissimilarly charged bodies must be separated by a nonconductor.

g. Materials differ in ability to serve as dielectric materials for capacitors. The reference is dry air and has a dielectric constant of 1.0. The dielectric constant (K) of a material is the ratio of the capacitor with that particular material as the dielectric to the capacitance with dry air as the dielectric. The table below gives the dielectric constants for some common materials; the greater the dielectric constant of a material used, the higher the capacitance rating for the capacitor.

Material	K
Dry Air	1.0
Mica	6.0
Flint Glass	9.9
Glycerin	56.2
Pure Water	81.0

h. Capacitance of a capacitor is proportional to the quantity of charge that can be stored for each volt applied across its plates. A capacitor possesses a capacitance of 1 farad (f) if a charge of 1 coulomb (6.25 x

10^{18} electrons) is stored when one volt is applied across its plates. A capacitor with a value of 1 farad would be of enormous dimensions. Hence, use of the farad as a unit is usually limited to definition and calculations. Practical units of capacitance are microfarad (μf) and micro-microfarad (μμf). A capacitor whose value is 1 microfarad is one in which a microcoulomb (6.25×10^{12} electrons) is stored when 1 volt is applied across its plates.

i. The capacitance of a capacitor depends on three factors:

j.

1) the area of the plates, A; more area, more capacitance
2) the distance between the plates, d; less distance, more capacitance
3) the dielectric constant of the material between the plates, k; higher dielectric constant, more capacitance

k. Capacitance can be calculated with the equation:

$$C=0.225\ \frac{kA}{d}$$

Where: C is in μμf (micro-microfarads)

k is the dielectric constant

A is the area of one plate in square inches

d is the distance between plates in inches

l. Eample: Calculate the capacitance of a capacitor with plates, 0.04 inches apart, with mica dialectric.

m. Answer:

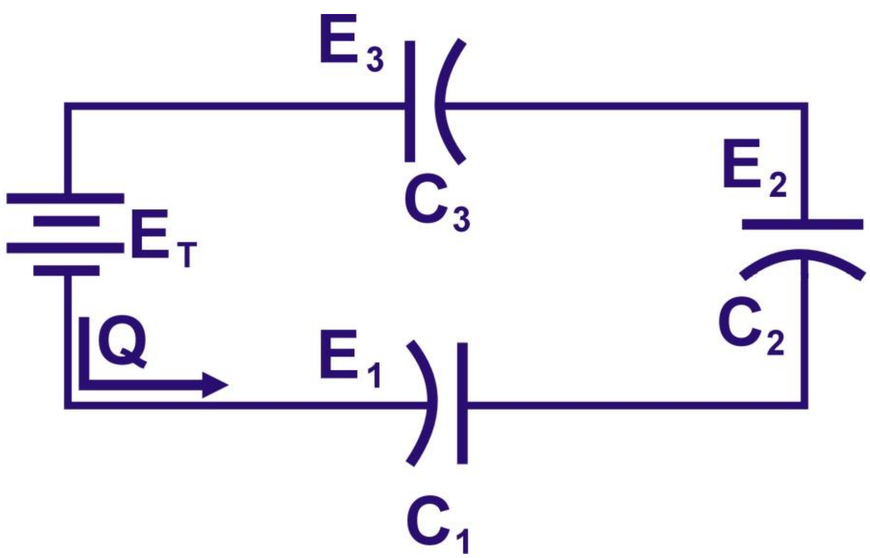
$$C = 0.225\frac{kA}{d}$$

$$= 0.225\frac{6\,x10}{0.04}$$

= 337.5 μμf

10. Capacitors in Series

a. The sum of the voltages for series capacitors (Picture 21) must equal the applied voltage and the current is equal for each circuit component. Applying these facts to the following circuit:



Picture 21, Series Capacitance Circuit

b. Kirchhoff's voltage law states:

ET=E1 + E2 + E3

c. Substituting from the equation for voltage across a capacitor:

$$\frac{Q_T}{C_T} = \frac{Q_1}{C_1} + \frac{Q_2}{C_2} + \frac{Q_3}{C_3}$$

d. Dividing by Q, because currents are equal:

$$\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$

e. Solving for C_T:

$$C_T = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}}$$

f. Hence, capacitors in series combine like resistors in parallel. The total capacitance of a series capacitive circuit will be less than the smallest capacitance.

g. Example: If one 10μf and two 5μf capacitors are connected in series, what is the total capacitance of the combination?

h. Answer:

$$C_T = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}} = \frac{1}{\frac{1}{10} + \frac{1}{5} + \frac{1}{5}} = \frac{1}{.1 + .2 + .2} = \frac{1}{15} = 2\mu f$$

i. If all capacitors are the same, total capacitance is the value of one capacitor divided by the number of series connected capacitors.

$$C_T = \frac{C}{N}$$

Where: C is the value of one capacitor

N is the number of series-connected capacitors

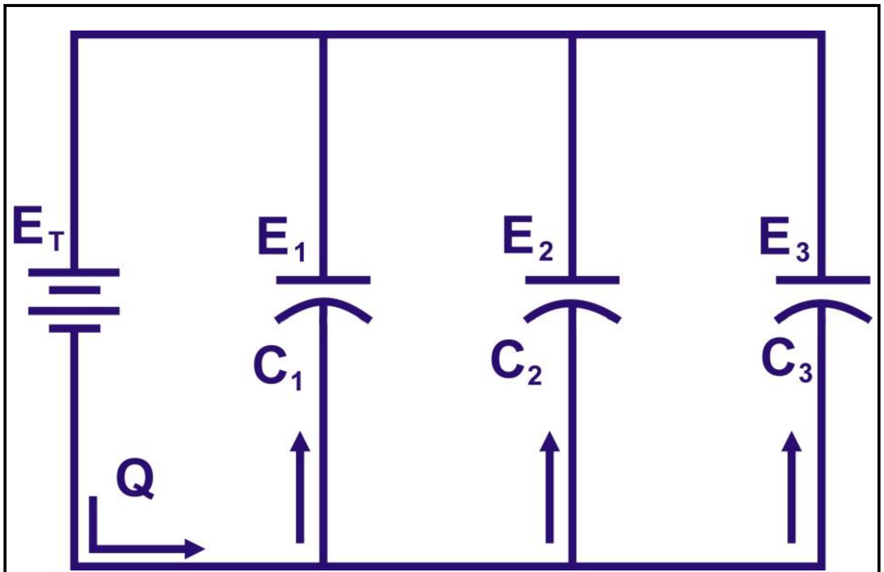
j. For two capacitors connected in series, the formula is:

$$C_T = \frac{C_1 \, x \, C_2}{C_1 + C_2}$$

k. Capacitors in series yield a total capacitance less than that of any individual capacitor. One reason they are used is that series-connected capacitors split the total applied voltage. Also, the price of a capacitor goes up steeply with its voltage rating; it is often more economical in high-voltage circuits (such as the electrical transmission grid) to series-connect a number of high value capacitors with relatively low voltage ratings than use a single, lower capacitance of high voltage rating.

11. Capacitors in Parallel

a. Voltages in a parallel capacitor circuit (Picture 22) are equal. The total current is equal to the sum of individual branch currents. With these facts an equation for total parallel capacitance can be determined.



Picture 22, Capacitors in parallel

b. Kirchhoff's current law states:

$Q_T = Q_1 + Q_2 + Q_3$

c. Substituting from the equation for voltage across a capacitor, solved for charge:

$E_T C_T = E_1 C_1 + E_2 C_2 + E_3 C_3$

d. Dividing by E, because voltages are equal:

$C_T = C_1 + C_2 + C_3$

e. Hence, the total capacitance in a parallel capacitive circuit is the sum of the individual capacitances.

f. Capacitors in parallel add like resistors in series. Total capacitance will be larger than the largest circuit capacitor. As they will be subjected to the same, voltage, each capacitor must have sufficient voltage rating to prevent breakdown of dielectric material.

g. Example: What is the total capacitance of a 2μf, 20,000 μμf, 0.005μf and 0.25μf capacitor if all are connected in parallel?

h. Answer:

$$\begin{aligned} C_T &= 2\mu f + 0.02\mu f + 0.05\mu f + 0.25\mu f \\ &= 2.275\mu f \end{aligned}$$

i. The amount of time that it takes for a capacitor to charge is called its charge time. The charge time for a capacitor is equal to five to six times the time constant associated with the charging circuitry. The time constant is found by multiplying the value of capacitance (in farads) by the total resistance (in ohms) in the change path.

j. Note that a fully charged capacitor presents the highest impedance/resistance. As frequency decreases the capacitor remains at higher level of change and consequently provides higher impedance.

TC = RC

Where: TC = Time constant for the circuit

R = Resistance in ohms through which the capacitor change

C = Value of capacitor in farads.

k. When a capacitor is connected to a DC source, the plates of the capacitor rapidly charge up to the voltage of the source. Energy taken from the source is stored in the electrostatic field between plates. Nothing further happens after the brief charging pulse and current ceases when potential between plates rises to the same value as the source. A capacitor, therefore, is an effective barrier to direct current.

l. When a capacitor is connected to an AC source, the plates become charged, discharged, and charged again in the opposite direction. This is done in rapid sequence and accordance with the alternating polarity of applied voltage. Electrons surging on and off the capacitor plates give rise to an alternating current that appears to flow "through" the capacitor. A capacitor, therefore, does not bar flow of alternating current, but does offer opposition to current.

m. The term used to describe opposition to current flow caused by capacitance of a circuit is capacitive reactance (X_C). Capacitive reactance is measured in ohms, as is resistance. In a purely capacitive AC circuit (no resistance or inductance) capacitive reactance replaces resistance in Ohm's law.

n. A method similar to one used to determine an equation for inductive reactance can be used for capacitive reactance. The result of the process is:

$$X_C = \frac{1}{2\pi fc}$$

where, X_C = Capacitive reactance in ohms;

π = 3.14

f = frequency of applied voltage in hertz

C = Capacitance in farads.

o. Example: What is the capacitive reactance of a capacitor operating at a frequency of 60 hertz, with a capacitance of 133 microfarad?

p. Answer:

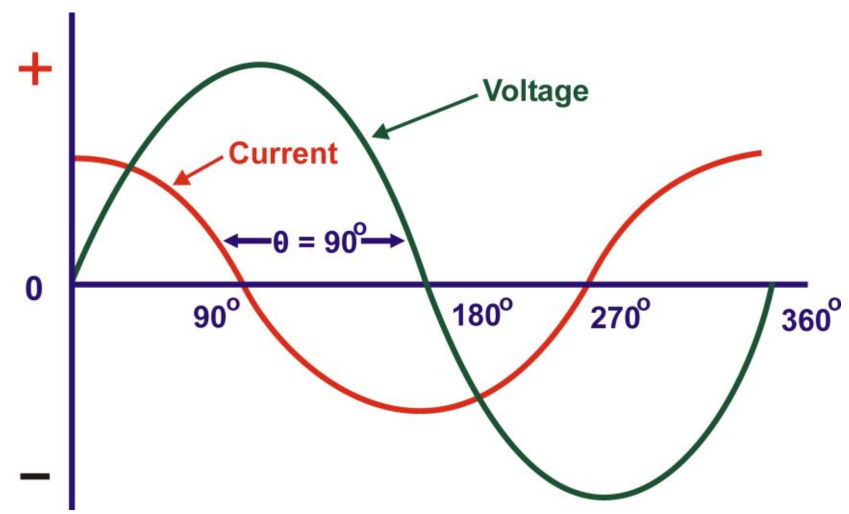
1) Convert microfarads.

$$133\mu f \, x \, \frac{1 farad}{10^6 \, \mu f} = 1.33x10^{-4} \, f$$

2) Solve for X_C.

$$X_c = \frac{1}{2\pi fc} = \frac{1}{2(3.14(60(1.33x10^{-4})))} = 20\Omega$$

q. If the frequency increases, capacitive reactance decreases. Current is greatest when the capacitor first starts to charge as there is little opposition to current flow. As the capacitor charges, current flow decreases due to increasing opposition until the capacitor is fully charged and current is zero (infinite opposition). If frequency increases, the capacitor undergoes the charging phase more often per unit time. The capacitor develops less opposing voltage as it is being charged because the circuit does not have enough time to create it. Therefore, opposition to current flow has decreased. The extreme example of this is that the lowest frequency possible is no frequency, or DC. After a brief charging period, current decreased to zero. This means capacitive reactance must be infinite (4). Capacitance opposes an instantaneous change in voltage. Current flowing "through" a capacitor at any instant depends on the rate voltage across it is changing. Therefore, with AC voltage applied, current is maximum when voltage is crossing zero axis, because voltage is then climbing or falling most rapidly. When applied voltage is at maximum, it is no longer changing, and current falls to zero. This relationship is shown in Picture 23.

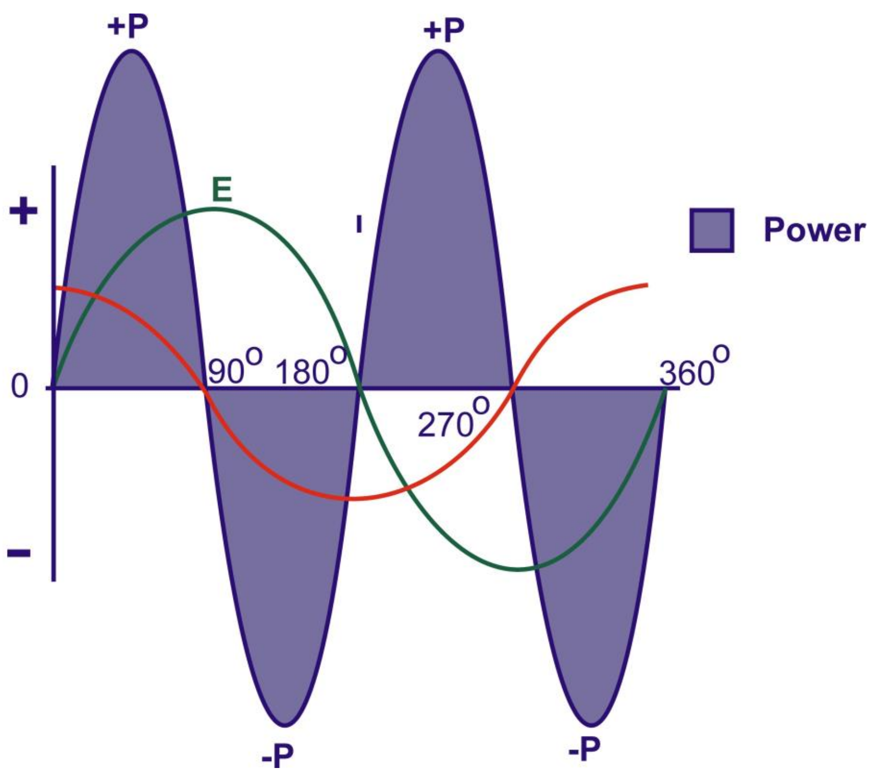


Picture 23, Graph of Applied Voltage and Current in a Purely Capacitive Circuit

r. When voltage is first applied, the uncharged capacitor immediately draws a large charging current. As potential difference between plates reaches the value of applied voltage, current drops to zero. A capacitor cannot be charged to a voltage higher than that applied. Current is greatest at the beginning of the voltage cycle and becomes zero at the maximum value of voltage. As applied voltage starts to decrease from peak value, the capacitor begins to discharge became the capacitor voltage is greater than applied voltage, and current flows in the opposite direction. This shows that current leads applied AC voltage by 90° in a purely capacitive circuit. Therefore, the phase angle (θ) of a purely capacitive circuit would be 90° in the leading direction or -90° from reference zero.

s. Returning to the mnemonic device "ELI the ICE man," discussed earlier, the ICE term relates the relationship between current (I) and voltage (E) in a capacitor (C). In a capacitive circuit current leads voltage.

t. Picture 24 illustrates the plot of power produced when instantaneous rms values (of voltage and current in pure capacitance) are multiplied at points along the time axis.



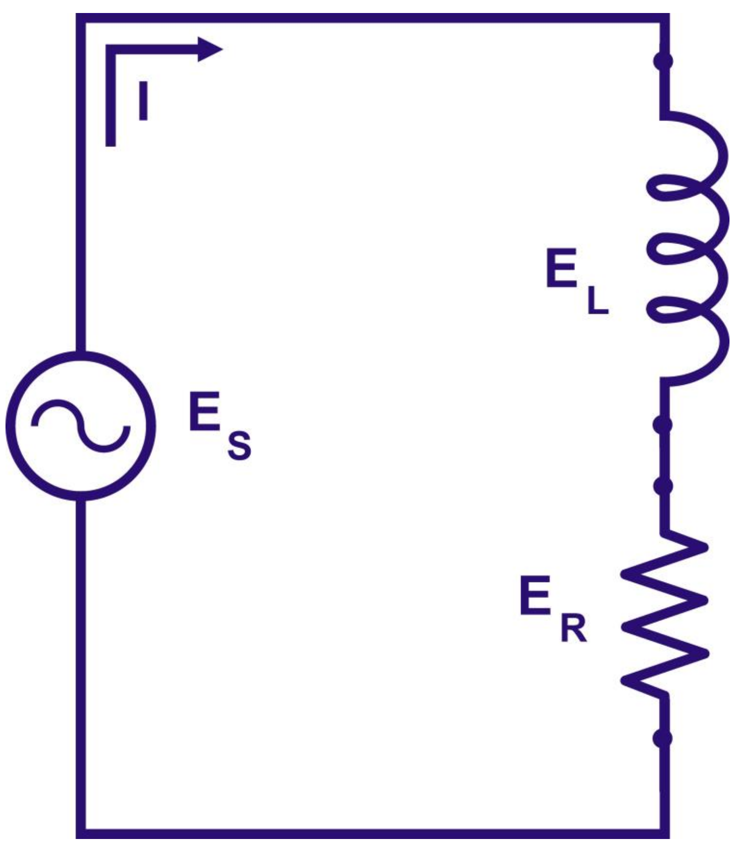
Picture 24, Graph of Power in a Pure Capacitance

u. This power curve has two positive and negative loops during one complete cycle of AC voltage, exactly as with that resulting from a load of pure inductance (Picture 17). Hence, no net power is consumed. Power is supplied to the capicitor and stored in its electric field during one quarter (charging) cycle. The same amount is returned during the next quarter-cycle of capacitor discharge. In any capacitor, a tiny amount of power is consumed by charge leakage between plates.

12. Impedance

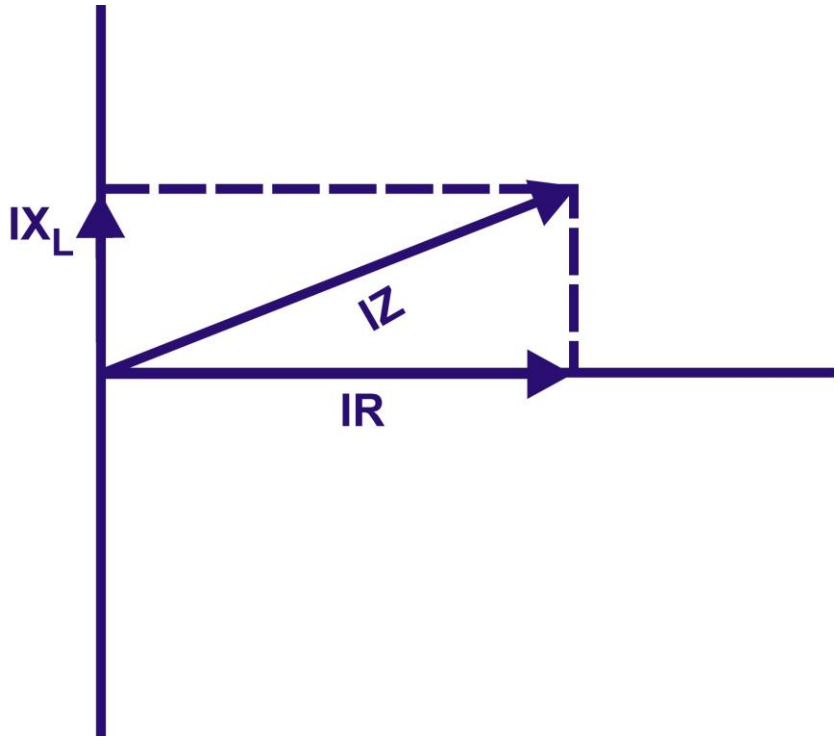
a. In a circuit, alternating current containing only resistance is in phase with applied AC voltage, while current in pure inductance lags applied voltage by 90°. In pure capacitance, current leads applied voltage by 90°. What happens when alternating voltage is applied to a circuit containing a combination of resistance and inductance, resistance and capacitance, or all three? The resulting alternating current would adjust itself to some value and assume a phase angle with respect to voltage somewhere between the extremes (□90°), depending upon amounts of resistance, inductance, and capacitance in the circuit. The combined opposition of resistance, inductive reactance, and capacitive reactance to alternating current is called impedance (Z).

b. In a series inductor-resistor circuit (Picture 25), the sum of voltage drops across the inductor and resistor must equal the source voltage (Kirchhoff's voltage law) and current is the same in all components.



Picture 25, Series inductor-resistor AC circuit

c. Voltage across the inductor leads the circuit current by 90° and is in phase with the current across the resistor. The voltage across each component, using Ohm's law, is IXL for the inductor, IR for the resistor and IZ for the source. These voltages are shown Picture 26, referenced to circuit current.



Picture 14, Voltage in series inductor-resistor

d. AC circuit

e. An equation can be written for the voltages, using the Pythagorean theorem.

$$(IZ)^2 = (IR)^2 + (IX)^2$$
$$I^2Z^2 = I^2R^2 + I^2X_L{}^2$$

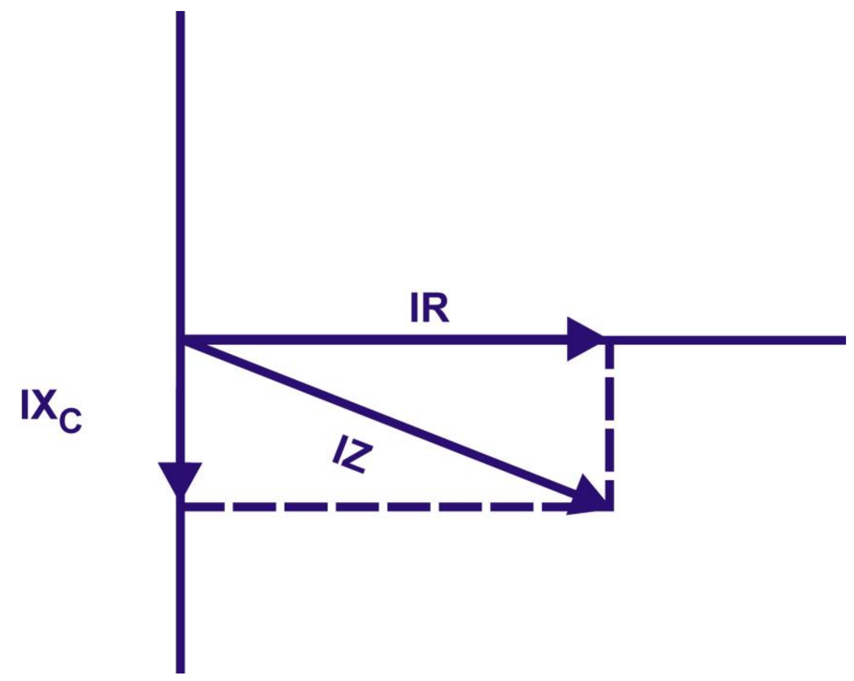
f. Because current is equal in all series circuit components, divide by I^2.

$$Z^2 = R^2 + X_L{}^2$$

g. Solve for impedance, Z:

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

h. Similar reasoning can be used to develop an equation for a series capacitor-resistor AC circuit. The voltage across the capacitor lags circuit current by 90° (Picture 27).

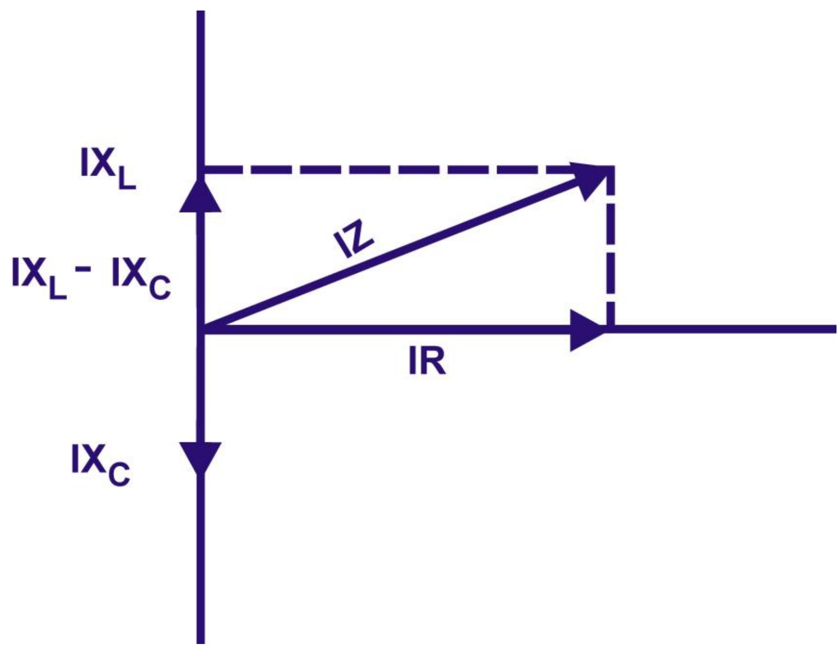


Picture 15, Voltage in series capacitor-resistor AC Circuit

i. While the voltage across the capacitor is "negative," the solution for impedance is:

$$(IZ)^2 = (IR)^2 + (IX_C)^2$$
$$I^2Z^2 = I^2R^2 + I^2X_C{}^2$$
$$Z^2 = R^2 + X_C{}^2$$
$$Z = \sqrt{R^2 + X_C{}^2}$$

j. In a series inductor-resistor-capacitor circuit, the voltage across the capacitor is subtracted from the voltage across the inductor (180° out of phase); the result is then combined with voltage across the resistor (Picture 28).



Picture 16, Voltage in series inductor-resistor capacitor AC Circuit

k. A solution for the circuit impedance (Z) is:

$$(IZ)^2 = (IR)^2 + (IX_L - IX_C)^2$$
$$I^2Z^2 = I^2R^2 + I^2(X_L - X_C)^2$$
$$Z^2 = R^2 + (X_L - X_C)^2$$
$$Z = \sqrt{R^2 (X_L - X_C)^2}$$

l. Impedance of a series resistance-reactance circuit must be determined vectorally. The above equation is vector addition of series circuit resistance and reactance.

m. Example: If a series 60Hz AC circuit has total resistance of 1000 Ω, total capacitance of 12μf, and total inductance of 6h, what is the circuit's impedance?

n. Answer:

1) Determine the inductive reactance.

$$X_L = 2\pi fL = 2 \text{ x } 3.14 \text{ x } 60 \text{ x } 6 = 2261\ \Omega$$

2) Convert capacitance to farads.

$$12\,\mu f \text{ x } \frac{1f}{10^6\,\mu f} = 1.2 \text{ x } 10^{-5}\ f$$

3) Determine the capacitive reactance.

$$X_C = \frac{1}{2\pi fc} = \frac{1}{2 \text{ x } 3.14 \text{ x } 60 \text{ x } 1.2 \text{ x } 10^{-5}}$$

$$= 221\Omega$$

4) Solve for total impedance.

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

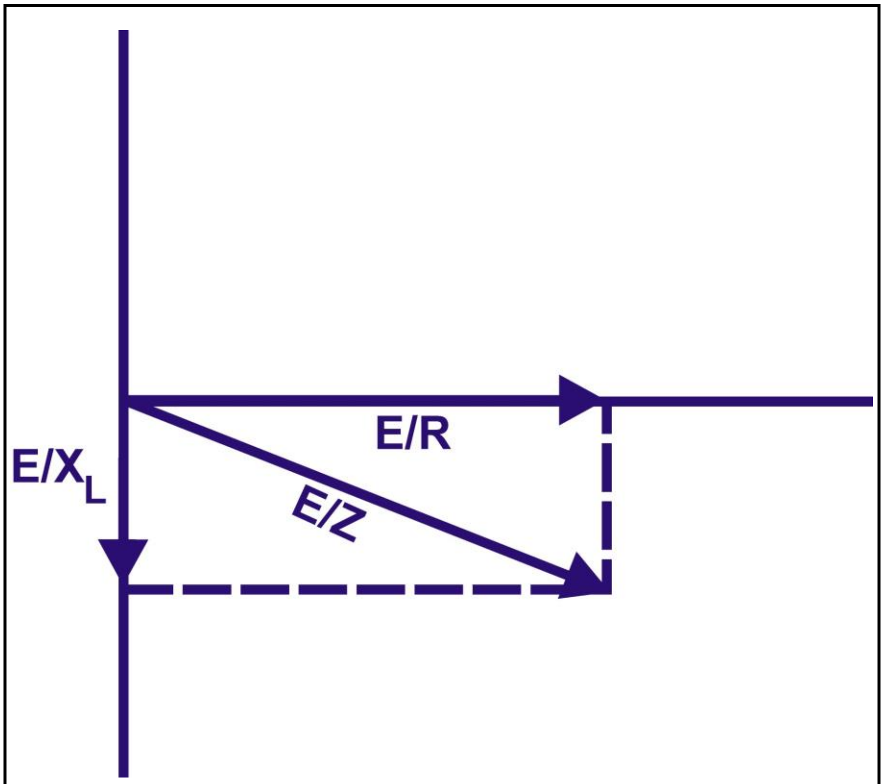
$$= \sqrt{(1000)^2 + (2261 - 221)^2}$$

$$= \sqrt{(1000)^2 + (2040)^2} = \sqrt{10^b + 4.16 \text{ x } 10^b}$$

$$= \sqrt{5.16 \text{ x } 10^b}$$

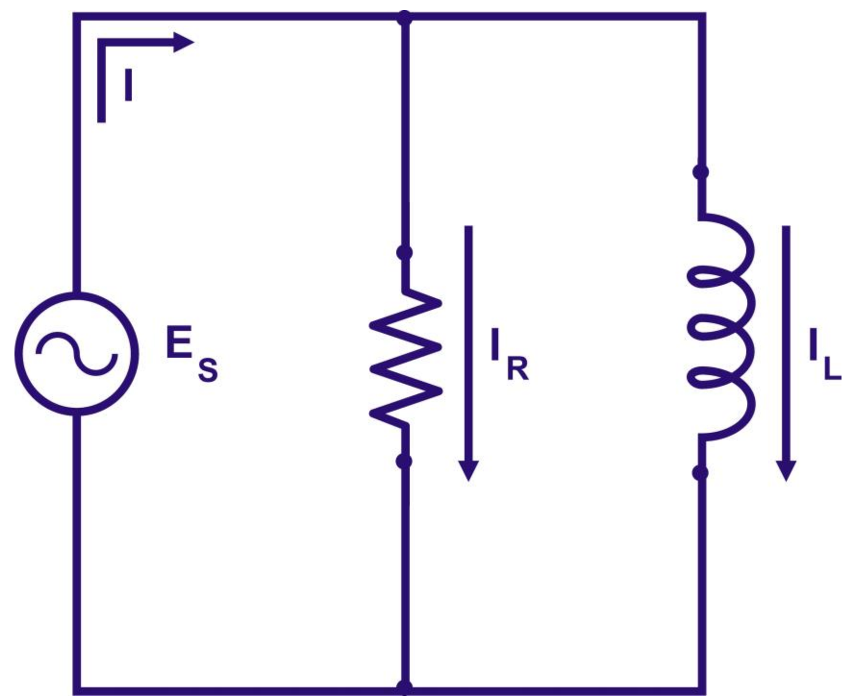
Therefore, Z = 2272Ω

o. In a parallel inductor-resistor circuit (Picture 29), the sum of currents through the resistor and inductor must equal the total current through the source (Kirchhoff's current law) and voltage is the same across all components.



Picture 29, Parallel inductor-resistor AC Circuit

p. Current through the inductor lags the voltage by 90°, and is in phase with the voltage across the resistor. Current through each component, using Ohm's law, is E/XL for the inductor, E/R for the resistor, and E/Z for the source. These currents are shown in Picture 30, referenced to circuit voltage.



Picture 17, Currents in parallel inductor-resistor AC circuit

q. An equation can be written for the branch currents, using the Pythagorean theorem.

$$\left(\frac{E}{Z}\right)^2 = \left(\frac{E}{R}\right)^2 + \left(-\frac{E}{X_L}\right)^2$$

$$\frac{E^2}{Z^2} = \frac{E^2}{R^2} + \frac{E^2}{X_L{}^2}$$

r. Because voltage is equal across all parallel components, divided by E^2.

$$\frac{1}{Z^2} = \frac{1}{R^2} + \frac{1}{X^2}$$

$$Z^2 = \frac{1}{\frac{1}{R^2} + \frac{1}{X_L{}^2}}$$

s. Solve for impedance:

$$Z = \frac{1}{\sqrt{\frac{1}{R^{L}} + \frac{1}{X_L{}^2}}}$$

t. Similar reasoning can be used to develop an equation for parallel capacitor-resistor AC circuits. The equation is:

$$Z \frac{1}{\sqrt{\frac{1}{R^2} + \frac{1}{X_C{}^2}}}$$

u. Likewise, the equation for impedance in a parallel inductor-resistor-capacitor circuit is:

$$Z = \frac{1}{\sqrt{\frac{1}{R^2} + \frac{1}{(X_C - X_L)^2}}}$$

v. Example: A 1000Ω resistor, 12µf capacitor, and a 6h inductor are placed in parallel in a 60HZ circuit. What is the circuit's impedance?

w. Answer:

1) From previous example:

$$X_L = 2261\Omega$$
$$X_C = 221\Omega$$

2) Solve for total impedance.

$$Z = \frac{1}{\sqrt{\frac{1}{R^2} + \frac{1}{(X_C - X_L)^2}}}$$

$$= \frac{1}{\sqrt{\frac{1}{1000^2} + \frac{1}{221 - 2261)^2}}}$$

$$= \frac{1}{\sqrt{\frac{1}{1000^2} + \frac{1}{(-2040)^2}}}$$

$$= \frac{1}{\sqrt{\frac{1}{10^6} + \frac{1}{4.1616x10^6}}}$$

$$= \frac{1}{\sqrt{10^{-6} + 0.24x10^{-6}}}$$

$$= \frac{1}{\sqrt{1.24x10^{-6}}} = \frac{1}{1.114x10^{-3}} = 0.898x10^3\ \Omega$$

x. Impedance in a parallel resistance-reactance circuit must be determined by vectors.

y. In a parallel circuit, the impedance increases as capacitive and inductive reactance get closer in value. If they are equal, impedance equals the resistor value.

z. Since most loads on the electrical grid are inductive, utilities insert large banks of capacitors for added capacitive reactance to counteract inductive reactance and lower grid impedance. Therefore, more power once lost to magnetic and electrostatic fields can be used for true resistive loads.

aa. Impedance also has a phase angle, in addition to magnitude. For now, the behavior of current related to the amount of resistance, inductive reactance, and capacitive reactance in a circuit can be summarized as:

Primary Circuit Characteristic	Relationship of Current and Voltage	
Inductive	Current will lead voltage	0 to 90° phase angle
Capacitive	Current will lag voltage	0 to 90° phase angle
Resistive	Current and voltage will be in-phase with one another	0° phase angle

E. AC Power

1. Definition of Power

   a. Power is rate of doing work. Recall from Chapter 2, in a DC circuit, power is the product of current and voltage. Units of measure for power are watt, kilowatt (1,000 watts), and megawatt (1,000,000 watts or 1,000 kilowatts). In DC circuits where voltage and current do not change direction, power consumed is always positive. But in AC circuits, current and voltage change direction (not always in phase), consequently, understanding and computation of power is more involved.

2. Apparent Power

   a. To the untrained eye, the power of an AC circuit would seem to be the product of voltage and current. The product of the rms values of voltage and current is called apparent power. It is measured in volt-amperes (VA), kilovolt-amperes (KVA), or megavolt-amperes (MVA).

$$P_a = I_r E_{ms}$$

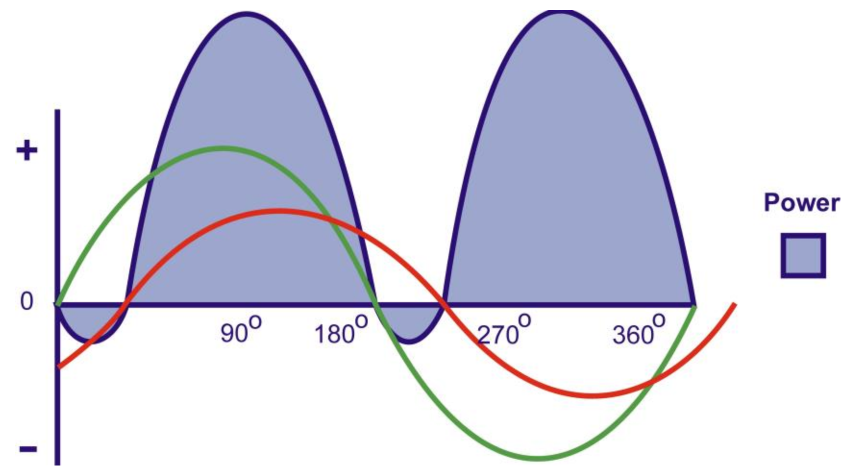
b. Most generators have an apparent power rating. Generator limits are based upon heating caused by total current flowing through the generator, not just the current used in the circuit it is supplying.

3. Real Power

a. Real power (or true power) is average power actually consumed by the load over one complete cycle. It is measured in watts.

b. Three elements affect current flow in an AC circuit: resistance, inductive reactance, and capacitive reactance. In power graphs for these elements, power consumed in a purely resistive circuit is equal to rms voltage times current (Picture 8), and power consumed in a purely inductive or capacitive circuit is zero (Picture 16 and 23). Most AC circuits contain a combination of resistance, inductance, and capacitance. Current usually assumes a phase angle somewhere between zero and 90° and some amount of power is consumed.

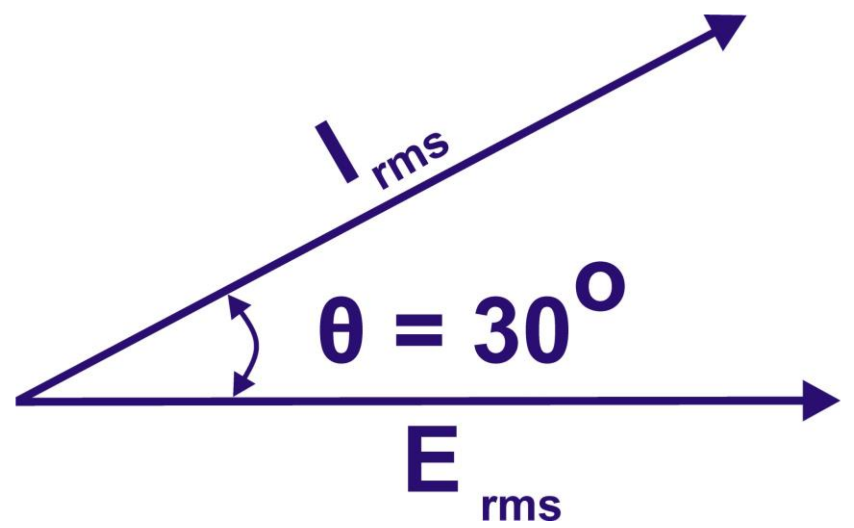
c. When the products of the instantaneous current and voltage are plotted for an intermediate phase angle (Picture 31, current lags voltage by 30°), the resulting power graph has positive lobes larger than the negative lobes. Power consumed by the circuit is then equal to the difference between the areas of the positive and negative power lobes.



Picture 31, Graph Showing Power When Current Lags Voltage by 30 Degrees

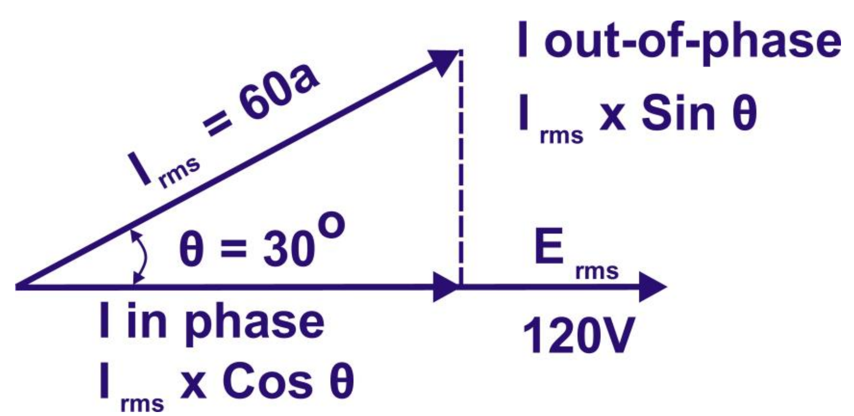
d. It is cumbersome to plot a power graph of instantaneous current and voltage values and then obtain power by finding difference between areas of positive and negative power lobes. The same results can be obtained far easier by drawing a vector diagram of the effective (rms) value of current and applied voltage, and then computing the amount of current in phase with the voltage. The product of voltage and in-phase current is the real power expended.

e. Picture 32 shows a vector diagram (current and voltage from Picture 31), with instantaneous current lagging voltage by a phase angle of 30 degrees.



Picture 32, Vector Diagram of Current Lagging Voltage by 30°

f. Value of I_{rms} is the resultant vector of the in-phase current vector and out-of-phase current vector. Picture 33 shows the current vectors.



Picture 33, Vector Diagram of Voltage and Current

g. True power requires that in-phase value of current and voltage be multiplied. Find the value of in-phase current ($I_{in\text{-}phase}$) by applying simple trigonometry, ($I_{in\text{-}phase}$) is equal to the cosine of the phase angle times the rms current. Therefore, true power expended in an AC circuit is:

$$P_t = IE\cos\theta$$

h. Example: The supply to a house is 110 volts rms and 100 amps rms. Current is lagging voltage by 25.8°. What is the maximum real power being supplied to the house?

i. Answer:

P_t = IE cos θ = 100 x 110 x .9

= 9900 watts or 9.9 kilowatts (kw)

j. Since the product of voltage and current must be multiplied by the cosine of the phase angle to obtain real power, cos θ is known as the power factor (pf) of the circuit. Rewriting the equation for AC power:

$$pf = \cos\theta = \frac{P_t}{IE} = \frac{P_t}{P_a}$$

k. The power factor of a single phase AC circuit is determined by dividing the wattmeter reading by the product of the voltmeter and ammeter readings.

l. Example: A small AC generator is supplying 50 amps at 110 volts to a house. The generator's power meter indicates 5000 watts. What is the power factor of the house loads?

m. Answer:

$$pf = \frac{P_t}{IE} = \frac{5000}{50\,x\,110} = 0.91$$

n. It cannot be determined if the current is leading or lagging voltage by power factor alone. Type of reactive power (inductive or capacitive) must also be known. If current is lagging voltage, as in an inductive dominant circuit, the power factor is a lagging power factor; if current is leading voltage, as in a capacitive dominant circuit, the power factor is a leading power factor.

o. If the circuit is purely resistive, the phase angle is 0°. The cosine of 0° is one, therefore, the real AC power in a purely resistive circuit:

$$P = 1 \text{ x } I \text{ x } E = IE$$

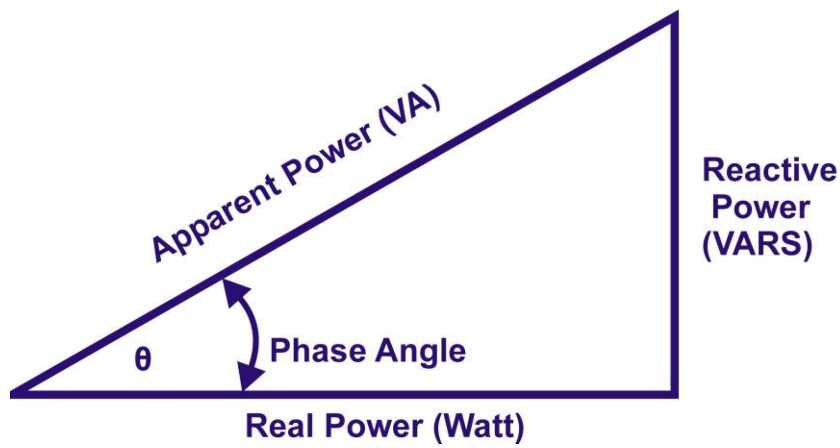
p. If the circuit is purely inductive, the phase angle is 90°. The cosine of 90° is zero, hence, the true power is zero.

q. This is also true for a purely capacitive circuit which has a phase angle of -90°. Because the cosine of -90° is zero, the power in a purely capacitive circuit is also zero.

4. Reactive Power

a. Three power relationships are shown by the power triangle, Picture 34. True (or real) power (IE cos θ), the actual power supplied (or consumed), is on the horizontal axis. Apparent power (E x I), expressed in volt-amperes, is the hypotenuse. It is the vector sum of true power and reactive power. Reactive power (Px), energy stored and returned by inductors and capacitors, is the vertical side. Reactive power, the units of which is VAR (volt-ampere reactive), is:

$$P_x = IE \sin\theta$$



Picture 34, Power Triangle

b. If the phase angle is positive, between 0 and 90 degrees (current lagging voltage) the sine of the phase angle is positive and reactive power is positive. The voltage source is supplying reactive power to an inductive dominant circuit. If the phase angle is negative, between 0 and -90 degrees (current is leading voltage), the sine of the phase angle is negative and reactive power is negative. The voltage source is either supplying reactive power to a capacitive dominant circuit or is acting as an inductive load on the circuit, requiring the circuit to supply its magnetic fields. Notice that the power factor is still positive ($\cos\theta = +$) which indicates the voltage source is still supplying real power to the circuit.

c. Example: A generator with a terminal voltage of 417 volts is supplying 139 amps of current (therefore, Pa= 57,963VA) which is lagging voltage by 26°. What is the phase angle, power factor, true power, and reactive power of the generator? (Assume that current and voltage are given in rms).

d. Answer:

1) Determine the phase angle: because current is lagging voltage, the phase angle must be positive; therefore, the phase angle must be + 26°.

2) Calculate the power factor:

$$\text{pf} = \cos\theta = \cos(+26°) = 0.8988 \cong 0.9$$

3) Compute true power:

$$P_t = IE\cos\theta = IEpf = P_a \text{ x pf}$$
$$57{,}963 \text{x } 0.9$$
$$= 52{,}167 \text{watts}$$

4) Calculate reactive power:

$$P_x = IE\sin\theta = P_a \text{ x} \sin\theta = 57{,}963\text{x } 0.4384 = 25{,}411 \text{VARS}.$$

e. Example: The same generator used in previous example has a terminal voltage of 417 volts and is supplying 139 amps resulting in an apparent power of 57,963VA. Now, the current is leading voltage by 26°. What is the phase angle, power factor, true power, and reactive power of the generator?

f. Anwer:

1) Determine the phase angle: because current is leading voltage, the phase angle must be negative by the convention set up. Therefore, the phase angle must be - 26°.

2) Calculate the power factor:

$$\text{pf} = \cos(-26°) = 0.8988 \text{or } 0.9 \text{roundedoff}.$$

3) Compute true power factor:

$$P_t = IE\cos\theta \, IEpf = 57{,}963 \text{x } 0.9$$
$$= 52{,}167 \text{watts}$$

4) Calculate reactive power:

$$P_x = IE\sin\theta = P_a \, x \sin\theta = 57{,}963x\,0.4384 = -25{,}411VARS$$

F. In Summary

1. Concepts and principles behind alternating current, voltage, and power are used throughout the generating station. When an AC pump is started or a bus is energized, the concept of impedance and its effect on the of various AC powers becomes vitally important.

2. Alternating current (AC) differs from direct current (DC) in that AC varies between some given positive and negative values. The advantage that AC has over DC is lower line losses (I^2R losses). Because of higher transmission voltage, it can be transmitted over a much greater distance.

3. The AC sine wave is actually one full cycle, positive and negative alternation. The number of cycles completed in a second is the frequency. Five different values can be used to describe magnitude of AC voltage or current. The peak value is the maximum obtained by voltage or current in both positive and negative directions. The difference between positive and negative peaks is the peak-to- peak value. Instantaneous value is the value at any point in time during armature rotation. By multiplying the peak value by 0.637, the average value of current or voltage is found. The most useful voltage and current value is the effective, or rms, value. The rms value can be determined by multiplying the peak value by 0.707. It is the amount of alternating current required to produce the same amount of heat in a given resistance as is produced by direct current. The rms values of voltage and current simplify resistance calculations. Five volts AC rms produces the same amount of power in a one ohm resistor as five volts DC.

4. The relationship between rise and fall of voltage and current is called phase angle. If voltage and current rise and fall together and reach their peaks at

the same time, they are in-phase. If the rise in voltage leads the rise in current, current lags voltage by the time difference between the two and has a positive phase angle. If current rises prior to voltage, current is leading voltage and the phase angle is negative by the time difference in degrees.

5. Inductance is the property of an AC circuit to resist an instantaneous change in current and is measured in henrys, (h). Self-inductance is the process by which a current-carrying conductor's magnetic field induces emf upon itself. Mutual induction is the process by which a current carrying- conductor's magnetic field induces emf in a separate conductor. Inductors follow the same rules for series and parallel combinations as resistance. The opposition an inductor imposes upon alternating current is called inductive reactance. Inductive reactance is measured in ohms and combines in the same manner as resistance. An inductor causes current to lag applied voltage by 90°. The phase angle for a purely inductive circuit would be +90°.

6. Capacitance is the property of an AC circuit to resist an instantaneous change in voltage and is measured in farads, (f). A capacitor stores energy in the electrostatic field of its dielectric instead of using a magnetic field. Capacitors in series combine like resistances in parallel. Capacitors in parallel combine like resistances in series. The opposition a capacitor imposes upon alternating current is called capacitive reactance. A capacitor causes current to lead voltage by 90□. The phase angle for a purely capacitive circuit would be -90°.

7. Impedance is combined opposition to current flow by total resistance, inductive reactance, and capacitive reactance in an AC circuit. Impedance of a circuit has both magnitude and phase, angle.

8.

9. Current and voltage phase relationships produce three types of AC power. Real power is power actually consumed by the circuit and measured in watts. To find the value of real power, it is necessary to multiply rms values of current and voltage by the cosine of the phase angle (called power factor). The product of rms values of current and voltage is called apparent power and is measured in volt-amperes. The vector of real power added to a vector of reactive power gives the resultant vector of apparent power. Reactive power is power stored in inductive and capacitive fields. The value of reactive power can be found by multiplying rms values of current and voltage (apparent power) by the sine of the phase angle and is measured in vars. If vars are positive, the voltage source is supplying energy to inductive fields of a primarily inductive external circuit. If vars are negative, the voltage source is either supplying energy to capacitive fields of a primarily capacitive external circuit or the external circuit is supplying inductive fields inside the voltage source.
10. By using DC circuit analysis learned previously, along with the knowledge of inductors, capacitance, impedance, and vector addition it is possible to solve problems involving series and parallel AC circuits.
11. Concepts and principles in this chapter will be used in future chapters about AC equipment. You will learn to parallel two AC generating machines and properly balance reactive loads. Concepts of mutual inductance will be required to discuss operation of transformers.

PRACTICE:

1 What is alternating current?

2. Which type of current was most widely used first, AC or DC.