

# Introduction to Electricity

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# 1. Basic Electrical Concepts

- Matter : Anything that has mass and occupies space
- Element : Any substance that can not be broken down into two or more simpler substances; carbon, oxygen
- Atom : The smallest particle of matter that retains the physical characteristics of an element
  
- Bohr Model : The simplest model of atom
- Nucleus : The central core of atom, contains proton and neutron
- Electrons : Particles that orbit the nucleus of an atom  
Every electron has both an electric charge(negative) and a magnetic field
  
- Atomic Number : Equal to the number of protons
- Shells : Electron orbital paths that circle the nucleus, each contains  $2n^2$  electrons
- Valance Shell : The outermost orbital path for a given atom,  
it is complete if there are 8 electrons

- Charge : An electrical force that causes two particles to be attracted to, or repelled from, each other
- Protons have a positive charge and electrons have a negative charge
- Positive Ion: An atom with a net positive charge, after losing electron
- Free Electron: One that is not bound to an atom and is free to drift from one atom to another

- Current : The directed flow of charge through a conductor
- Voltage : A force that generates the flow of electrons (current)
- Resistance : The opposition to current provided by a material, component or circuit

- The intensity of current , the amount of charge flowing per second

$$I (\text{ampere}) = \frac{Q}{t} = \frac{\text{coulomb}}{\text{second}}$$

- Coulomb is the total charge on  $6.25 \times 10^{18}$  electrons
- Electron flow theory defines current as the flow of electrons from negative to positive
- Conventional current theory defines current as the flow of electrons from positive to negative
- DC : current is in one direction only
- AC : current continually changes direction

- Voltage is a difference of potential that generates current, is a force that moves electrons electric force(E), electromotive force (EMF)
- Amount of electrical force that uses how much energy to move a per charge.

$$V (\text{volt}) = \frac{\text{joule}}{\text{coulomb}} = \frac{J}{C}$$

- One ohm is the amount of resistance that limits current to one ampere when one volt of electrical force is applied

- Conductor : Extremely low resistance, conducts with very little voltage applied, copper, silver, aluminum
  - Insulator : Extremely high resistance, conducts only when an extremely high voltage is applied, rubber, teflon, mica
  - Semiconductor : Midway between conductor and insulator, limits current at a given voltage, graphite, silicon
- 
- Conductivity : The ease with which an element or compound conducts electricity
  - The fewer valence shell electrons, the easier to force the atom to give up free electrons
  - The best conductors contain one valence electron per atom
  - With more atoms per unit volume a given voltage generate more free electrons
- 
- Insulators blocks current, has complete valence shells (8 electrons ), relatively few atoms per volume
  - Semiconductors' valence shells are half complete (4 electrons), relatively high number of atoms per volume
- 
- Resistivity is the resistance of a specific volume of an element ( $\Omega - cm$ ) (özdirenç)
- $$R = \rho \frac{\ell}{A}$$
- Resistivity of some materials  

silver < copper < gold < aluminum < iron < carbon



## 2. Ohm's Law and Power

- George Simon Ohm, German physicist, states that current is directionally proportional to voltage and inversely proportional to resistance

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

- Power : Amount of energy used per unit time

$$\text{watt} = \frac{\text{joule}}{\text{second}}$$

- Watt's Law

$$P = I \times E$$

- Transducer : A device that converts energy from one form to another
- Efficiency : The ratio of circuit output power to input power, given as percentage
- Energy measurement : determined by measuring the amount of power used and the time over which it is used
- 1 Kilowatt-Hour (kWh): The amount of energy used by a 1000W device for one hour

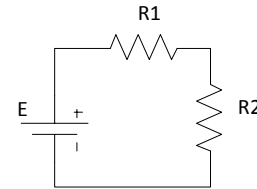
# 3. Series Circuits

- Series Circuit : A circuit that contains only one current path

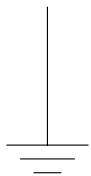
$$R_T = R_1 + R_2 + \dots + R_n \quad E = V_1 + V_2 + \dots + V_n \quad P = P_1 + P_2 + \dots + P_n$$
$$I_T = \frac{E}{R_T} = I_1 = I_2$$

- Kirchhoff's Voltage Law states that the sum of the component voltages of a series circuit must equal the source voltage
- Ground (or Common) : A point that serves as the reference for all voltages in the circuit
- Voltage Drop : Change from one potential to a lower potential
- Voltage Divider : Source voltage is divided among the components in the circuit.

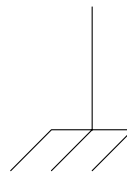
$$V_{RN} = E \times \frac{R_n}{R_T}$$



- Overload : A high current circuit
- Catastrophic Failure : The complete (and sometimes violent) failure of a component



Earth Ground  
provides a physical connection to the earth  
via grounding electrode



Chassis Ground  
does not provide a physical connection to the earth  
0V reference for the components

# 4. Parallel Circuits

- Parallel Circuit : A circuit that provides more than one current path between any two points
- Branch : Each current path in a parallel circuit

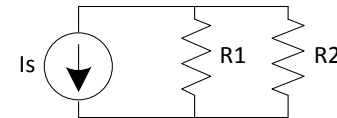
$$I_T = I_1 + I_2 + \dots + I_n \quad E = V_{R1} = V_{R2} = \dots = V_{Rn} \quad P = P_1 + P_2 + \dots + P_n$$

$$R_T = \frac{E}{I_T} = R_1 || R_2 = \frac{R_1 \times R_2}{R_1 + R_2}$$

- Current Divider: A parallel circuit which divides the source current among its branches
- Kirchhoff's Current Law  
states that the current leaving any point in a circuit must equal the current entering the point
- Node : A point connecting two or more current paths.
- Current Source : A source that provides an output current value that  
remains relatively constant over a wide range of load resistance values
- Current Divider : Source current is divided among the components in the circuit.

$$I_n = I_S \times \frac{R_T}{R_n} = I_S \times \frac{R_1 || R_2}{R_n}$$

$$I_{R1} = I_S \times \frac{R_2}{R_1 + R_2}$$



- Load : The current demand on the output of a circuit
- Overload : A load that exceeds the design limits of a circuit
- Surge : A sudden and momentary current overload, commonly caused by the startup of a machine

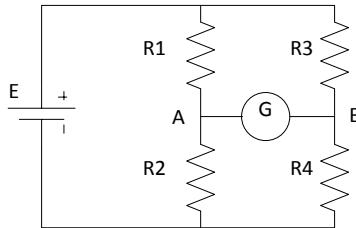


# 5. Series - Parallel Circuits

- Equivalent Circuit : A circuit derived by combining groups of parallel and/or series components in one circuit to obtain an equivalent simpler circuit
- No-Load Output Voltage : The voltage measured at the load terminals of a circuit with the load removed  
This is the max. output voltage produced by the circuit
- Voltmeter Loading : The reduction in component voltage that can result from connecting a voltmeter across a relatively high-resistance (or open) component
- Wheatstone Bridge : A circuit containing four resistors and a meter “bridge” that provides extremely accurate resistive measurements
- Galvanometer: A current meter that indicates both the magnitude and direction of a low-value current

$$V_A = E \times \frac{R_2}{R_1 + R_2}$$

$$V_B = E \times \frac{R_3}{R_3 + R_4}$$



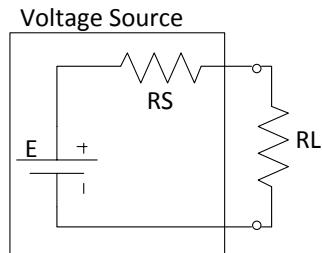
$$V_A (>, <, =, ) V_B$$

$$\frac{R_2}{R_1} (>, <, =, ) \frac{R_4}{R_3}$$

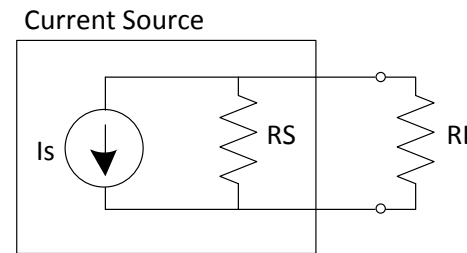
- Wheatstone bridge places of use: measuring of a resistance, temperature alarm circuit...
- Decade Box : A device contains several series-potentiometers that allows the resistance value between 1 Ω -10M Ω
- Potentiometer : Three terminal resistor, adjustable voltage divider
- Thermistor : A component whose resistance varies with temperature

# 6. Source and Load Analysis

- Network Theorems : Analysis techniques that are used to solve specific types of circuit problems
- Load Analysis : Analyzing the effect that a change in load has on the output from a voltage or current source



Source resistance  
typically less than 50  $\Omega$

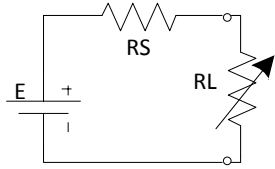


Source resistance  
typically high k $\Omega$  range

- Thevenin's Theorem states that any resistive network can be represented as a voltage source ( $E_{TH}$ ) in series with a source resistance ( $R_{TH}$ )
- $E_{TH}$  is equal to no-load output voltage  $V_{NL}$  (voltage at the output terminals with load removed)
- $R_{TH}$  load removed and source shorted.
- Norton's Theorem states that any resistive network can be represented as a current source ( $I_N$ ) in parallel with a source resistance ( $R_N$ )
- $I_N$  load removed and an ammeter ( $0\Omega$  resistance) is connected across the load terminals, shorting load terminals
- $R_N$  load removed and source shorted.

$$R_{TH} = R_N \quad I_N = \frac{E_{TH}}{R_{TH}}$$

- Maximum Power Transfer Theorem: maximum power transfer from a voltage source to its load occurs when the load resistance is equal to the source resistance



Max Power is obtained while  $R_S = R_L$   
But in this case, efficiency is %50.

- Superposition Theorem: The response of a circuit to more than one source can be determined by analyzing the circuit's response to each source and combining results
- Superposition theorem can not be applied to circuits with voltage (or current) controlled resistance values (solid state electronic circuits)



# 7. Magnetism

- Magnetic Flux ( $\Phi$ ) : The lines of force produced by a magnet
- Maxwell (Mx) : A unit of measure of magnetic flux, equal to 1 line of flux

$$1 \text{ Weber (Wb)} = 10^8 \text{ Mx} \quad 1 \text{ Mx} = 1 \text{ line of flux} \quad 1 \mu\text{Wb} = 100 \text{ Mx}$$

- Magnetic Field : The are of space surrounding a magnet that contains magnetic flux
- The strength of magnet depends on: the field size and the amount of flux it contains
- Flux Density ( $B$ ) : An indicator of magnetic strength

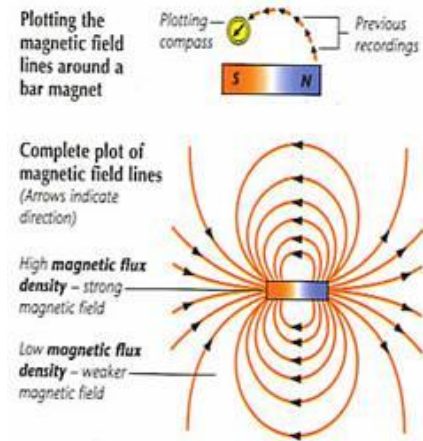
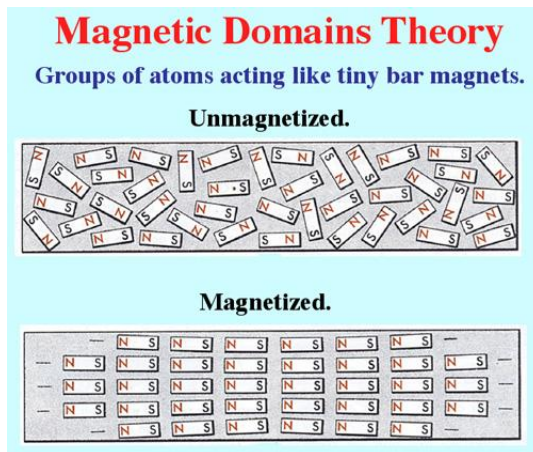
$$B = \frac{\Phi}{A} = \frac{\text{Wb}}{\text{m}^2} = \text{Tesla (T)}$$

- Permeability ( $\mu$ ) : A measure of the ease with which lines of magnetic force are established within a material  
Higher permeability, the easier to produce magnetic lines of force (transformer design)  
(mıknatıs geçirgenliđi)

- Relative Permeability ( $\mu_r$ ) : ratio to free of space (unit free),  $\mu_0 = 4\pi 10^{-7} \frac{\text{Wb}}{\text{A}\cdot\text{t}\cdot\text{m}} \left[ \frac{\text{Henry}}{\text{m}} \right]$

## The Source of Magnetism: Domain Theory

- Every electron has both an electric charge(negative) and a magnetic field
- Electric charge is always negative and is offset by a matching positive charge in the nucleus
- Each electron spins in clockwise or counterclockwise direction
- When atom contains equal number of electrons spinning in each direction, their magnetic fields cancel each other, atom does not generate magnetic force
- Domain theory : Atoms with like magnetic fields will join together to form magnetic domains  
Each domain acts as a magnet, with two poles and a magnetic field  
In an nonmagnetized material, the domains are randomly positioned, no net magnetic force  
If the domains are aligned, the material generates magnetic force



- Induction : Producing a magnet by aligning magnetic domains using an external force
  - Most magnets are artificially produced in three ways
    1. by permanent magnet motion over the object
    2. by placing near the object
    3. by a strong DC current through coil over the object
- } Magnetic induction
- Magnetic Induction : Using magnetic field to align magnetic domains (methods 1 and 2)

Higher permeability, easier to align magnetic domains, easier to magnetize, but magnetic strength quickly fades  
 Low-permeability materials difficult to magnetize, but tend to keep magnetic strength for a long time

- Retentivity ( $B_r$ ): The ability of an artificial magnet to retain its magnetic characteristics
  - high-retentivity materials (hardened steel) : to produce permanent magnet
  - low-retentivity materials (soft iron) : temporary magnets

- Reluctance : The opposition that a material presents to magnetic lines of force(magnetic flux)  
 Magnetic resistance

$$\mathfrak{R} = \frac{\ell}{\mu A} = \frac{\text{length}}{\text{permeability} \cdot \text{area}} = \frac{A \cdot t}{Wb} = \frac{1}{\text{Henry}} = \frac{1}{\text{Permeance}(P)}$$

- This Henry unit is different from the inductance Henry. Permeance is analogous to electric conductance.

| Materials                         | Ferromagnetic       | Paramagnetic            | Diamagnetic                |
|-----------------------------------|---------------------|-------------------------|----------------------------|
| Relative Permeability ( $\mu_r$ ) | $\gg 1$             | $> 1$                   | $< 1$                      |
| Retentivity ( $B_r$ )             | Low                 | Moderate                | High                       |
| Reluctance ( $\mathfrak{R}$ )     | Low                 | Moderate                | High                       |
|                                   | Magnetic            | Slightly magnetic       | Nonmagnetic                |
| Example                           | Iron, Steel, Nickel | Aluminum, Air, Platinum | Copper, Silver, Gold, Zinc |

- In 1820, Danish physicist Hans Christian Orsted discovered that electric current produces magnetic field
- He found that compass always aligned itself at  $90^\circ$  angles to a current carrying wire
- Left hand rule: fingers shows the direction of the flux, thumb points the direction of current ← conductor case
- Left hand rule → electron flow method
- Right hand rule → conventional method
- Coil (Bobin) : A wire wrapped into series of loops for the purpose of concentrating magnetic flux
- Core (Nüve) : The space in the center of a coil
- Left hand rule: fingers shows the direction of current, thumb points the direction of the flux ← coil-core case

- Magnetomotive Force ( $F$ , mmf) : The force that generates magnetic flux in a material that has reluctance  
Magnetic counterpart to emf.
- Rowland's Law: magnetic counterpart of Ohm's law

$$\Phi = \frac{F}{\mathfrak{R}} = \frac{A \cdot t}{A \cdot t / Wb} = Wb$$

- Ampere-Turns ( $A \cdot t$ )  
mmf produced by a coil is proportional to  
current through the coil and the number of turns

$$mmf = N \cdot I$$

- Flux density:

$$B = \frac{\Phi}{A} = \frac{F / \mathfrak{R}}{A} = \frac{NI / \frac{\ell}{\mu A}}{A} = \frac{\mu NI}{\ell} \quad B = \frac{\frac{Wb}{A \cdot t \cdot m} A \cdot t}{m} = \frac{Wb}{m^2} = T$$

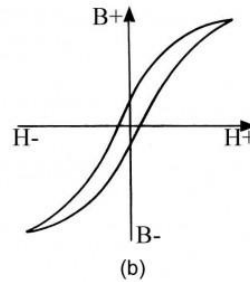
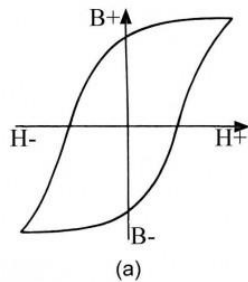
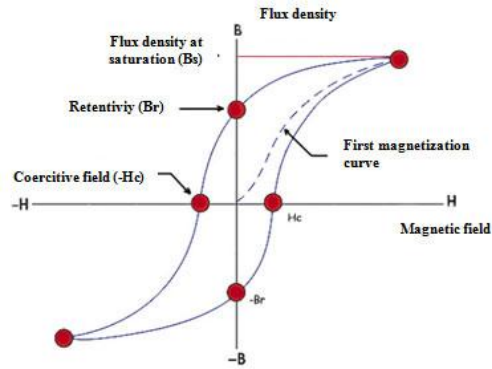
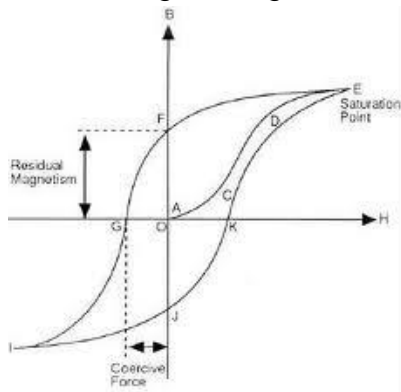
$$B = \mu H$$

- Magnetic field strength  $H$

$$H = \frac{NI}{\ell} = \frac{A \cdot t}{m}$$

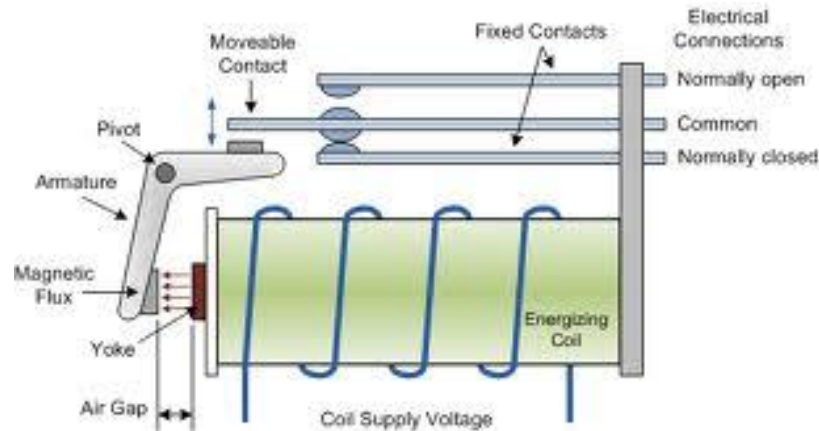


- Hysteresis: The time lag between removal of a magnetizing force and the resulting drop in flux density (is the dependence of a system not only on its current environment but also on its past environment)
- Magnetization Curve : Flux density (B) as a function of field strength (H)
- Residual Flux Density : The flux density that remains in a material after a magnetizing force is removed
- Coercive Force : The magnetizing force required to return the residual flux in a material to zero



- (a) the hysteresis loop for hard magnetic material suitable for permanent magnet, hardened steel  
 (b) the hysteresis loop for soft magnetic material suitable for a transformer core ,soft iron

- Relay : A switch that is opened or closed by an input
- Electromagnetic Relay
  - Allow a high-value current with a low-value current control signal
  - Complete electric isolation between source and load circuits
  - Can be heard switching on and off, troubleshooting



Physical breakdown risk, dirty contacts problem

Slower than electrical switches

Produce a reverse voltage (counter or kick emf) that can damage other components during switching

# 8. Inductance and Inductors

## ➤ Review : Current & Magnetic Flux

- Current through wire generates magnetic lines of force (flux)
- When a wire is wrapped in series of loops, coil, the lines of force add together
- The strength of magnetic field is determined by  $NI/l$  ( $A \cdot t/m$ )
- The polarity of the flux determined by the current direction

## ➤ Inductor is simply a coil, a wire wrapped into series of loops

permeability depends to the type of material

$N$  and  $\ell$  are the physical characteristics of coil

Only current can be easily changed

$$B = \frac{\Phi}{A} = \frac{F/\mathfrak{R}}{A} = \frac{NI/\frac{\ell}{\mu A}}{A} = \frac{\mu NI}{\ell} \quad B = \frac{\frac{Wb}{A \cdot t \cdot m} A \cdot t}{m} = \frac{Wb}{m^2} = T$$

## ➤ Inductance : The ability of a component to induce a voltage across itself

or a nearby circuit by generating a changing magnetic field

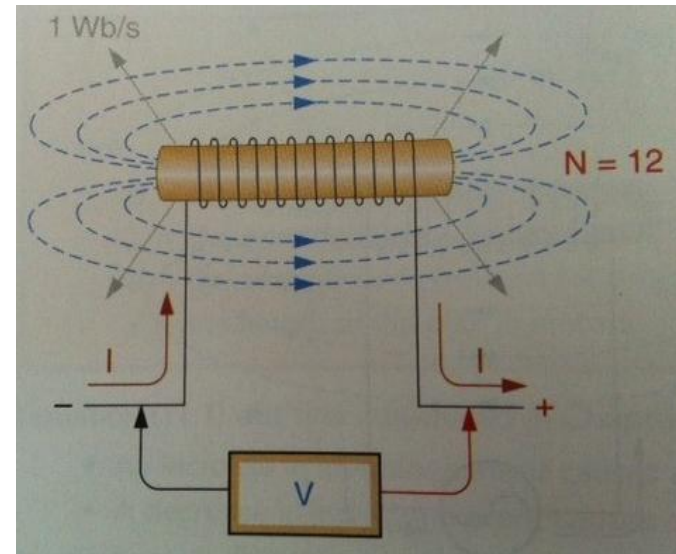
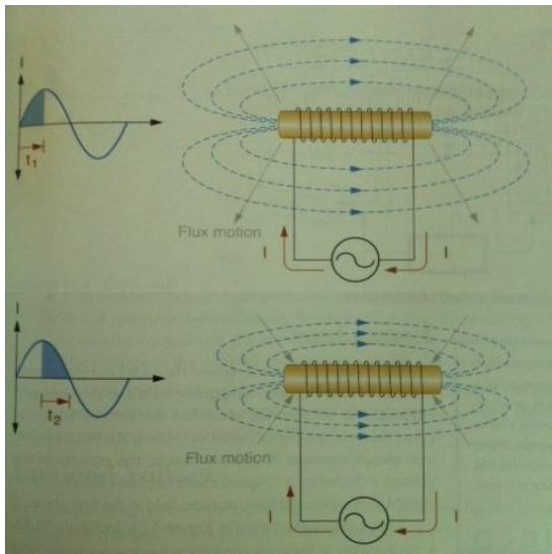
The property of a component that opposes any change(increase/decrease) in current

## ➤ Inductor : A component designed to provide a specific measure of inductance

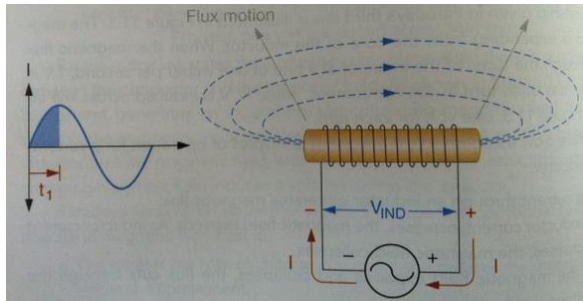
Is able to delay and reshape changing currents

## ➤ If the rate of change of current is 1A/s, and the resulting emf is 1V, then inductance is 1H.

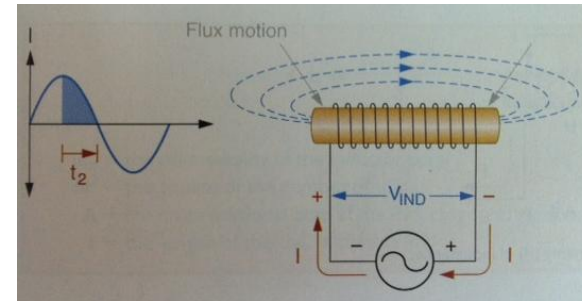
- Varying (AC) Current Effect
  - Inductor current increases, flux density increases, magnetic field expands outward
  - Inductor current decreases, flux density decreases, magnetic field collapses back into the component
  - Impact of this is described by three Faraday's Law of Induction
- Faraday's Law of Induction (1831)
- Electromagnetic Induction: To induce (generate) a voltage across a conductor by using magnetic field
  - Law 1: To induce a voltage across a wire, there must be a relative motion between the wire and the magnetic field
    - Expanding and collapsing regarding to varying current
  - Law 2: The voltage induced is proportional to the rate of change in magnetic flux encountered by the wire
    - Changing current → changes in magnetic flux → changes in voltage
  - Law 3: When a wire is cut by  $10^8$  perpendicular lines of force per second (1 Wb/sec), one volt is induced across the wire
    - $emf = N \frac{d\Phi}{dt}$



- Self Inductance: the process whereby a coil induces a voltage across itself by generating a changing magnetic field
  - Current through an inductor generates magnetic flux
  - As inductor current increases/decreases → magnetic field expands/collapses
  - Flux cutting through the coils induces a voltage across the inductor
  
- To understand full impact of self-inductance: Lenz's Law (Russian physicist, 1834)
  - Relation between magnetic field and the voltage it induces
  - An induced voltage always opposes its source
  - Means; polarity of the voltage induced by magnetic field opposes the change in current
  
  - Lenz add the minus sign (direction of emf) to Faraday's third law;  $emf = -N \frac{d\Phi}{dt}$



Inductor current increase, magnetic field expands  
 Expanding magnetic field, cuts through coil, induce voltage  
 Polarity of voltage opposes the increase in current



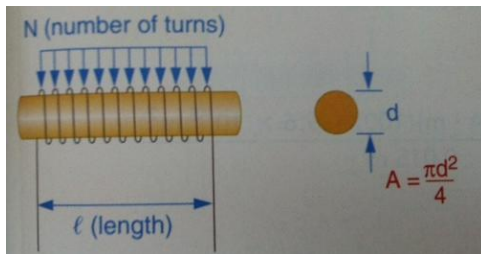
Inductor current decrease, magnetic field collapses  
 Collapsing magnetic field, cuts through coil, induce voltage  
 Polarity of voltage opposes the decrease in current

The induced voltage is referred as Counter EMF

- Counter EMF (Induced Voltage) : The induced voltage across an inductor that opposes any change in coil current

$$V_{IND} = -L \frac{di}{dt}$$

- Henry : 1 Henry of inductance generates 1 V counter emf when inductor current changes by 1 A/s.



$$L = \frac{\mu N^2 A}{l} = \frac{\frac{Wb}{A \cdot t \cdot m} t^2 m^2}{m} = \frac{Wb \cdot t}{A} = \text{Henry}$$

works only for this type of solenoid.  
but exposes the factors that effects inductance.

$$emf = -N \frac{d\Phi}{dt} = -N \frac{d(BA)}{dt} = -N \frac{d \left( \frac{\mu NI}{l} A \right)}{dt} = - \frac{N \mu N A}{l} \frac{dI}{dt} = - \frac{\mu N^2 A}{l} \frac{dI}{dt}$$

- Mutual Inductance : When expanding/collapsing flux produced by an inductor induces a voltage across another inductor that is in close proximity
- Coupled : Describes two components (circuits) that are connected so that energy is transferred one to the other

$$L_m = k\sqrt{L_1L_2}$$

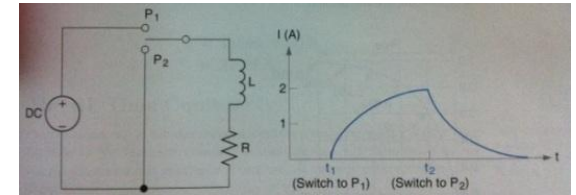
- Coefficient of Coupling ( $k$ ) : the degree of coupling that takes place between two or more coil, range : [0-1]
- Unity Coupling :  $k = 1$  , ideal condition, all flux from the first coil cuts through the turns of second coil
- $k$  depends on the distance and the relative angle between the components

- Series Connection :  $L_T = L_1 + L_2 + \dots + L_n$        $L_T = L_1 + L_2 \pm 2L_M$

- Parallel Connection :  $L_T = \frac{1}{\frac{1}{L_1} + \frac{1}{L_2} + \dots + \frac{1}{L_n}}$

- Inductors in DC Circuits

How inductor opposes a change in current and stores energy in electromagnetic field

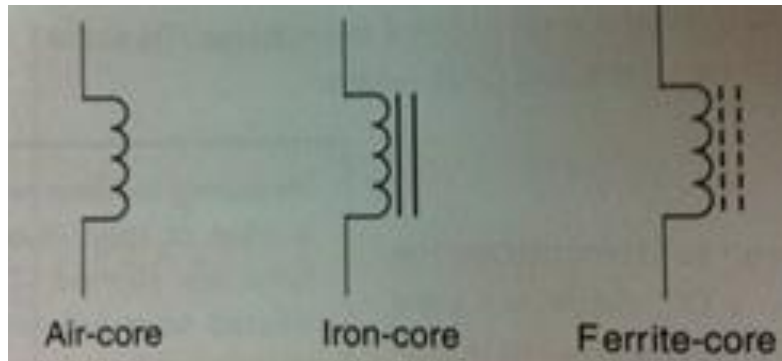


- The voltage across an inductance with DC current is zero because the rate of change of current is zero
- Since the inductor has current through it but no voltage across it, it is a short circuit

- Rise Curve, Decay Curve

- Time Constant ( $\tau$ ) = the duration of each time interval,  $\tau = \frac{L}{R}$

each curve is divided into  $5\tau$

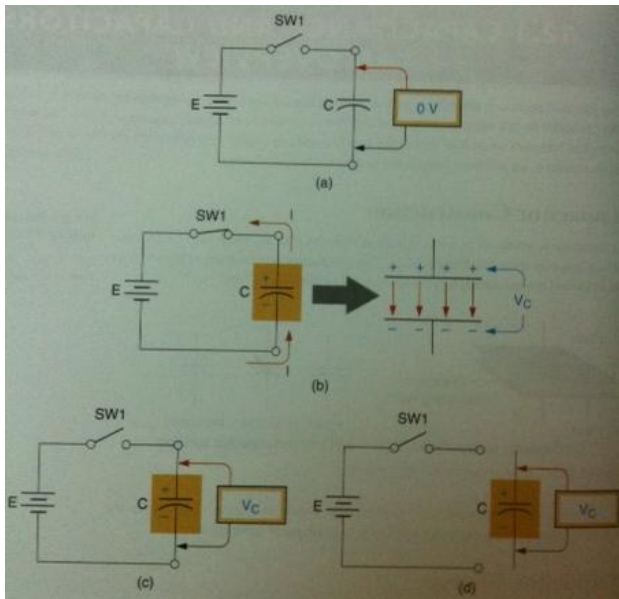
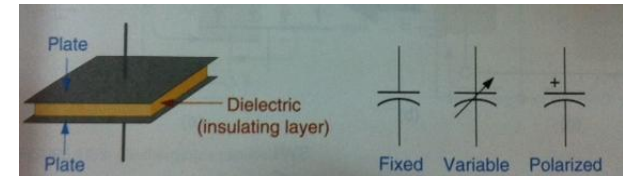


- Iron Core : in low frequency applications; high current DC and AC power circuits, because the DC winding resistor is much lower than air,  $\mu_{iron} = 200 \times \mu_{air}$   
fewer turns  $\rightarrow$  shorter length of wire  $\rightarrow$  lower winding resistance for the same inductance
- Air Core : Self supporting or ceramic tube
- Ferrite Core : consists of iron oxide  
has much higher relative permeability  
higher values of inductance can be obtained
- Toroids : Doughnut-shaped magnetic core  
Nearly all flux produced by the coil remains in the core  
Small by volume and weight, produce less EMI  
Shape lead to near complete magnetic field cancellation outside of the coil



# 9. Capacitance and Capacitors

- Capacitance : The ability of a component to store energy in an electrostatic charge, opposes change in voltage
- Capacitor : A component that provides a specific value of capacitance
- When a capacitor is connected to a DC voltage source an electrostatic charge develops across the plates



Positive terminal of voltage source draws electrons away from the positive plate leaving an excess of positive charges on this plate

Negative terminal of voltage source forces electrons toward the negative plate producing an excess of negative charges on this plate

The charges on the plates exert a force of attraction on each other

When it reaches its capacity, it blocks the flow of charge (current) → DC open

- Capacity : The ability to store a specific amount of charge (per volt applied)

There is no current passing through capacitor, since there is insulator

But charge flows to and from capacitor (charge/discharge cycles)

- Capacity : Max. charge a capacitor can store

$$C = \frac{Q}{V} = \frac{\text{Coulomb}}{\text{Volt}} = \text{farad}$$

- Farad : The amount of capacitance that stores 1 coulomb of charge for each 1V difference of potential

$$C = (8.85 \times 10^{-12}) \epsilon_r \frac{A}{d} \quad (\text{only for parallel plates})$$

$(8.85 \times 10^{-12})$  : permittivity of vacuum ( $F/m$ )

$\epsilon_r$  : relative permittivity

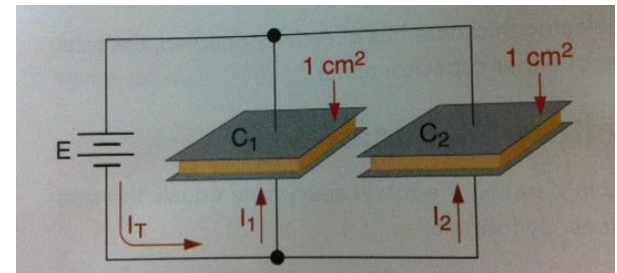
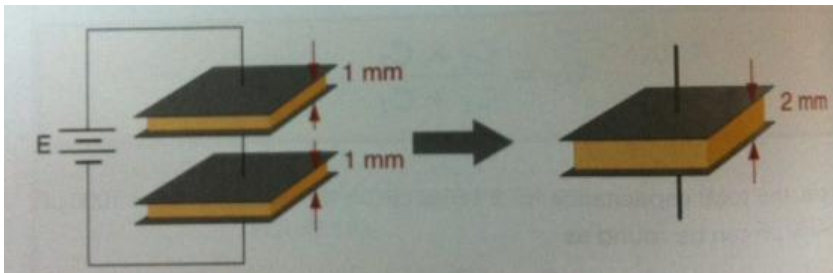
$A$  : the area of either plate ( $m^2$ )

$d$  : the distance between plates ( $m$ ), the dielectric thickness

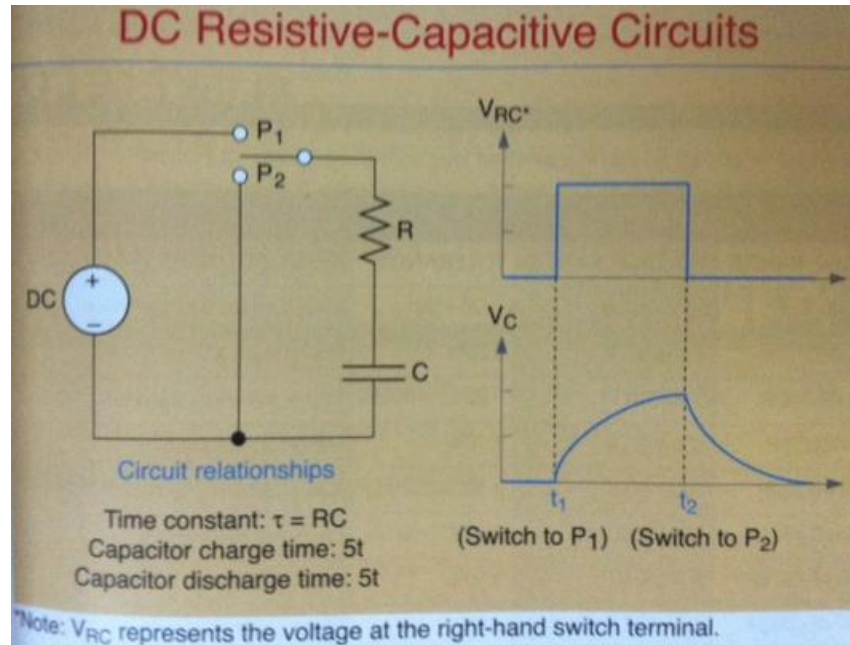
- Permittivity ( $\epsilon$ ) : A measure of the ease with which lines of electrical force are established within a given material  
Electrical equivalent of magnetic permeability ( $\mu$ )
- Relative permittivity ( $\epsilon_r$ ) : Ratio of a material's permittivity to that of vacuum

- Series Connection :  $C_T = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \dots + \frac{1}{C_n}}$

- Parallel Connection :  $C_T = C_1 + C_2 + \dots + C_n$



- Capacitance: opposes an increase or decrease in voltage  
stores energy in an electrostatic field



- Most capacitors are named for their dielectric material
- Electrolytic Capacitor : Contains conducting liquid that serves one of its plates  
Low frequency circuits, power supplies, normally polarized
- Ceramic Capacitor : Inexpensive, very common
- Super Capacitor : used as energy storage devices for AC power systems, can achieve hundreds of volts
- Glass, Mica, Oil, Porcelain, Teflon, Vacuum etc...
- There are also Variable Capacitors

# 10. Alternating Current (AC)

- Alternating Current : Any current that periodically changes direction
- Magnitude : absolute value  $|x(t)|$  of amplitude  $x(t)$ , scalar.
- Amplitude : a measure of how far and in what direction that variable differs from zero.
  
- Waveform : A graph of the relationship between magnitude and time
- Sine Waveform : A waveform whose magnitude varies with the sine of its phase
  
- AC Systems : Voltage polarity and current direction periodically changes
- Crest Factor =  $\frac{\text{peak value of the waveform}}{\text{RMS value of the waveform}}$  determines the amount of distortion, for pure sinusoidal it is  $\frac{1}{\sqrt{2}}$
  
- Alternation : The positive and negative halves of a waveform (half cycle)
- Cycle : The complete transition through one positive and negative alternation
- Periodic Waveform : A waveform that repeats itself periodically
  
- Period ( $T, ms$ ) : The time required to complete one cycle of an AC waveform
- Frequency ( $f, Hz$ ) : The rate at which waveform cycles repeat themselves, in cycles per second

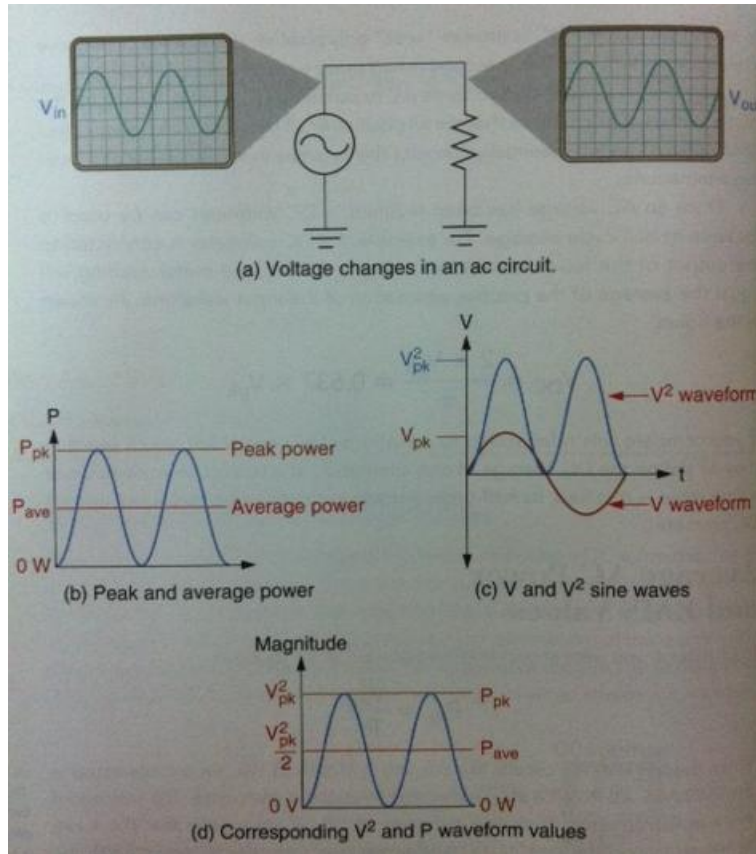
$$\left(1 \frac{\text{cycle}}{\text{second}} = 1\text{cps} = 1\text{Hertz}\right) \quad f = \frac{1}{T}$$

- Instantaneous Value : The voltage or current magnitude at a specific point on waveform
- Half Cycle Average : DC average of one alteration

$$V_{AVE} = \frac{2 \times V_{peak}}{\pi} \cong 0.637 \times V_{peak} \quad (\text{for pure sine})$$

- Rectifier : A circuit that converts AC to pulsating DC

When AC voltage rectified, a DC voltmeter measures its half cycle average



Average AC Power : The value that falls midway between 0 W and the peak power value  $P_{pk}$

$$\text{Load Power : } P_{RL} = \frac{V_{RL}^2}{R_L}$$

Comparing power and  $V^2$  waveform → shapes are identical

$$P = P_{AVE} \quad \text{when} \quad V^2 = \frac{V_{pk}^2}{2}$$

RMS value gives the average power :  $V_{RMS} = \frac{V_{pk}}{\sqrt{2}} = 0.707 \times V_{pk}$

RMS value is the effective value

It is the equivalent DC value which gives the same effect

(48 V RMS sine wave provides same amount of power to a resistive load as a 48 V DC source)

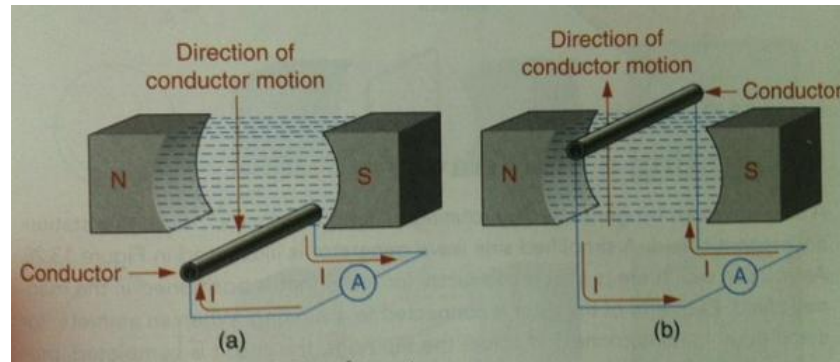
- Averaging Meter : An AC meter that measures the half-cycle average of a waveform and then converts that value to an RMS  
Works only for pure sine, less expensive

$$V_{AVE} = 0.637 \times V_{pk}$$

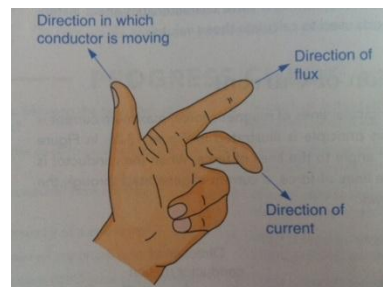
$$V_{RMS} = 1.11 \times V_{AVE} = 1.11 \times 0.637 \times V_{pk} = 0.707 \times V_{pk}$$

- True - RMS Meter : AC meter uses relatively complex circuitry to directly measure the RMS value of any true AC waveform
- Current can be used to produce magnetic field,  
also the field produced by a magnet can be used to generate current through a conductor
- Magnetic Induction of Current

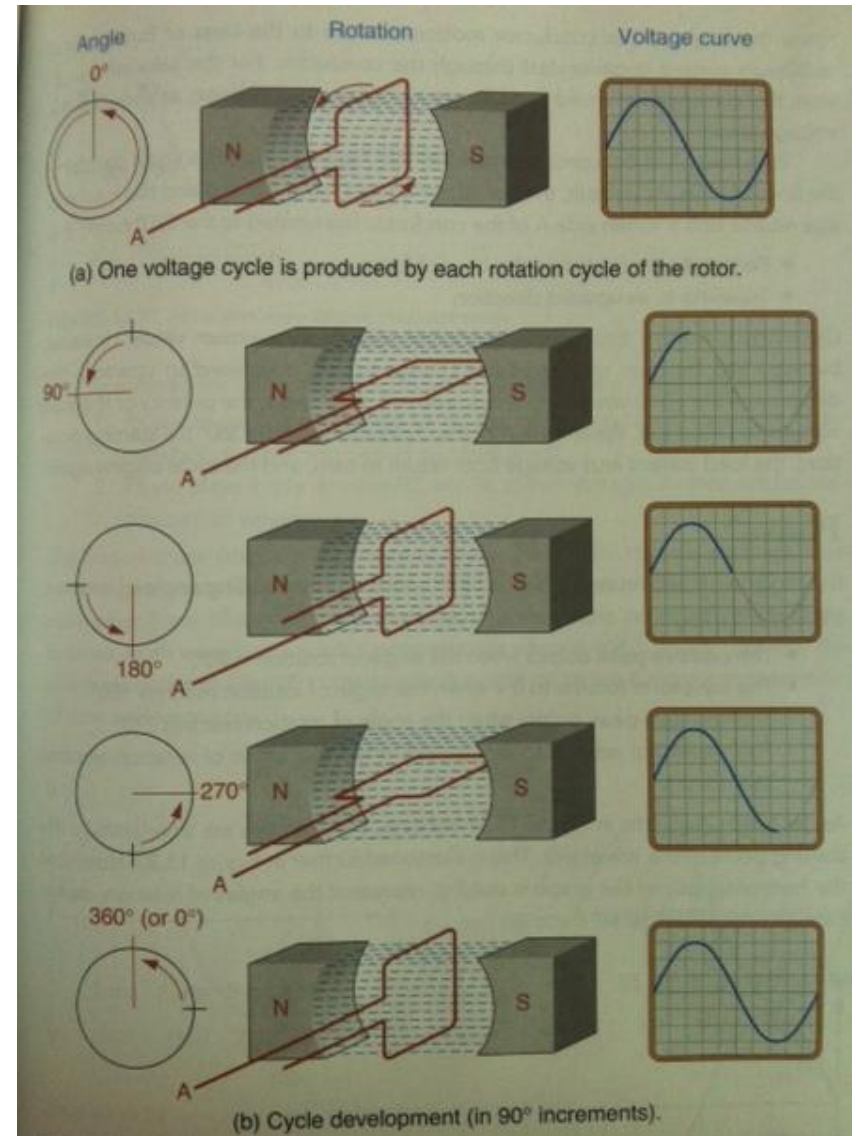
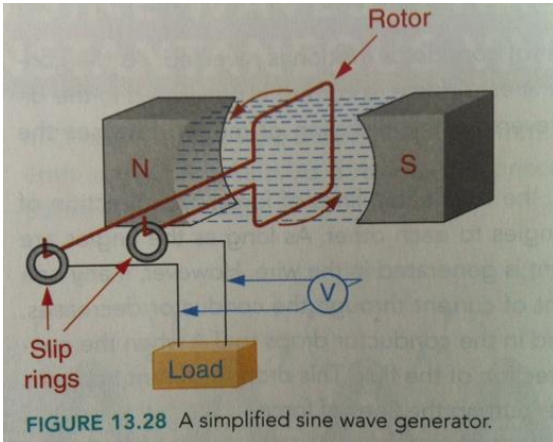
Conductor, lines of force and direction of conductor motion are all at 90°, max current is generated



Left Hand Rule:  
determines the direction of current that is generated in a conductor passing through a magnetic field



Generating a Sine Wave : can be generated by rotating a “loop conductor” through a stationary magnetic field



Side A of conductor is at  $0^\circ \rightarrow$  its motion is parallel to flux  
 Not cutting lines of force  $\rightarrow$  current and voltage is zero

A rotates through  $90^\circ \rightarrow$  perpendicular to flux, downward direction  
 Maximum current is generated

A reaches  $180^\circ \rightarrow$  motion parallel to lines of force  
 Conductor current is 0, load voltage is 0

A reaches  $270^\circ \rightarrow$  perpendicular to flux, upward direction  
 Maximum current is generated, but direction has reversed

A reaches  $360^\circ \rightarrow$  load current and voltage is 0

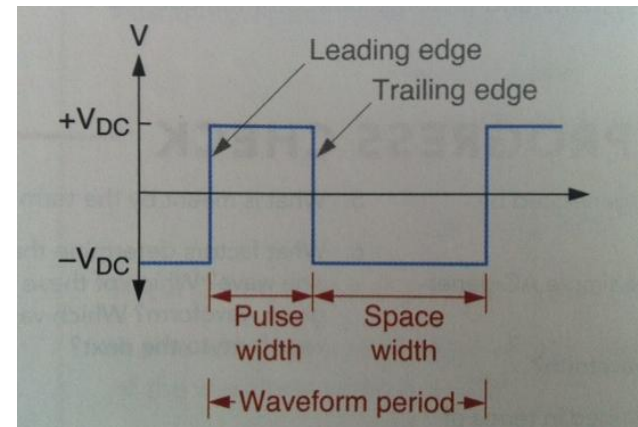
- Phase : The position of a given point relative to the start of the waveform, measured in degree
- Phase Degree : The phase difference between two waveforms
- In Phase : peak and zero crossing occur at the same time (x Out of Phase)

### Summary

- A sine wave can be generated through magnetic induction
- When a conductor cuts through a stationary magnetic field, a current is induced in the conductor
- The value of the current is proportional to the angle of the conductor relative to the magnetic field
  - When conductor cuts magnetic field at  $90^\circ \rightarrow$  max. current
  - When conductor is parallel to magnetic field  $\rightarrow$  min. current

### Rectangular Waves

- Rectangular Waves : alternates between two DC levels
- Pulse Width (PW) : Positive alteration of a rectangular waveform
- Space Width (SW) : Negative alteration of a rectangular waveform
- Duty cycle : The ratio of PW to waveform period, as percent
- Square Wave : Equal PW and SW, duty cycle is %50

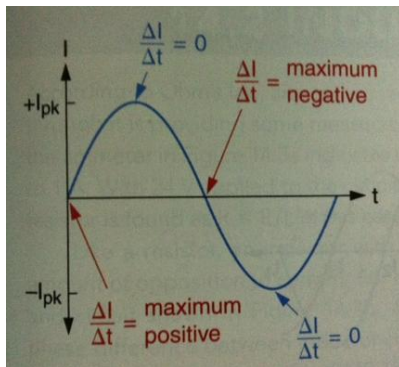


- Symmetrical Waveform : has identical alternations, symmetrical in time and amplitude
- Solid State Relay : A semiconductor relay that is used to control an AC signal

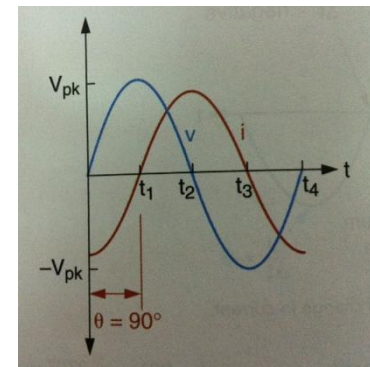


# 11. Series RL Circuits

- Inductance : is the ability of a component with a changing current to induce a voltage across itself or a nearby circuit by generating a changing magnetic field oppose any change in current, store energy in an electromagnetic field Response to AC source will be studied in this chapter.
- Linear Load : purely resistive, inductive or capacitive.
- Nonlinear Load : has two or more of these properties.
- Purely resistive circuit :  $I = \frac{V}{R}$  Purely inductive circuit :  $V_{IND} = L \frac{\Delta I}{\Delta t}$



| WAVEFORM PHASE | RATE OF CHANGE IN CURRENT | INDUCTOR VOLTAGE |
|----------------|---------------------------|------------------|
| 90°            | Zero                      | Zero             |
| 180°           | Maximum                   | Maximum          |
| 270°           | Zero                      | Zero             |
| 360°           | Maximum                   | Maximum          |

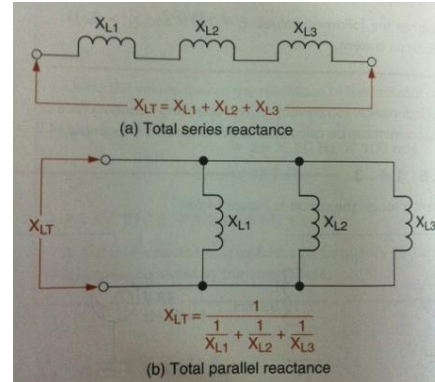


voltage leads current 90° / current lags voltage 90°

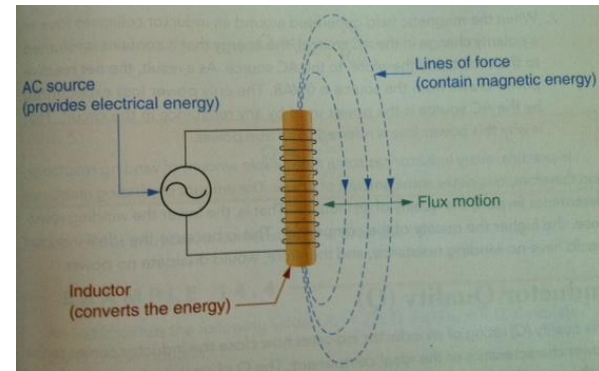
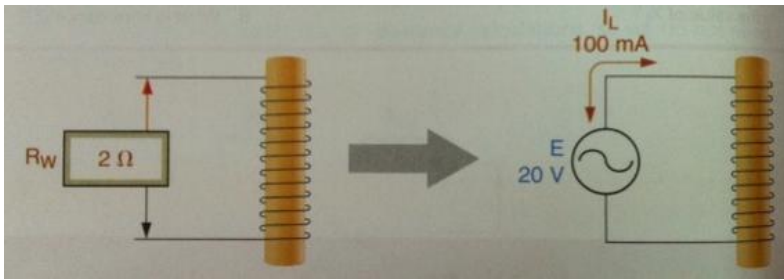
- Inductive Reactance ( $X_L$ ) : The opposition that an inductor presents to an alternating current, ( $\Omega$ )
- The current changes direction  $\rightarrow$  the magnetic field changes polarity  $\rightarrow$  generates a voltage opposes the original current

$$X_L = \frac{V_{RMS}}{I_{RMS}} = 2\pi fL$$

- Series and Parallel Values of  $X_L$



- Static : A value that does not change in response to circuit conditions, like resistance
- Dynamic : A value that changes when specific circuit conditions change, like reactance
- Impedance ( $Z$ ) : The total opposition to current in an AC circuit, geometric sum of resistance and reactance ( $\Omega$ )
- Apparent Power ( $P_{APP}$ ) : The value of ( $V \times I$ ) in AC circuit
  - Result does not indicate true value of power dissipation
  - The combination of resistive and reactive power (VA)
- Winding Resistance ( $R_W$ ) : The resistance of a coil
- Resistive (True) Power ( $P_R$ ) : The power actually dissipated (as heat) by the ( $R_W$ ) of an inductor, (W),  $P_R = I^2 \times R_W$
- Reactive (Imaginary) Power ( $P_X$ ) : Value that indicates the rate at which energy is transferred to and from an inductor's electromagnetic field during expanding/collapsing, (VAR)
 
$$P_X = I^2 \times X_L$$



- Power is dissipated whenever current passes through any measurable amount of resistance
 
$$R_W = 2\Omega \quad P = I^2 \times R_W = (100mA)^2 \times 2\Omega = 20mW \quad P = I_L \times V_L = 100mA \times 20V = 2W$$

- There is a discrepancy between the two calculations, not in calculation but in interpretation
- 2W energy is used per second
- However only 20mW is the energy used.
- Rest 180mW represents the rate which inductor is transferring energy to its magnetic field
- It comes from AC source via inductor which converts electrical energy into magnetic energy

1. Reactive power does not represent a true power
2. When magnetic field generated around inductor collapses → energy it contains is returned to the AC source
 

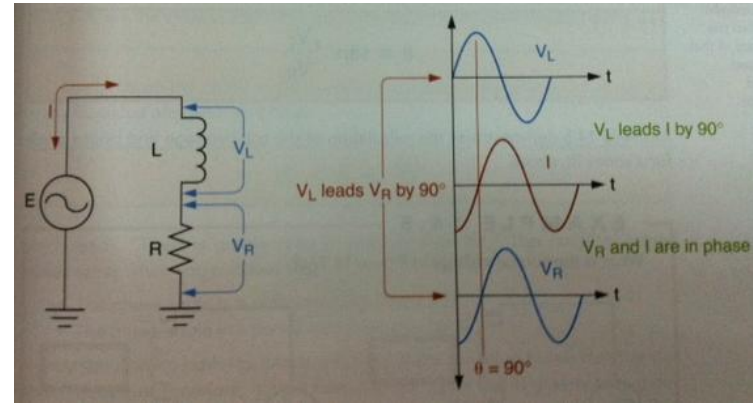
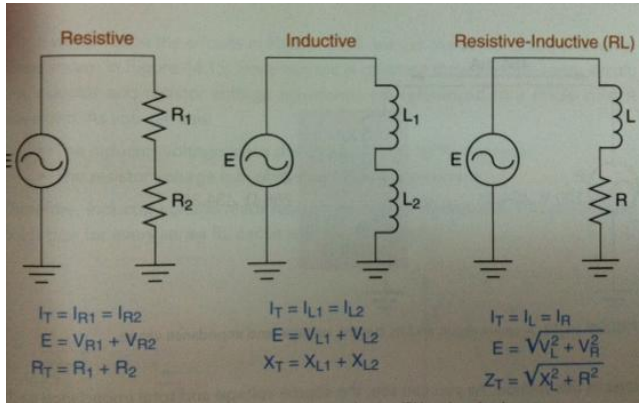
The net reactive power drawn from the source is 0Var

The only power loss is the power used by any resistance, true power

- Inductor Quality (Q) : how close inductor comes to the ideal component,  $R_W = 0, Q = \infty$

$$Q = \frac{P_X}{P_{RW}} = \frac{I^2 \times X_L}{I^2 \times R_W} = \frac{X_L}{R_W}$$

➤ RL Circuit Voltage and Impedance



$$\theta = \arctan \frac{V_L}{V_R} = \arctan \frac{I \times X_L}{I \times R} = \arctan \frac{X_L}{R}$$

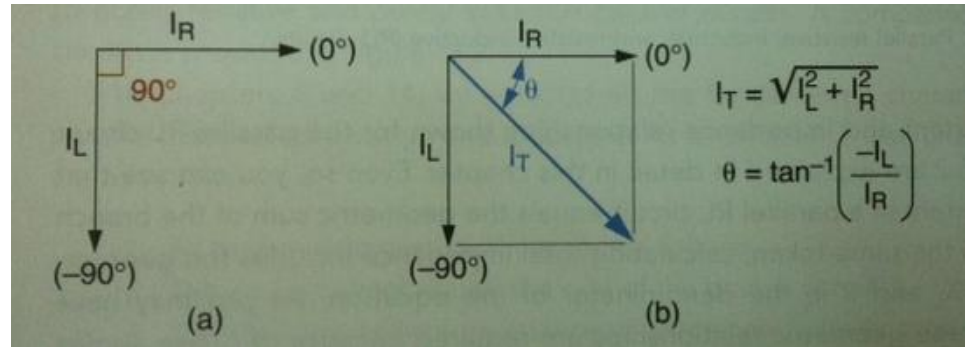
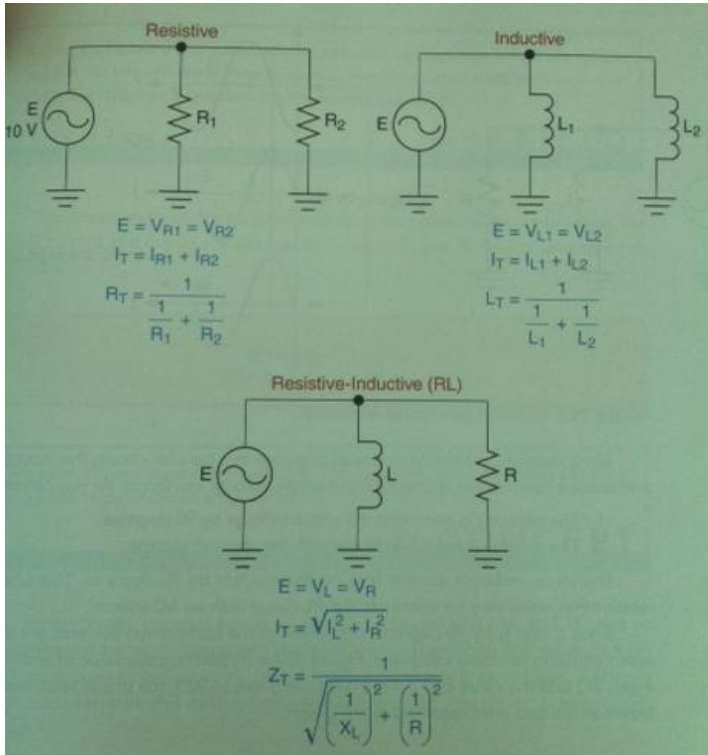
- Any values that are not in phase, such as reactance and resistance, must be added geometrically
- Phase angle :  $0^\circ < \theta < 90^\circ$

$$P_{APP} = \sqrt{P_X^2 + P_R^2}$$

$$\theta = \arctan \frac{P_X}{P_R} \text{ (phase angle of apparent power relative to circuit current)}$$

$$PF = \frac{P_R}{P_{APP}} \quad 0 < \theta < 1$$

# 12. Parallel RL Circuits



$$-90^\circ < \theta < 0^\circ$$

$$\theta = \arctan\left(\frac{-I_L}{I_R}\right) = \arctan\left(\frac{R}{X_L}\right)$$

The first gives the phase of the circuit current relative to the source voltage

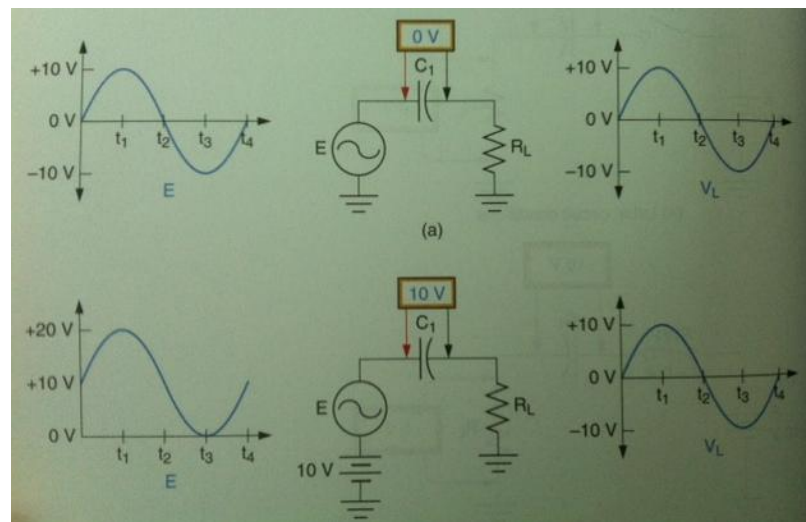
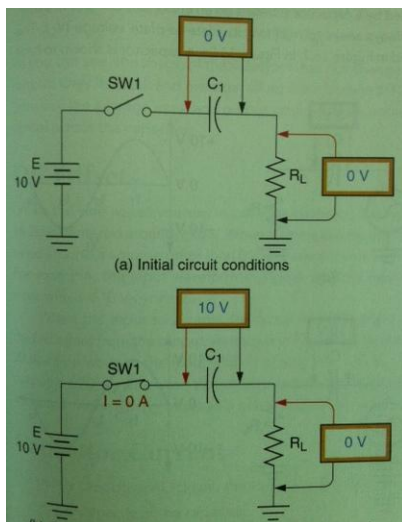
The second gives the phase of the source voltage relative to the circuit current

Circuit current lags source voltage, circuit impedance leads source voltage

The two phase angles have opposite signs and equal magnitudes

# 13. Series RC Circuits

- Capacitance : is the ability of a component to store energy in electrostatic field, opposes a change in voltage
- When capacitor is fully charged, there is no movement of electrons between its plates and its dielectric contains electrostatic force
- Placing to large charge on a capacitor will break the dielectric. Example: Thunderstorm, dielectric is air
- Coupling : When a component (or circuit) allows electrical energy to pass from one point to another
- Isolation : When a component (or circuit) prevents electrical energy from passing between two points
- Capacitor provides AC coupling and DC isolation

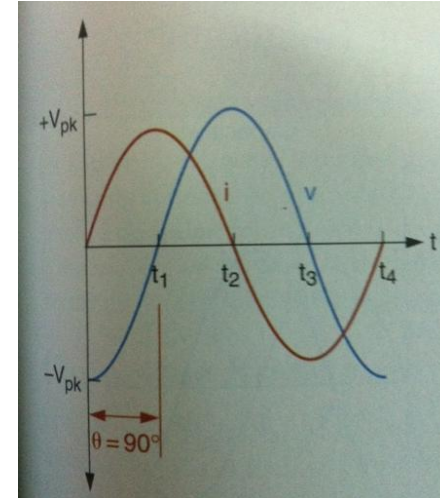


- DC Offset : When a sine wave (or another waveform) is centered around a voltage other than 0V
- When the input of a capacitor contains DC offset, capacitor isolates the DC offset from the output, plate-to-plate voltage
- Instantaneous value of capacitor current:

$$I_C = C \frac{\Delta V}{\Delta t}$$

Current leads voltage by  $90^\circ$   
 Voltage lags current by  $90^\circ$

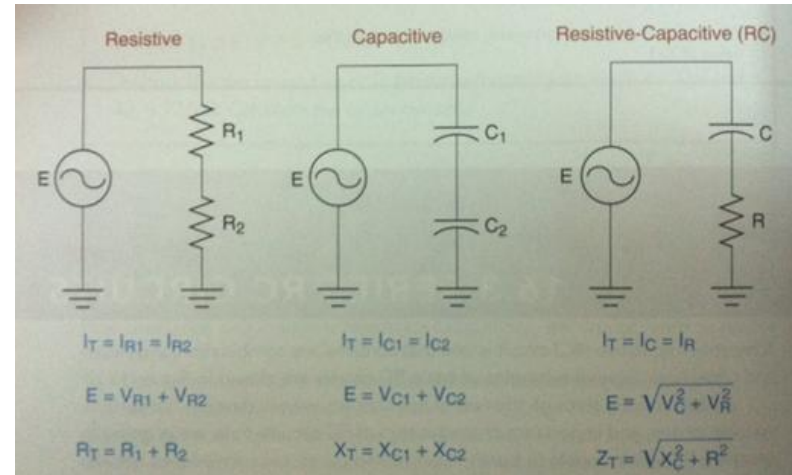
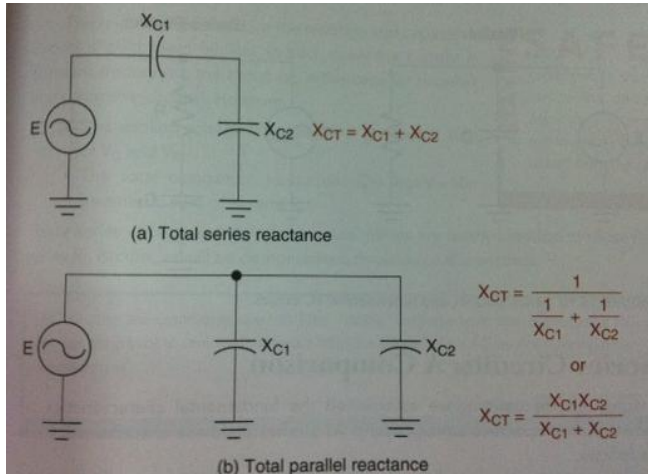
(Current is used as the phase reference in series circuit since its constant at all points)



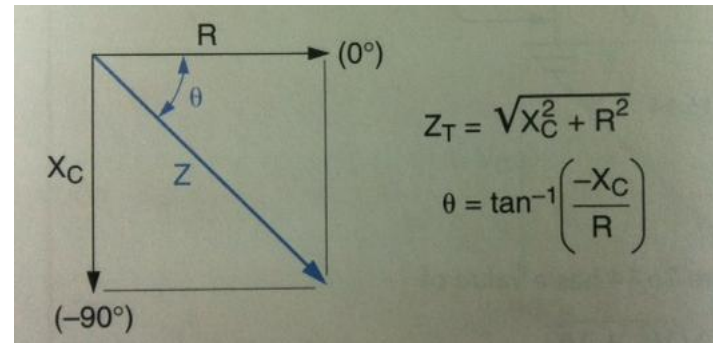
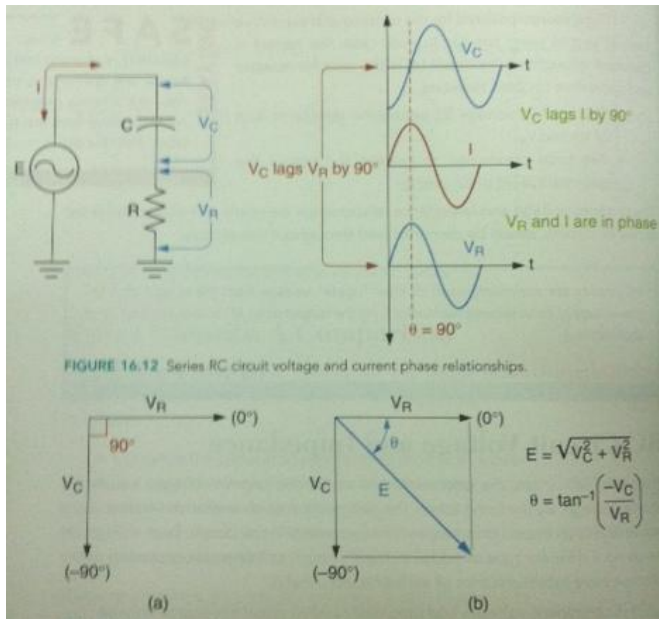
- Capacitive Reactance  $X_C$  : Capacitor's opposition to alternating current, ( $\Omega$ )
- Capacitor Resistance
  - Dielectric (True) Resistance : assumed to be infinite
  - Effective Resistance : Capacitive reactance, lower than true resistance

$$X_C = \frac{V_{RMS}}{I_{RMS}} = \frac{1}{2\pi f C} \quad E = I \times X_C$$

➤ Series and Parallel Values of  $X_C$



- RC circuits are commonly used to filter ripple voltage from the output of DC power supply or remove harmonics from the output of AC source



Voltage phase angle relative to the circuit current

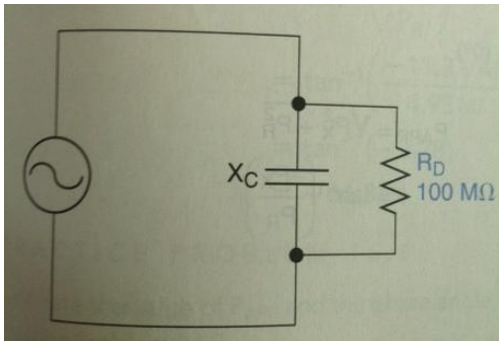
$$-90^\circ < \theta < 0^\circ$$

$$\theta = \arctan\left(\frac{-V_C}{V_R}\right) = \arctan\left(\frac{-X_C}{R}\right)$$

Voltage Divider :  $V_n = E \frac{Z_n}{Z_T}$



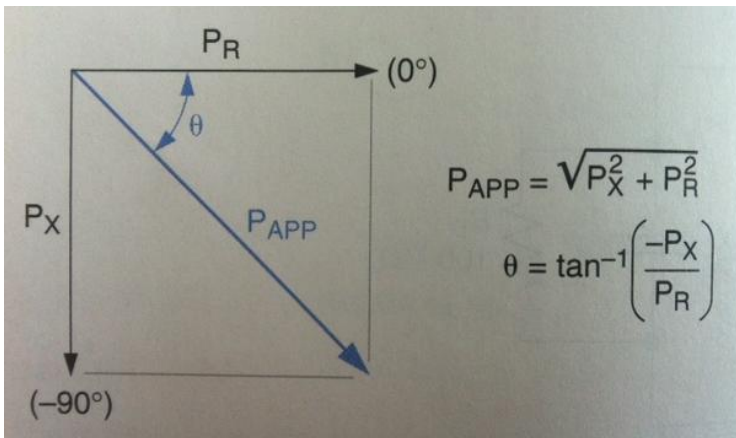
- Resistive (True) Power  $P_R$  : The power dissipated by the resistance
- Reactive Power  $P_X$  :  $P = I^2 X_C$  The energy per unit time that is actually stored in the capacitor's electrostatic field, and is returned to the circuit when the component discharges
- Leakage Current : The current that leaks through a capacitor's dielectric, typically in the low  $\mu A$  range



Capacitor's true dielectric resistance is very high

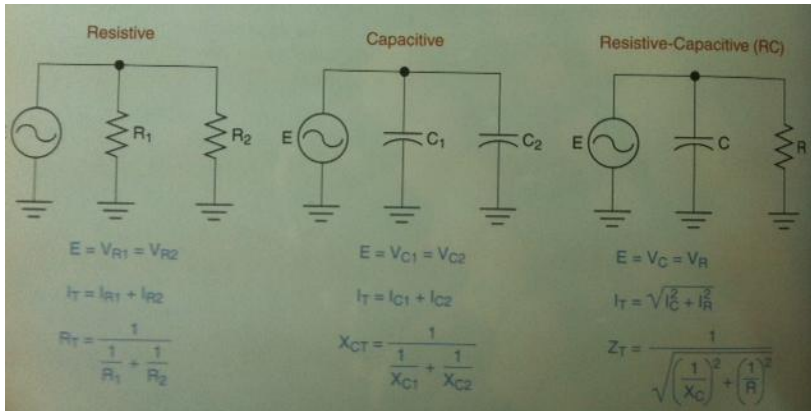
$$X_C \ll R_D$$

Phase angle relative to the circuit current

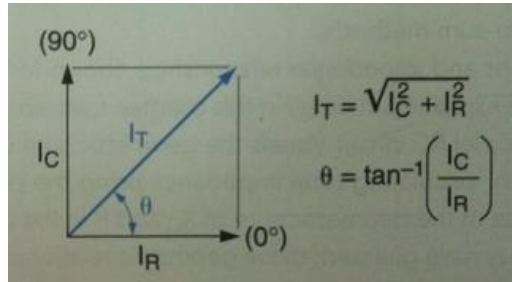


$$\text{Power Factor : } PF = \frac{P_R}{P_{APP}}$$

# 14. Parallel RC Circuits



Phase angle of the circuit current relative to the source voltage



Circuit current phase angle relative to the source voltage

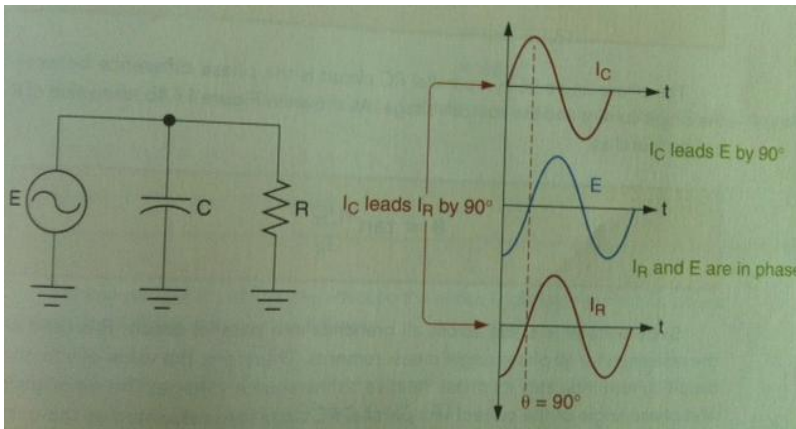
$$0^\circ < \theta < 90^\circ$$

$$Z = \frac{E}{I_T} \quad X_C = \frac{E}{I_C} \quad R = \frac{E}{I_R}$$

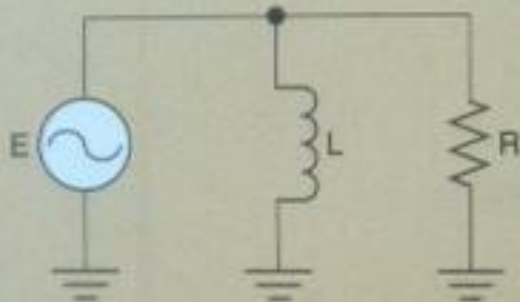
$$\theta = \arctan \frac{I_C}{I_R} = \arctan \frac{R}{-X_C}$$

The first gives the phase of the circuit current relative to the source voltage

The second gives the phase of the source voltage relative to the circuit current



## RL and RC Parallel Circuits



Reactance:

$$X_L = 2\pi fL$$

Circuit impedance:

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

$$\theta = \tan^{-1}\left(\frac{R}{X_L}\right)$$

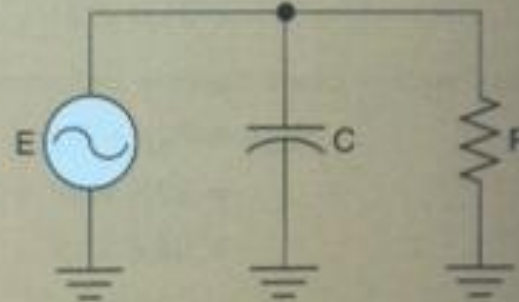
Lags source voltage

Circuit current:

$$I_T = \sqrt{I_L^2 + I_R^2}$$

$$\theta = \tan^{-1}\left(\frac{-I_L}{I_R}\right)$$

Lags source voltage



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

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

$$\theta = \tan^{-1}\left(\frac{R}{-X_C}\right)$$

Lags source voltage

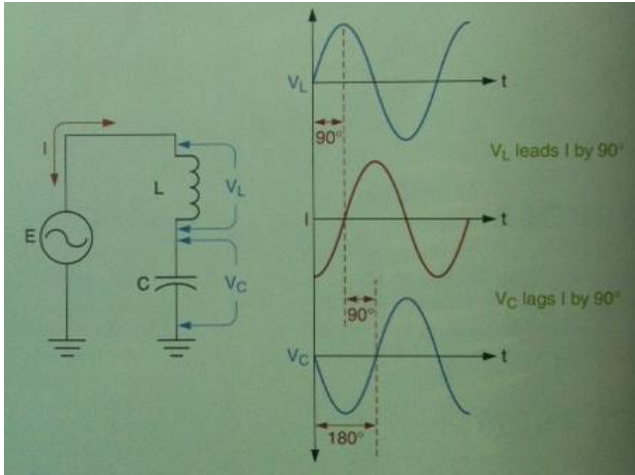
$$I_T = \sqrt{I_C^2 + I_R^2}$$

$$\theta = \tan^{-1}\left(\frac{I_C}{I_R}\right)$$

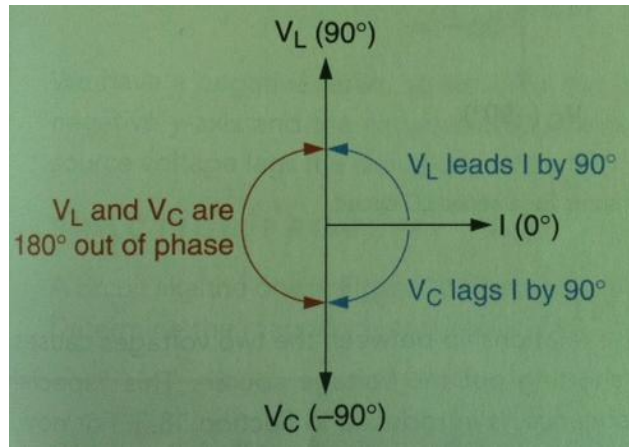
Lags source voltage

# 15. RLC Circuits

## Series LC Circuits



3 conditions :  $V_L > V_C$  ,  $V_L = V_C$  ,  $V_L < V_C$



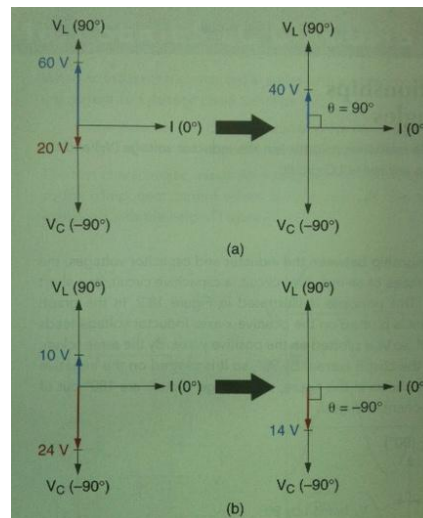
- $I_C = I_L$
- Inductor and capacitor voltages are  $180^\circ$  out of phase
- Total Voltage  $E = V_L - V_C$

Net Series Reactance ( $X_S$ ) :

When an inductor and capacitor are connected in series

$$X_S = X_L - X_C \quad (3 \text{ conditions: } X_L \geq < X_C)$$

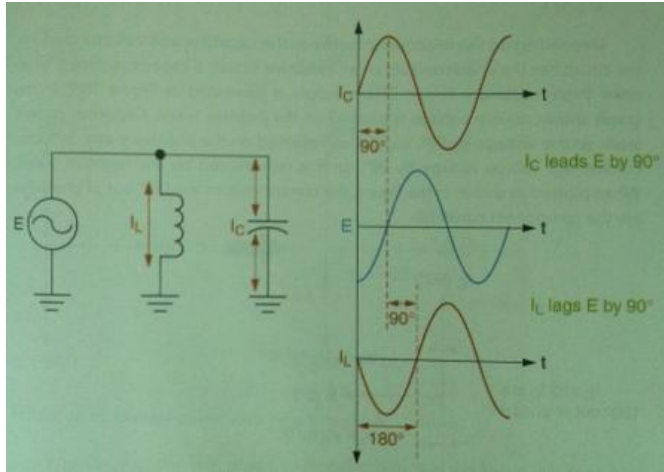
$V_L = V_C$  series resonance, shorting out voltage source



$V_L > V_C$   
Inductive characteristic  
Voltage leads current  $90^\circ$

$V_L < V_C$   
Capacitive characteristic  
Voltage lags current  $90^\circ$

➤ **Parallel LC Circuits**



1.  $V_C = V_L$
2. Inductor and capacitor currents are  $180^\circ$  out of phase
3. Total Current  $I = I_C - I_L$

3 conditions :

$I_C > I_L$  : capacitive characteristic

$I_C < I_L$  : inductive characteristic

$I_C = I_L$  :  $I = 0$  open circuit, parallel resonance

Net Parallel Reactance ( $X_P$ ):

$$X_P = \frac{1}{\frac{1}{X_L} + \frac{1}{X_C}}$$

$X_C$  must be entered as a negative value (-)

The net reactance of a parallel LC circuit is always greater than the value of one or both of the branch reactances

$X_P > 0 \rightarrow$  inductive, current lags voltage  $90^\circ$

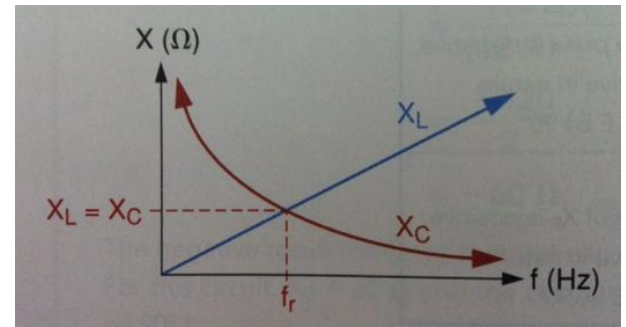
$X_P < 0 \rightarrow$  capacitive, current leads voltage  $90^\circ$

The greater branch current determines the overall nature of the circuit

- Resonance : For an LC circuit the operating state where  $X_L = X_C$
- Resonant Frequency ( $f_R$ ) : for an LC circuit, the frequency at which  $X_L = X_C$

$$f_R = \frac{1}{2\pi\sqrt{LC}} \quad (\text{is valid both for series and parallel circuits})$$

- $f \downarrow \rightarrow X_L \downarrow, X_C \uparrow$



### Series-resonant and Parallel-resonant LC Circuits

Resonant frequency:  $f_r = \frac{1}{2\pi\sqrt{LC}}$

Reactance:  $X_L = X_C$   
\* $X_S = 0 \Omega$

Other relationships:  $V_L$  and  $V_C$  are  $180^\circ$  out of phase.  
 $V_L + V_C = 0 V$   
 $I$  is limited only by source resistance ( $R_S$ ).  
 $I$  is in phase with  $E$ .

Resonant frequency:  $f_r = \frac{1}{2\pi\sqrt{LC}}$

Reactance:  $X_L = X_C$   
\*\* $X_P$  approaches  $\infty \Omega$

Other relationships:  $I_L$  and  $I_C$  are  $180^\circ$  out of phase.  
 $I_L + I_C = 0 A$

\* $X_S$  represents the total series reactance.  
\*\* $X_P$  represents the total parallel reactance.

#### Series Resonant LC Circuits :

Net series reactance is  $0\Omega$

Voltage across the series LC circuit is  $0V$ , sum is  $0V$

the values of  $V_L$  and  $V_C$  may be greater than source voltage

Circuit voltage and current are in phase, resistive circuit

#### Parallel Resonant LC Circuits :

Net current through parallel LC circuit is  $0A$ ,  $I_L = I_C$

Reactance is infinite, acts as open

➤ Series and Parallel RLC Circuits :

➤ Series RLC :

$X_L > X_C$  : net series reactance is inductive, series RL circuit, voltage leads current

$X_L = X_C$  : net series reactance is  $0\Omega$ , purely resistive, voltage and current in phase

$X_L < X_C$  : net series reactance is capacitive, series RC circuit, voltage lags current

➤ Total Series Impedance :

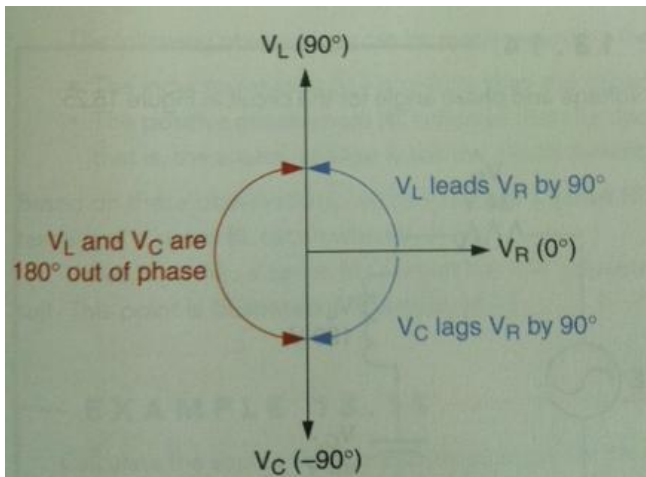
$$Z_T = \sqrt{R^2 + X_S^2} \quad X_S = X_L - X_C$$

$$\theta = \arctan \frac{X_S}{R}$$

$\theta > 0$  inductive     $\theta = 0$  resistive     $\theta < 0$  capacitive

Current is considered  $0^\circ$  reference

Voltage vectors:



$$V_{LC} = V_L - V_C$$

$$E = \sqrt{V_R^2 + V_{LC}^2}$$

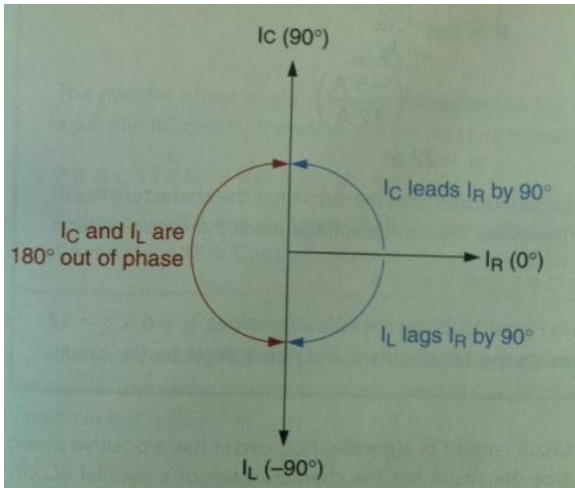
$$\theta = \arctan \frac{V_{LC}}{V_R}$$

➤ Parallel RLC Circuits :

$I_L > I_C$  : net reactive current inductive, parallel RL circuit

$I_L = I_C$  : resonant LC has net 0A, resistive circuit, in phase

$I_L < I_C$  : net reactive current capacitive, parallel RC circuit

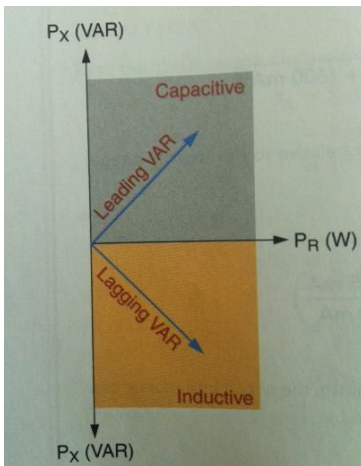


$$I_T = \sqrt{I_{LC}^2 + I_R^2}$$

$$I_{LC} = I_C - I_L$$

$$\theta = \arctan \frac{I_{LC}}{I_R}$$

$\theta < 0$  inductive     $\theta = 0$  resistive     $\theta > 0$  capacitive



Lagging VAR : when a load is inductive, reactive power (VAR) lags resistive power (W)

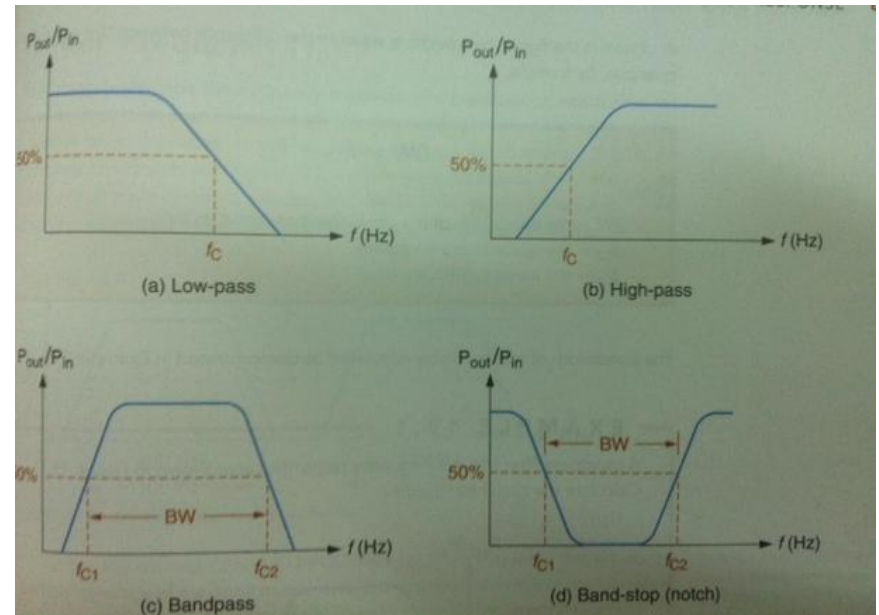
Leading VAR : when a load is capacitive, reactive power (VAR) leads resistive power (W)



- Power Factor Correction : Using a circuit to improve the power factor, train analogy
- $0 < PF = \frac{P_R}{P_{APP}} < 1$
- Static Correction : Power factor correction that is implemented for each individual motor
- Centralized (Bulk) Correction : A power factor correction technique where compensating capacitor banks  
are located at the line input to a plant
- KVAR-Sensitive Controller (Intelligent Power Factor Controller) : Measures changes in the power factor and  
switches capacitor banks
- Harmonic : A whole-number multiple of a given frequency
- $f \uparrow \quad X_C \downarrow \quad X_L \text{ of motor } \uparrow \rightarrow$  can result high harmonic currents in the capacitors,  
to prevent this, series inductor are connected.  
inductance is chosen as it has little reactance at lower harmonic frequencies  
and it has high reactance at higher harmonics (usually  $\geq 5^{\text{th}}$  harmonic)

# 16. Frequency Response and Filters

- Frequency Response : The reaction of a circuit has to a change in frequency
- Attenuation : Any signal loss caused by the frequency response of a circuit
- Decibels : The ratio of one circuit value to another, ratio of circuit output voltage (power) to input voltage (power)
- Gain : The ratio of circuit's output amplitude to input amplitude; voltage, current or power gain
- Unity Gain : 1
- Frequency Response Curve : A graph that shows the effect that frequency has on circuit gain, (f vs. gain graphs)
- Cutoff Frequency : The frequency at which the power gain of a circuit drops to %50 of it max. value
- Filter : A circuit designed to pass and block a specific range of frequencies  
Low Pass, High Pass, Bandpass, Bandstop (Notch)



- Bandpass and notch filters are described by bandwidth (BW) and center frequency.
- Bandwidth (BW): The range (or band) of frequencies between the cutoff frequencies

$$BW = f_{C2} - f_{C1}$$

- Center Frequency  $f_0$  : Equals the geometric average of the cutoff frequencies to accurately describe bandpass and notch filters

$$f_0 = \sqrt{f_{C1}f_{C2}} \quad \text{SO; } \frac{f_0}{f_{C1}} = \frac{f_{C2}}{f_0}$$

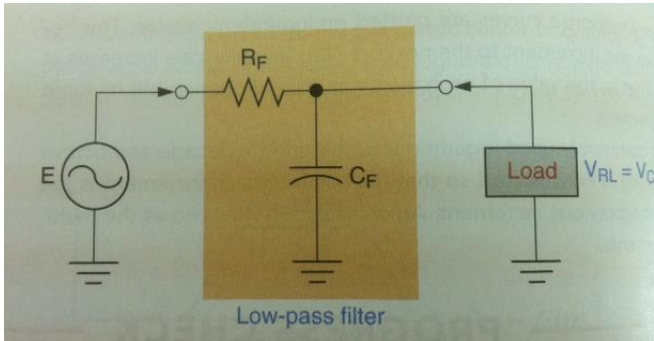
- Quality (Q) : For a bandpass or notch filter, the ratio of its center frequency to its bandwidth

$$Q = \frac{f_0}{BW}$$

- Average Frequency  $f_{AVE}$  : For a bandpass or notch filter  $f_{AVE} = \frac{f_{C1}+f_{C2}}{2}$
- Logarithmic Scale : A scale with a frequency spread between increments that increases at geometric rate  
Commonly used : Decade and octave scales
- Decade Scale : Value of each increment is 10 times the previous increment
- Octave Scale : Value of each increment is 2 times the previous increment

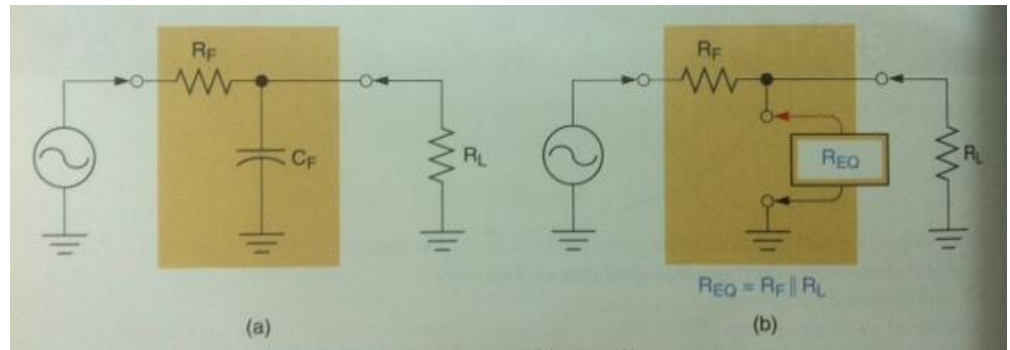
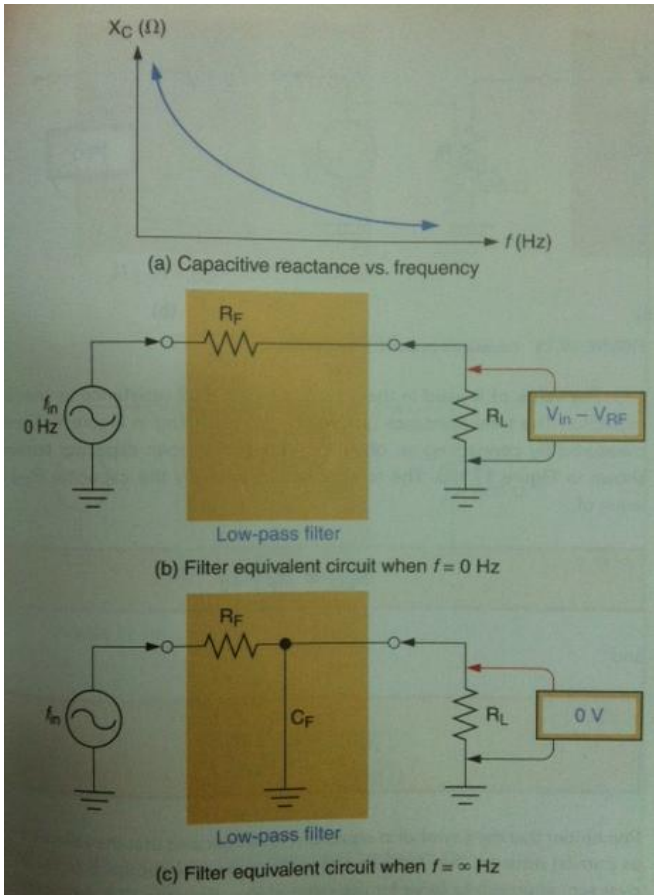
When logarithmic scale is used, center frequency falls in the physical center of the curve

➤ RC Low-Pass Filters



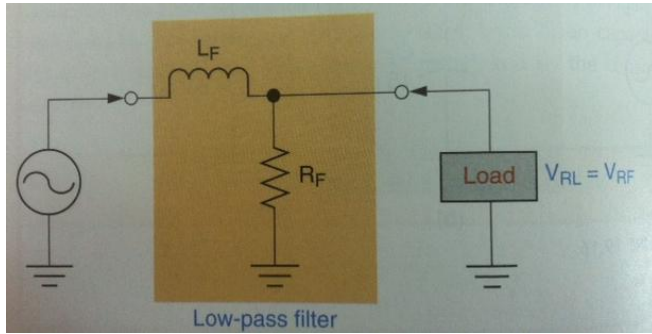
- $f_C = \frac{1}{2\pi R_{EQ} C}$      $R_{EQ} = R_F || R_L$
- $R_{EQ}$  is the total resistance seen by capacitor

Power gain of the circuit is reduced to %50 of its maximum when operating frequency is  $f_C$



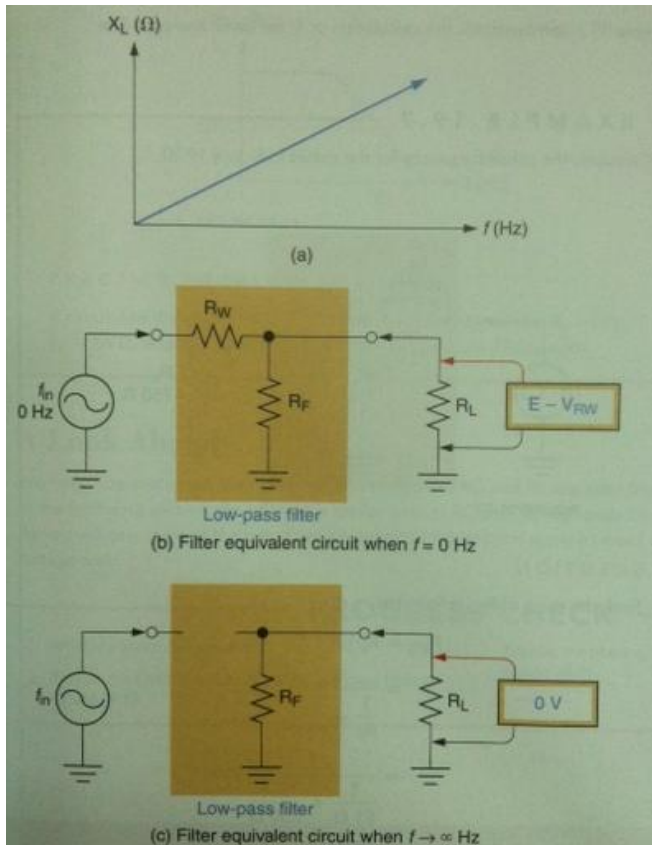
- Shunt : connection from a signal path to ground

➤ RL Low Pass Filters

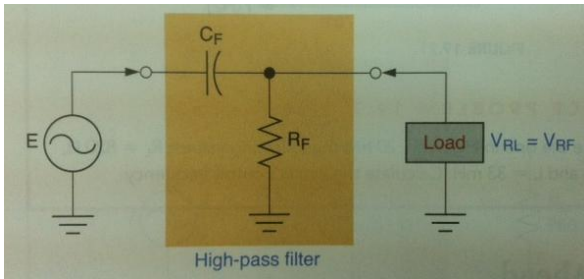


➤  $f_C = \frac{R_{EQ}}{2\pi L}$   $R_{EQ} = R_F || R_L$

Power gain of the circuit is reduced to %50 of its maximum when operating frequency is  $f_C$

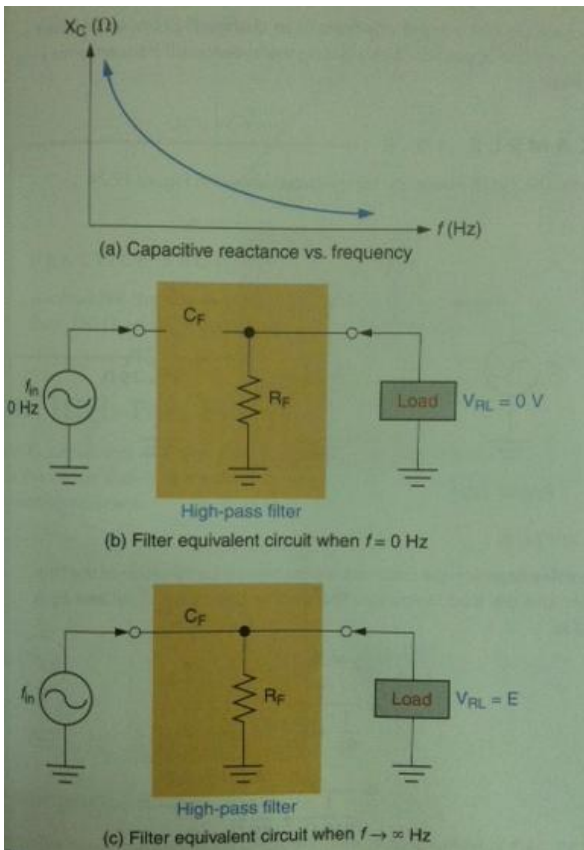


➤ RC High Pass Filters

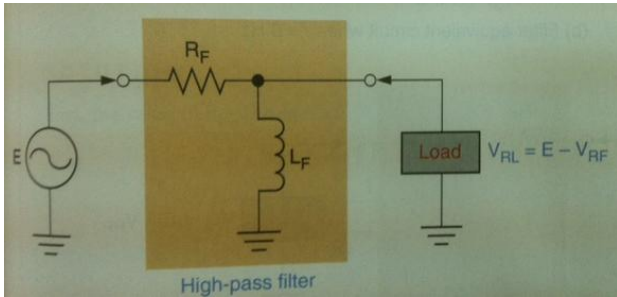


- $f_c = \frac{1}{2\pi R_{EQ} C}$      $R_{EQ} = R_F || R_L$
- $R_{EQ}$  is the total resistance seen by capacitor

Power gain of the circuit is reduced to %50 of its maximum when operating frequency is  $f_c$

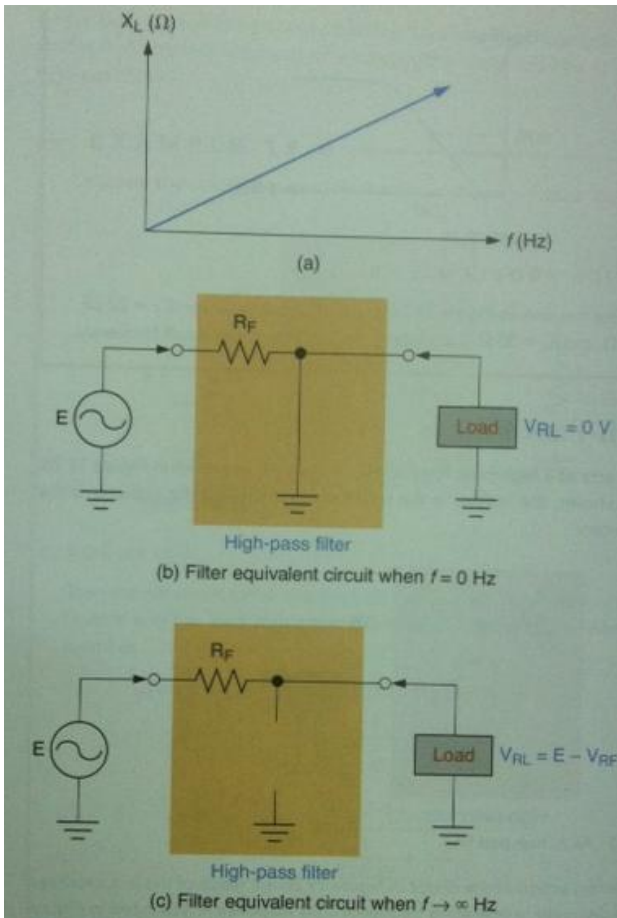


➤ RL High Pass Filters

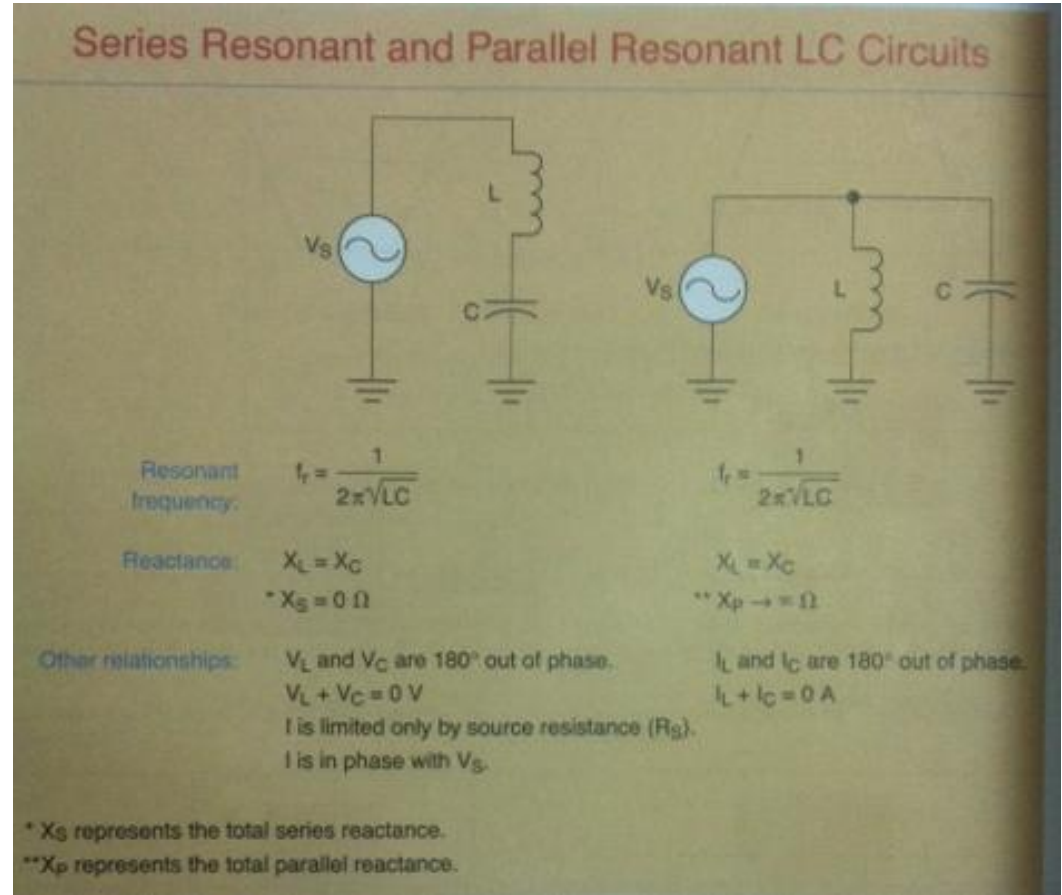
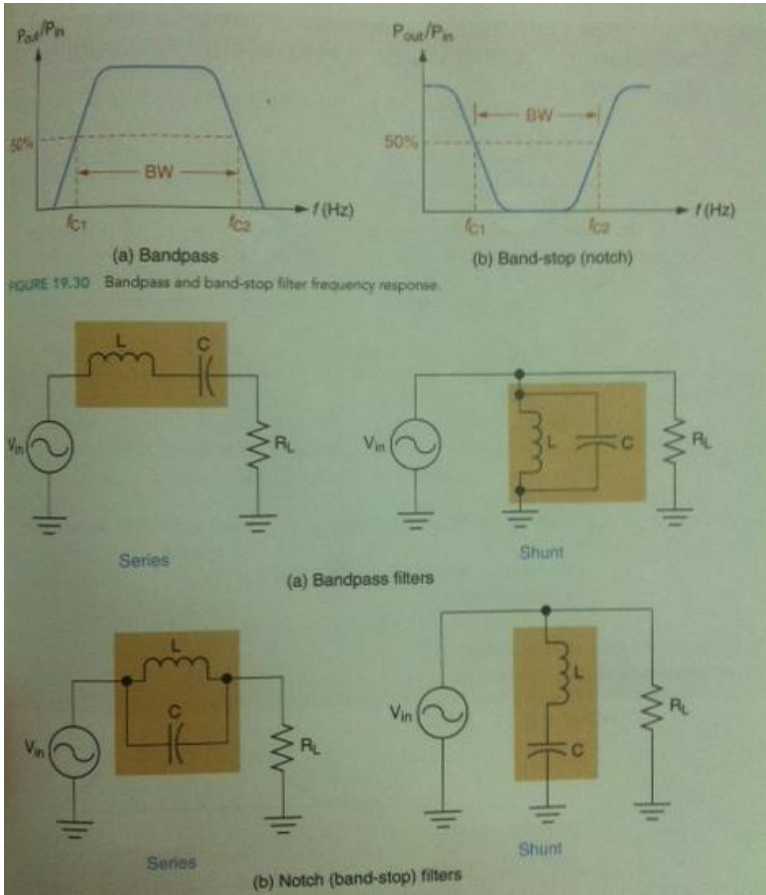


➤  $f_C = \frac{R_{EQ}}{2\pi L}$   $R_{EQ} = R_F || R_L$

Power gain of the circuit is reduced to %50 of its maximum when operating frequency is  $f_C$

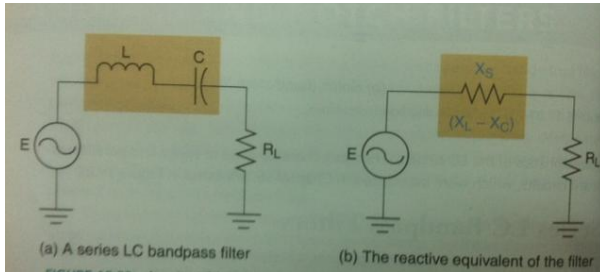


➤ Bandpass and Notch Filters





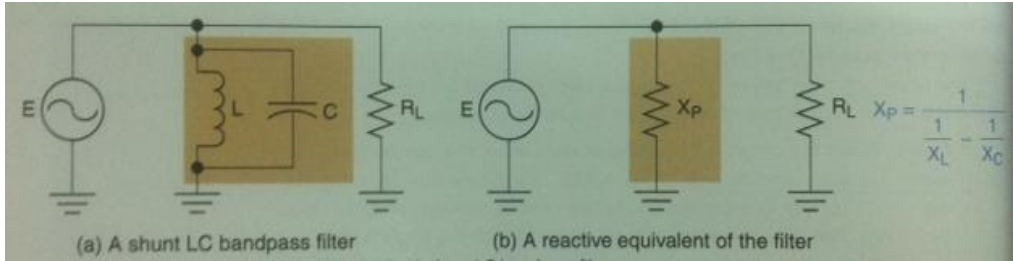
## Bandpass Filters



$f_{in} = f_r \rightarrow X_S = 0 \rightarrow I_T = E/R_L$  resistive circuit

$f_{in} < f_r \rightarrow X_C \uparrow X_L \downarrow \rightarrow X_S$  is capacitive  $\rightarrow f_{in}$  reaches 0Hz  $X_S = \infty I_T = 0A$

$f_{in} > f_r \rightarrow X_C \downarrow X_L \uparrow \rightarrow X_S$  is inductive  $\rightarrow f_{in}$  reaches 0Hz  $X_S = \infty I_T = 0A$

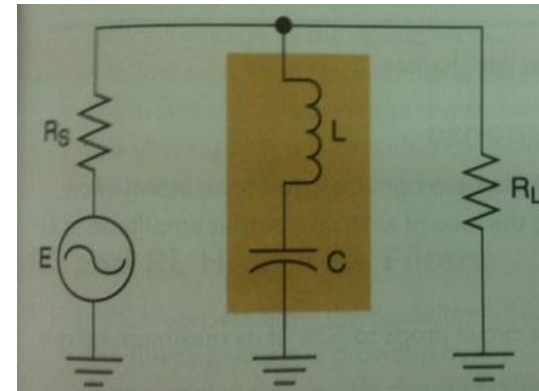
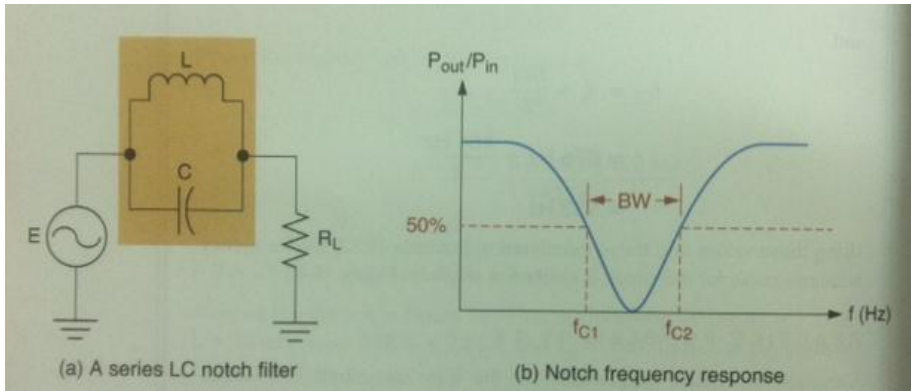


$f_{in} = f_r \rightarrow I_L = I_C X_P = \infty V_{RL} \cong E$  resistive circuit

$f_{in} < f_r \rightarrow X_L \downarrow \rightarrow$  short out the load  $V_{RL} \cong 0V$

$f_{in} > f_r \rightarrow X_C \downarrow \rightarrow$  short out the load  $V_{RL} \cong 0V$

## Notch Filters



$f_{in} = 0 \rightarrow X_L = 0 \rightarrow$  short out the load  $V_{RL} \cong E$

$f_{in} = f_r \rightarrow X_P = \infty V_{RL} \cong 0V$

$f_{in} = \infty \rightarrow X_C = 0 \rightarrow$  short out the load  $V_{RL} \cong E$

$f_{in} = 0 \rightarrow X_C = \infty \rightarrow$  open  $V_{RL} \cong E - V_{RS}$

$f_{in} = f_r \rightarrow X_P = 0 \rightarrow$  short out the load  $V_{RL} \cong 0V$

$f_{in} = \infty \rightarrow X_L = \infty \rightarrow$  open  $V_{RL} \cong E - V_{RS}$



# 17. Three Phase Power

- Three Phase Power : A means of generating and transmitting power using three sine waves that are  $120^\circ$  out of phase with each other
- Armature : The current carrying conductor in a generator or motor (the rotor in this case)
- Generating Sine wave : by rotating a conductor through a stationary magnetic field using a stationary armature and a rotating magnet
- To induce a voltage across a conductor  
a relative motion between the conductor and the magnetic field is required (Faraday 1<sup>st</sup> law)  
The armature can be stationary (or stator), magnet can be rotating element (or rotor)
- Phase Sequence : The order in which three output sine waves reach their peak values  
Counterclockwise : A-B-C    Clockwise : C-B-A
- Advantages of Three Phase Power :
  1. Three phase motors are less complex and have higher horsepower ratings than single phase
  2. Three phase transformers have greater output capabilities than single phase transformers
  3. Single phase circuits require larger diameter (heavier) conductors than three phase circuits (1.15 times)

- WYE (Y) Circuit : Three components that are connected in the shape of Y (tee or star connection)
- Delta ( $\Delta$ ) Circuit : Three components that are connected in the shape of  $\Delta$
- Balanced Load : One in which the load currents are equal in balance and  $120^\circ$  out of phase

Balanced WYE Circuit :

Phase Voltage : Phase – N Voltage

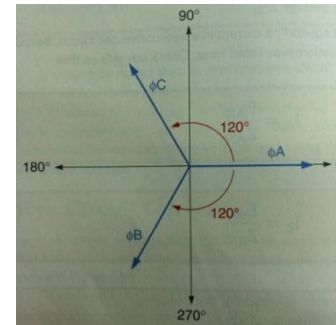
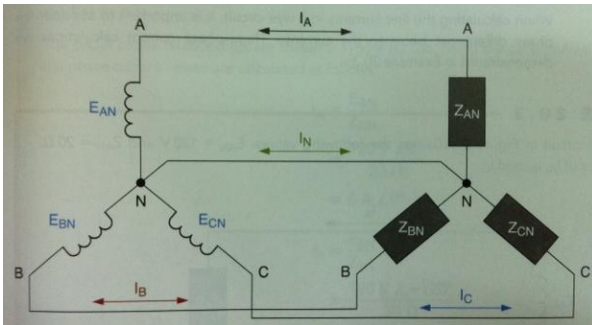
Line Voltage : Phase – Phase Voltage

$$E_{Line} = \sqrt{3} \times E_{phase} \angle 30^\circ$$

$$I_{Line} = I_{phase}$$

$$I_N + I_A + I_B + I_C = 0$$

$$E_{AB} = \sqrt{3} \times E_{AN} \angle 30^\circ$$



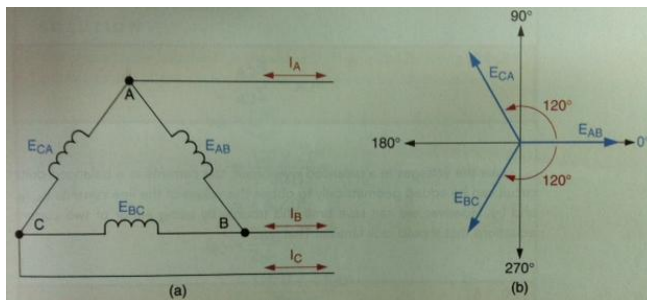
Balanced Delta Circuit :

$$E_{Line} = E_{phase}$$

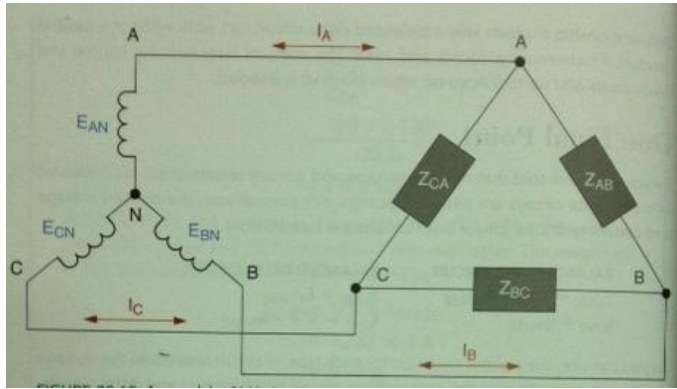
$$I_{Line} = \sqrt{3} \times I_{phase} \angle -30^\circ$$

$I_N = 0$  there is no need for a neutral conductor for balanced case

$$I_A = \sqrt{3} \times I_{AB} \angle -30^\circ$$



➤ A wye-delta circuit

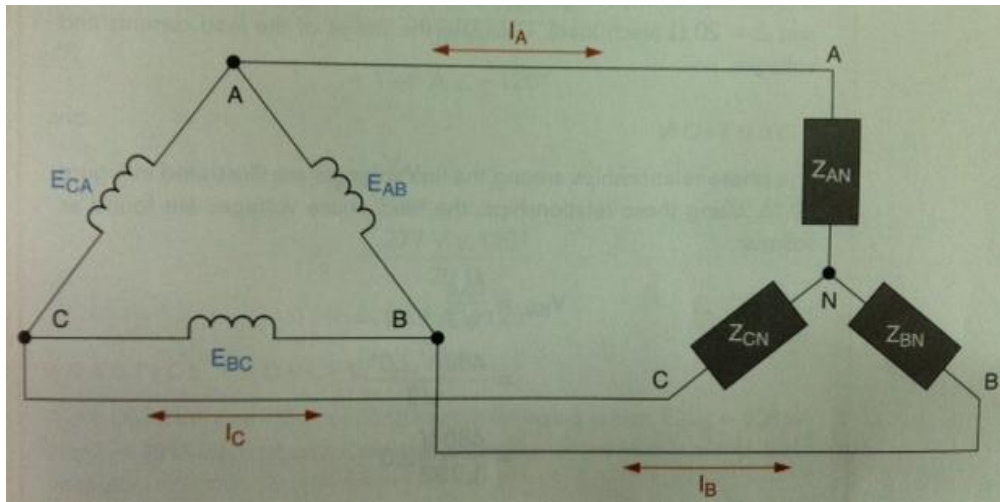


$$V_{AB} = E_{AN} + E_{BN} = E_{AB}$$

$$V_{BC} = E_{CN} + E_{BN} = E_{BC}$$

$$V_{CA} = E_{AN} + E_{CN} = E_{CA}$$

➤ A delta-wye circuit



$$V_{BN} = \frac{E_{AB}}{\sqrt{3}}$$

$$V_{CN} = \frac{E_{BC}}{\sqrt{3}}$$

$$V_{AN} = \frac{E_{CA}}{\sqrt{3}}$$

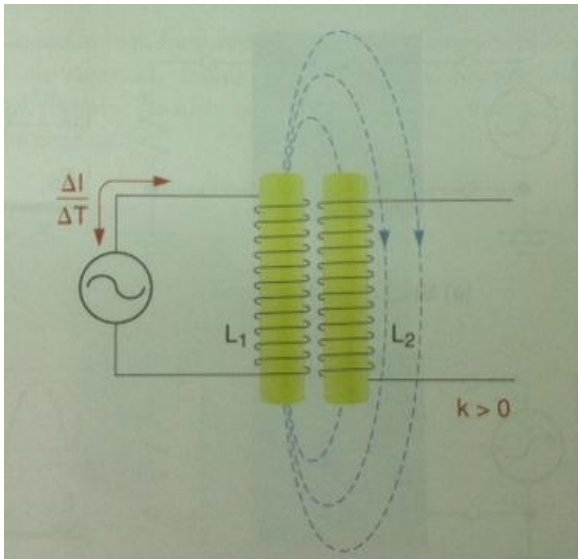
➤ For any delta or wye circuit

$$P_{APP} = 3 \times E_P \times I_P$$

$$P_{APP} = \sqrt{3} \times E_L \times I_L$$

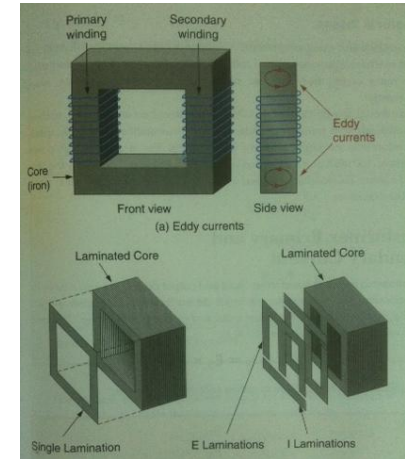
# 18. Introduction to Transformers

- Transformer : A component that uses electromagnetic induction to pass an AC signal from one circuit to another, while providing DC isolation between two
- Coupling : When a component or circuit passes an AC signal from one point to another
- Isolation : When a component or circuit prevents a signal from passing between points



- Voltage induced across  $L_2$  has the same shape as  $L_1$
- Inductors are not physically connected. Primary coil does not generate a changing magnetic field when DC voltage is applied
- Turn : Each loop of wire in a coil
- Turns Ratio :  $\frac{N_P}{N_S} = \frac{E_P}{E_S} = \frac{I_S}{I_P}$
- $P_P = P_S$        $E_P \times I_P = E_S \times I_S$  (ideal conditions)
- Efficiency :  $\eta = \frac{P_S}{P_P} \times 100$

- Copper Losses :  $I^2R$  losses
  - All wire has some resistance
  - Power dissipated when current passes through the primary and secondary coils
  - Constructing transformer using largest practical wire diameter
  
- Eddy Current Loss : unique to iron core transformers
  - When magnetic flux generated in the primary, it passes through the iron core
  - iron core is conductor, flux generates a current within the core; eddy current
  - circular motion, this loss can be reduced by using laminated core
  
- Hysteresis Loss : The energy used to overcome the retentivity of a transformer (inductor) core
  - Refers the energy expended to overcome the core's retentivity
  - Each time transformer input reverses polarity, polarity of magnetic field must be reverse
  - Using low-retentivity materials; air, silicon steel, laminated core
  
- Stray Loss : no transformer has a perfect coefficient of coupling ( $k=1$ )
  - some magnetic flux does not cut into secondary
  - flux that does not reach secondary may interact with nearby conductors, resulting stray loss
  
- Mechanical Loss : Expanding and collapsing magnetic field in a high-power transformer can produce
  - mechanical stresses on the component's wires, core and support structure

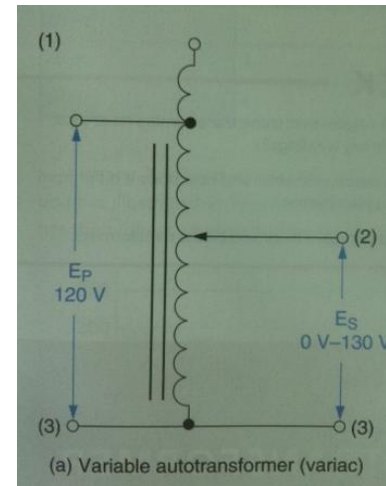
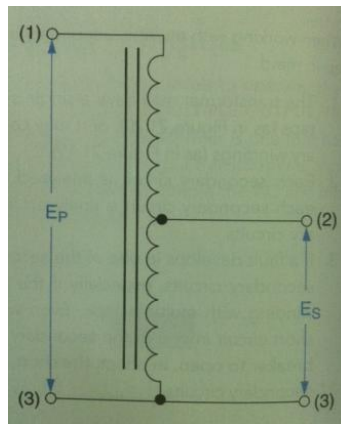


- Center Tapped Transformer : has an additional lead connected to center of its secondary winding
- Split Phase : The output from the center-tapped transformer because the two output waveforms are 180° out of phase
- Multiple-Output Transformer : Has two or more secondary coil
- Autotransformers : A transformer made up of a single coil that typically has three terminal connections

Variac : A variable autotransformer

can be wired in either a step-up or step-down configuration  
does not provide DC isolation

Autotransformer can be adjusted to act as either a buck or boost transformer



- Buck Transformer : Step downs its input voltage as much as 20%
- Boost Transformer : Step ups its input voltage as much as 20%

- Harmonic : A whole number multiple of a given frequency
- Harmonic Series : A group of frequencies that are whole number multiples of the same frequency
- Fundamental Frequency : The reference (lowest) frequency in a harmonic series
- N-Order Harmonics : The frequencies in a harmonic series
- Harmonic Distortion : An undesired change in the shape of a fundamental sine wave
  
- Motors can be greatly impacted by harmonic voltage distortion ;
  - decrease efficiency
  - overheating
  - vibrating
  - high-pitched noises
  
- Harmonic Sources;
  - Single-Phase Circuits
    - air conditioners, dryers (first switch on), fax machines, copiers,
    - medical diagnostic equipment, fluorescent light ballasts, computer systems
  - Three Phase Circuits
    - Automation and environmental equipment
  
- Harmonics can;
  - decrease the system power factor
  - produce excessive heat in distribution transformers, shortening lifespan
  - produce voltage waveform distortion
  - produce high currents in neutral conductors



- Two general approach to deal with harmonics;

dealing with symptoms

increase the size of neutral conductor

shorten the distance between service panel and loads to reduce the voltage produced by the harmonics

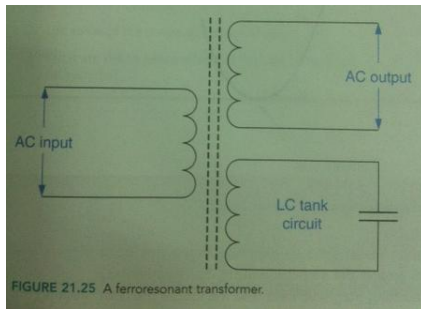
in three phase systems

provide a separate neutral for each phase

increase the size of the phase(hot) wires

minimizing the effects of harmonics

using ferroresonant transformers



first coil couples the AC input (fundamental frequency)

second coil is tuned using a capacitor to form a parallel resonant circuit

using harmonic cancellation technique

a special type of transformer (phase shifting transformer) is used to shift harmonics 180° and then combine them with harmonics from another source

- Transformer Hum : Humming sound is a result of magnetostriction.

Magnetostriction : When the laminations in an iron core transformer are exposed

to expanding and contracting magnetic fields, they expand and contract slightly.

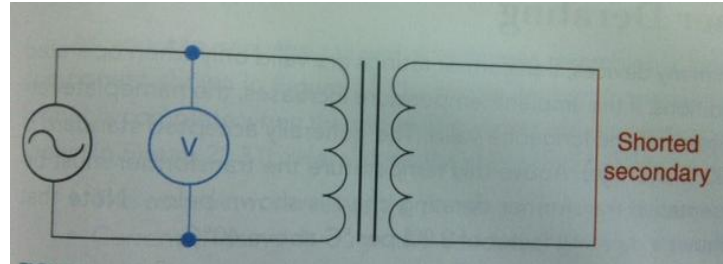
The volume of hum depends on the amplitude of the AC input. Hum frequency is twice per input cycle

- Inrush Current : A high initial current in the primary of a transformer.

Can be made worse by residual flux in the transformer core

- Percent Impedance (%Z) : The transformer primary voltage (as a percentage of its rated value) that generates maximum current through a shorted secondary

$$\%Z = \frac{E_{P(measured)}}{E_{P(rated)}} \times 100$$



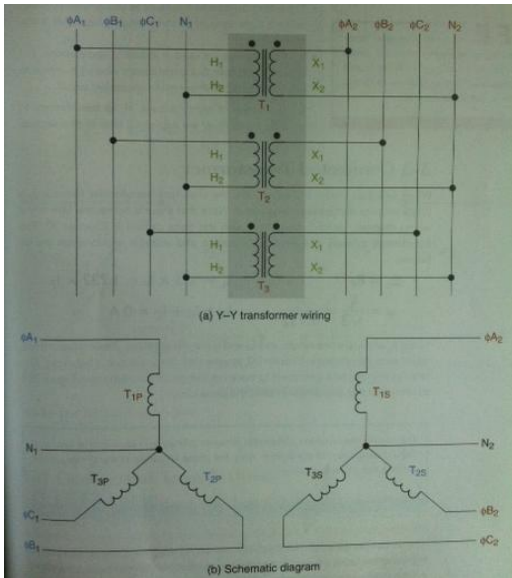
- %Z of transformer relates to its voltage regulation.
- Voltage Regulation : The ability of a transformer to maintain a stable output (secondary) voltage when the load demand changes

$$Regulation = \frac{E_{NL} - E_{FL}}{E_{NL}} \times 100$$

Lower %Z; better voltage regulation

# 19. Three Phase Transformers

## ➤ Y-Y Connected



$$E_L = \sqrt{3}E_P \angle 30^\circ \quad I_L = I_P$$

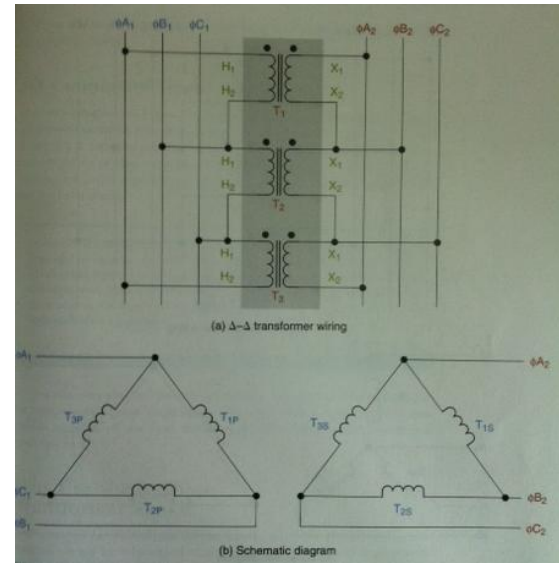
Industrial applications where neutral needed

To avoid excessive heating,

both input and output neutrals must have grounded

and phase-neutral load imbalance < %10

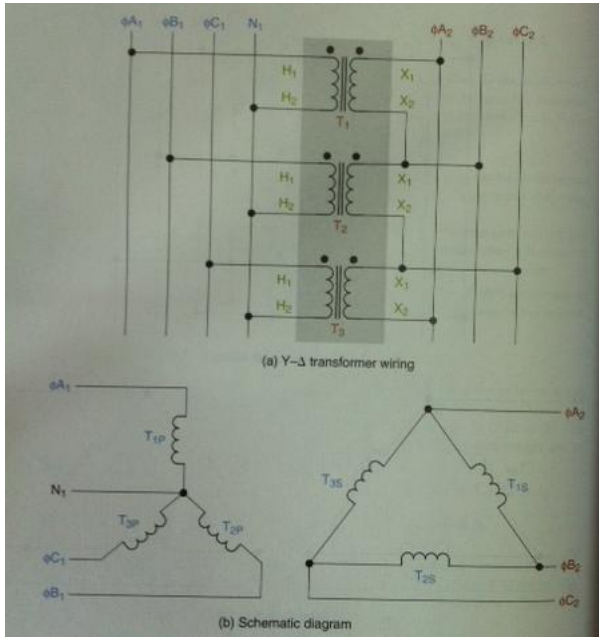
## ➤ $\Delta$ - $\Delta$ Connected



$$E_L = E_P \quad I_L = \sqrt{3}I_P \angle -30^\circ$$

Angular difference between primary and secondary is zero

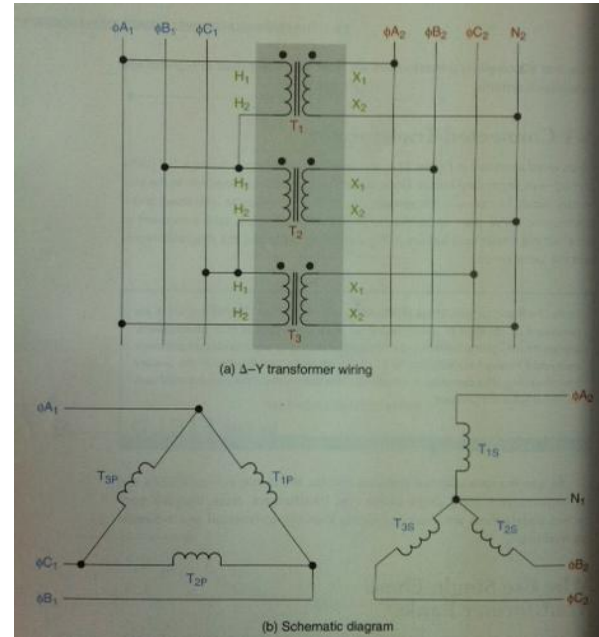
➤ Y-Δ Connected



Angular difference between primary and secondary is  $30^\circ$

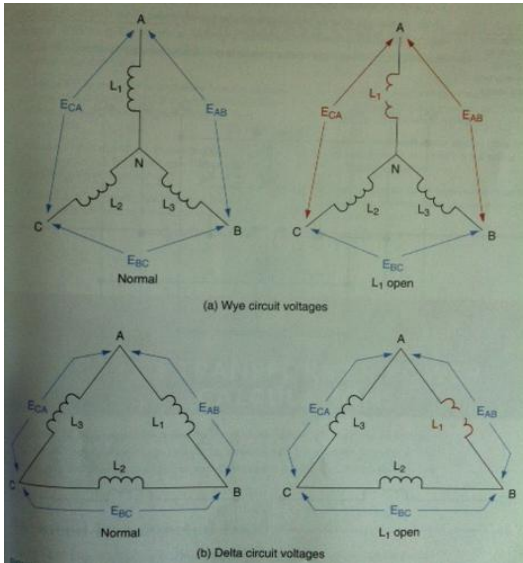
Most commonly used in high voltage transmission systems

➤ Δ-Y Connected



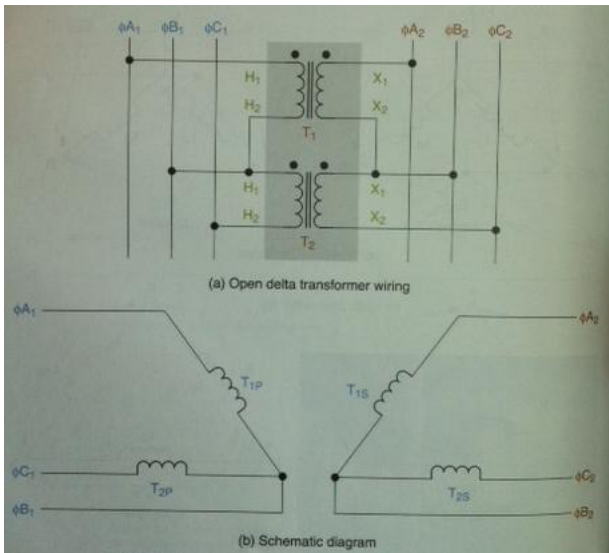
Triplen harmonic currents ( $3^{\text{rd}}$ ,  $9^{\text{th}}$ ,  $15^{\text{th}}$  etc) pass through secondary winding but are trapped by and circulate in the primary  $\rightarrow$  overheating

Commonly in commercial and industrial applications



- When one of the phase inductors in a Y circuit opens circuit reduced to a single phase circuit, only  $E_{BC}$  is unchanged
- When one of the phase inductors in a  $\Delta$  circuit opens circuit still operates as a three-phase circuit but at reduced capacity

### ➤ Open Delta Connection

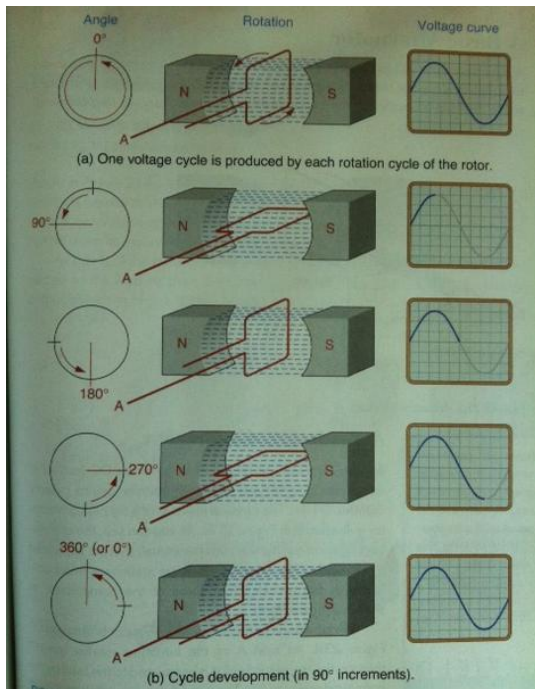


- Producing three phase circuit using only two single phase transformers
- Rarely encountered anymore
- limited to approx. 87% of the sum of the two single-phase transformer's kVA ratings
- equal to 57.7% of the kVA capability of a comparable full delta transformer

- Distribution Transformer : to step down the voltages transmitted by power utilities to values required by customers
- Pole-Type Transformer : A distribution transformer that is mounted on a pole, 15-500kVa
- Pad-Mounted Transformer : Mounted on a rectangular concrete pad, 75-2500kVa
- Dry-Type Transformer : Air cooled and may have louvers to aid cooling,  $\leq 500\text{kVA}$
- Wet-Type Transformer : cooled using mineral oil or high temperature hydrocarbons  $> 2\text{MVA}$ 
  - more efficient than dry-type, outdoor use
  - contain fluids that are flammable
  - must ensure fluid can not leak, increase cost
- Vault-Type Transformer : Designed for underground installation
- Submersible Transformer : used in underwater power transmission systems

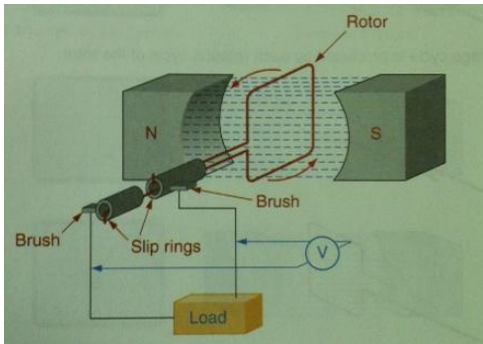
# 20. DC Machines: Generators & Motors

- DC generators produce single-polarity output voltages, industrial and automotive applications
- DC motors are used primarily where variable motor speeds are required
- Generator : A machine that converts mechanical energy to electrical energy
- Alternator : An AC generator



- A voltage is induced across the loop conductor (armature) as it cuts through the stationary magnetic field
- The magnitude and polarity of the voltage depend on
  - the angle of rotation of the armature relative to the magnetic lines of force
  - the strength of the magnetic field, flux density
  - the speed at which the armature rotates

➤ A Basic Alternator :

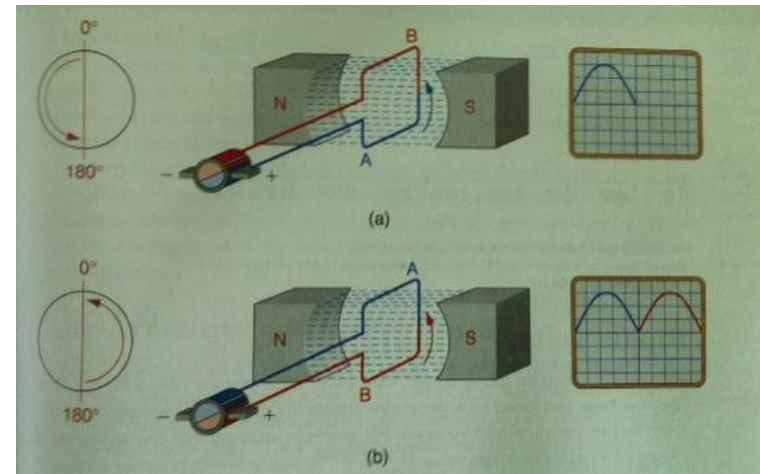
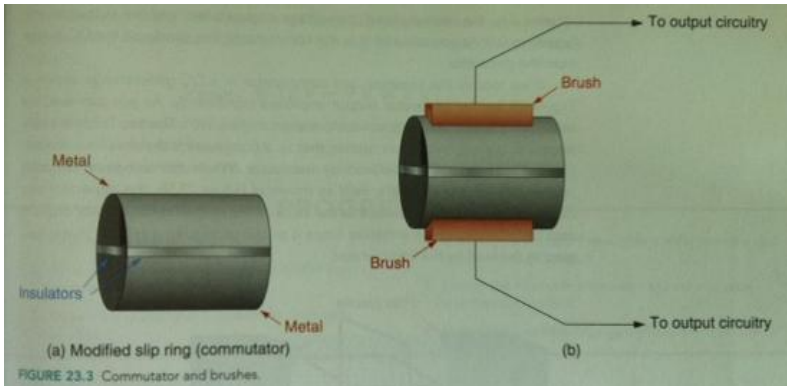


- Armature is attached to a pair of slip rings
- As the armature and slip rings rotate,
- the voltage induced across the loop is coupled to the load by the brushes

➤ A Basic Generator :

An alternator can be modified to generate DC by replacing the slip rings with a similar device; commutator

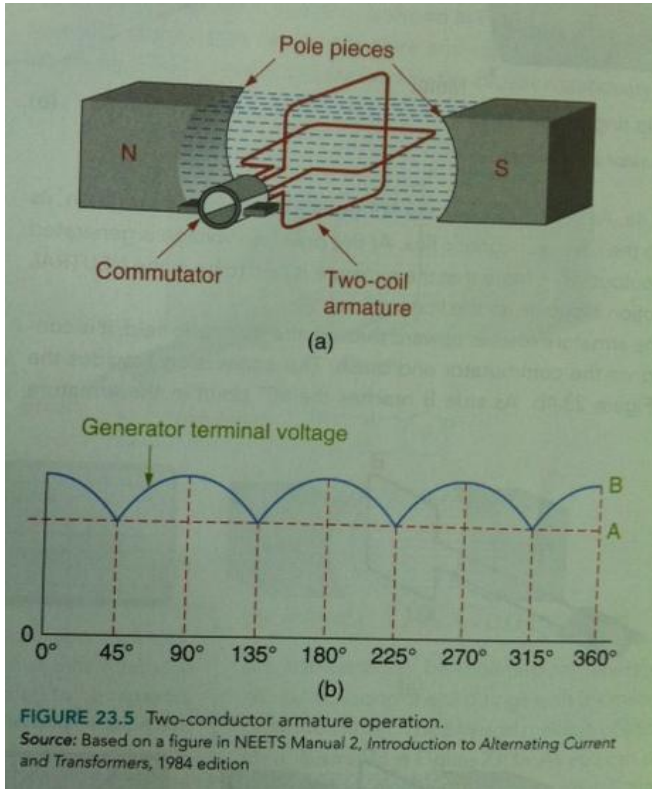
Commutator : A device that converts the output of an alternator to DC



- As side A reaches 90° point in the armature rotation, its motion is parallel to the lines of magnetic flux → no voltage  
armature is said to be in the neutral plane
- As side B of the armature rotates upward through the magnetic field, it is connected to the load via the commutator and brush
- Neutral Plane : The space above and below a stationary magnet where a spinning rotor is in parallel with the magnetic field outside of the magnetic field



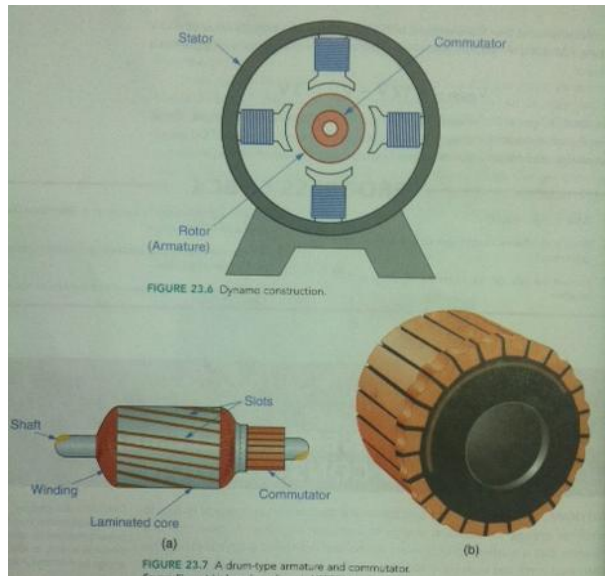
- If we modify the armature and commutator in a DC generator, output improves significantly



- Armature contain two loop conductors at an angle  $90^\circ$
- The two loops connected to a 4-segment commutator (4 conductive surfaces separated by insulators)
- The output voltage never drops to zero because one of the armature loops is always producing a voltage

- Ripple Voltage : The voltage variations in the output from a DC generator
- Label A : 12V Label B :9V  $V_{Ripple} = 3V$
- Ideal DC generator, no variations at all
- Goal of DC generator design is to produce the least amount of ripple possible

- Dynamo : An electromechanical device that can convert mechanical energy to electrical energy, or vice versa
- Generator : is a dynamo that is configured to convert mechanical energy to electrical energy
- Motor : is a dynamo that is configured to convert electrical energy to mechanical energy



Every dynamo has

- a stationary structure : stator (made up of frame, pole cores, interpoles, windings)
- a rotating structure : rotor (armature conductors, armature core and commutator)

A typical generator armature : drum type armature

Shaft allows it to spin freely

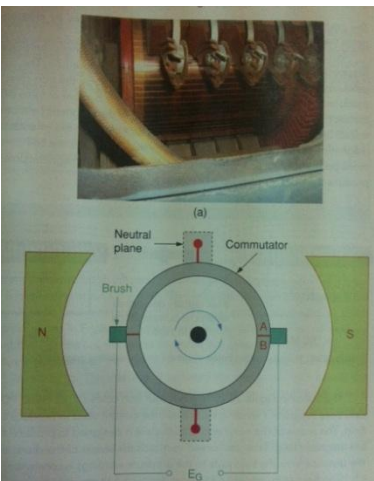
Laminated iron core (or drum) hold armature windings

Both end of windings are connected to the commutator

Commutator has many segments that are separated by insulating layers

Simplex Winding : armature winding consists of a single conductor

Multiplex Winding : armature winding consists of multiple conductors



Eddy Current Losses : Eddy currents are produced when an iron core is exposed to a magnetic field

Like the iron core in transformer, armature drum is susceptible to power losses from eddy currents

→ laminated armature drums

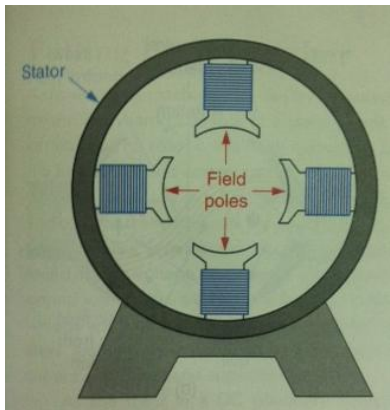
Generator Brushes : The stationary contacts that couple the output from rotor of a DC generator to load

Carbon, carbon graphite, low resistance, good surface wear quality

Commutator rotates → brushes provide an electrical connection between two commutator segment

Brushes shorting out two segments, but loop conductors are in neutral plane

so there is little or no voltage across the segments



Field Poles : A stator pole that supports a current carrying winding used to produce a magnetic field  
 The shape of outer end is designed to produce a more stable magnetic field,  
 curved to match the shape of the drum armature so the distance is constant

Field Poles can be wired as

series (for high voltage, low current) → wave wound

parallel (for low voltage, high current) → lap wound

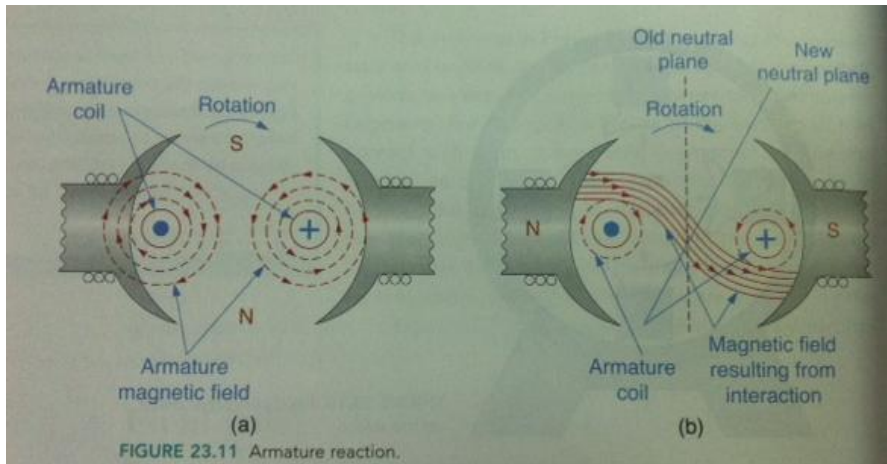
series-parallel (moderate voltage and current) → frog-leg wound, (most commonly used)

The armature in a DC generator must be wired so that each conductor originating at the commutator end of the device  
 passes through one magnetic polarity

### Compensating Windings :

When current passes through the rotating armature windings in a generator  
 magnetic flux is generated around the wires.

This magnetic flux interfere with the stationary magnetic field generated by the field poles



The interaction between magnetic fields causes the neutral plane shift  
 in the direction of armature rotation, known as armature reaction

Each time load current varies, neutral plane shifts

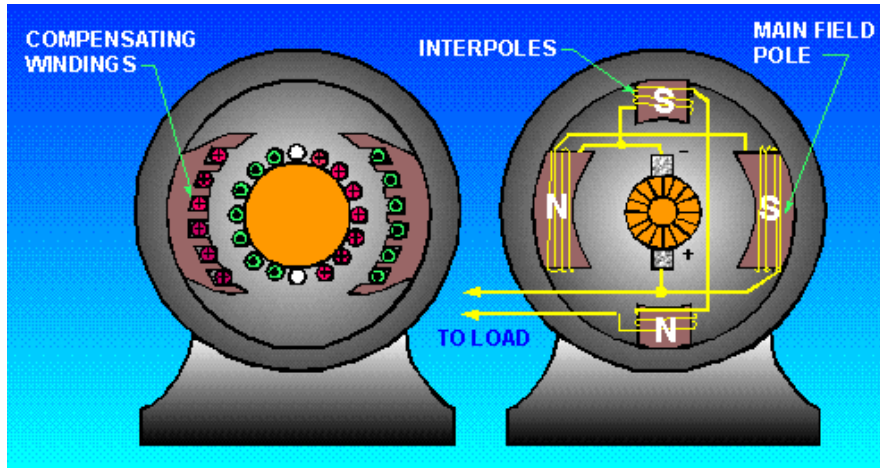
For commutator to operate properly

the brushes must be shifted (reposition to new neutral plane)  
 or neutral plane must be shifted back to original position

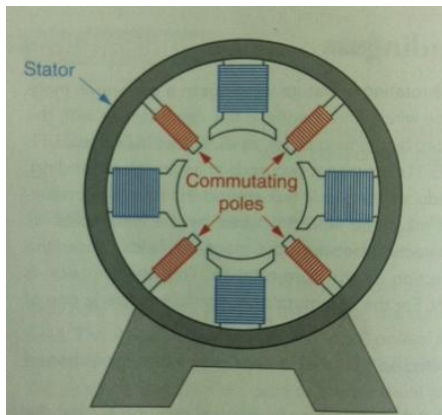
Small DC generators, shifting brushes → not complete solution, current varies neutral plane varies

Larger DC generators, shifting neutral plane

- Shifting neutral plane can be accomplished using coils that are series wound on commutating poles (or interpoles)
- **Commutating Poles (Interpoles, yardımcı kutup)** : Series wound poles that produce magnetic flux that counters the flux produced by the armature current, restoring the neutral plane to its original orientation
- Neutral plane correction is also accomplished using compensating windings
- **Compensating Windings** : short, series-wound coils wrapped at 90° angles to the field coils

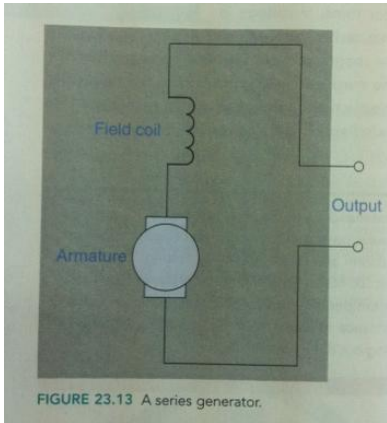


Interpoles and Compensating Poles are connected in series with the armature  
 Varies directly with armature current, opposes the magnetic field of the armature



Interpoles : have a few turns of large wire and  
 are connected in series with the armature

➤ **Series (Wave) Generators :**



Armature current passes through the field coil  
classified as self-excited generator, because it provides its own field coil current via the armature

Generator Voltage : depends on  
the number of armature conductors  
the number of field poles  
the flux per pole  
rotational speed of the armature

$$E_G = \frac{z}{a} \times \Phi \times P \times \frac{\text{rpm}}{60}$$

where

- $E_G$  = the generator voltage
- $z$  = the number of armature conductors
- $a$  = the number of parallel paths
- $\Phi$  = the flux per pole, in webers (Wb)
- $P$  = the number of poles
- rpm = the rotational speed, in revolutions per minute

In addition, output voltage of a series generator can also be affected by the load current

$$V_{OUT} = E_G - I_L(R_A + R_W)$$

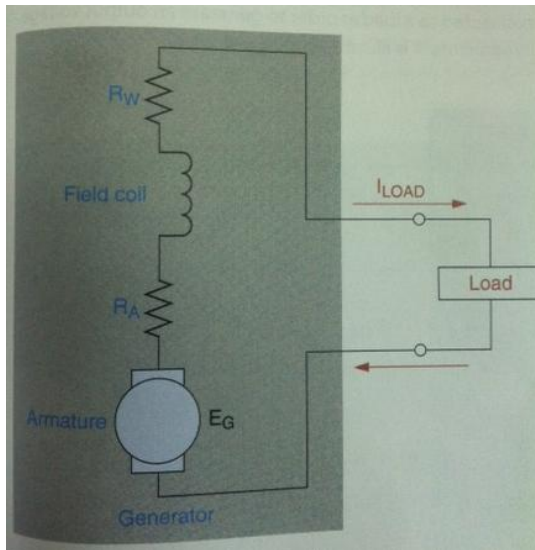
$R_A$  : internal resistance of armature, armature, commutator, brush resistance

$R_W$  : winding resistance of the field coil

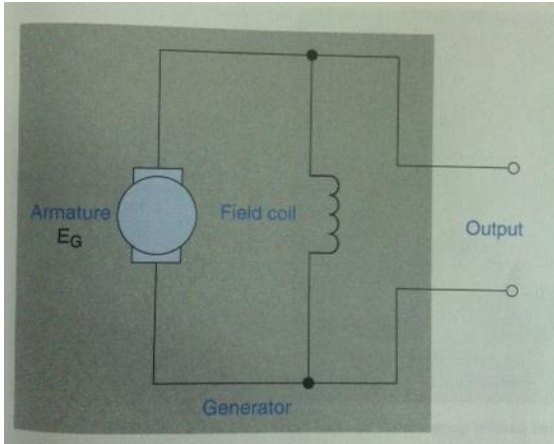
Increase in load demand causes a decrease in generator output, and vice versa

**Open Load Condition :**

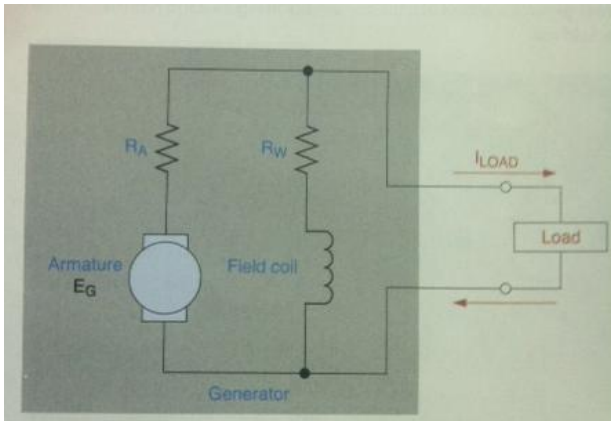
When the load is open, there is no current path through generator's internal circuit  
field coil does not generate mmf and magnetic field → output voltage is 0V



➤ **Parallel (Lap) Generators:**



- Voltage across the field coil equals the armature voltage
- Current through the field coil is relatively independent of the armature current



- If load current demand increases, generator output decreases slightly

$$E_{OUT} = E_G - I_A R_A$$

- Lap Generator is also self-excited
  1. Current is generated in the generator armature as it spins
  2. The armature current passes through the field coils
  3. The current through the field coils generates a magnetic field
  4. The magnetic flux produced by the field coils permeates the armature inducing a voltage across its windings

- How does the cycle begin?

### Voltage Build Up

When a DC generator begins to rotate,

residual magnetism in the field cores induces a slight voltage across the armature windings

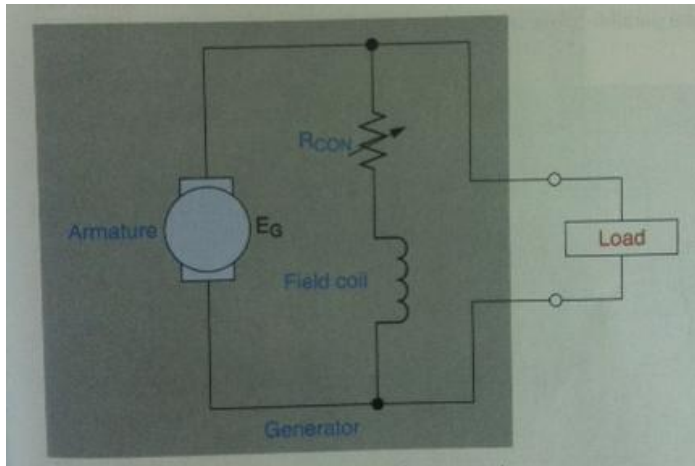
This voltage generates a low-level current that passes through the field coils

The current through the field coils increases the flux density, causing voltage induced across armature to increase

The increased armature voltage increases the current through the field coils, and so on.

If the generator operating properly, the cycle continues until the generator output voltage builds up its rated value

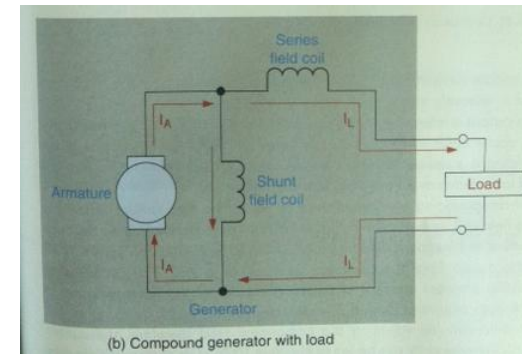
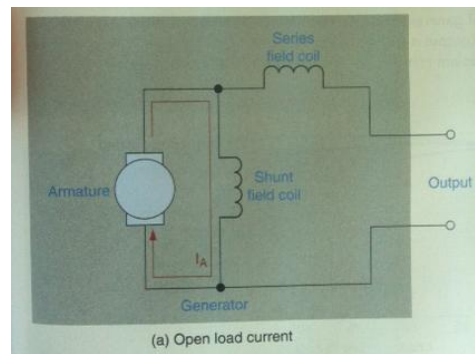
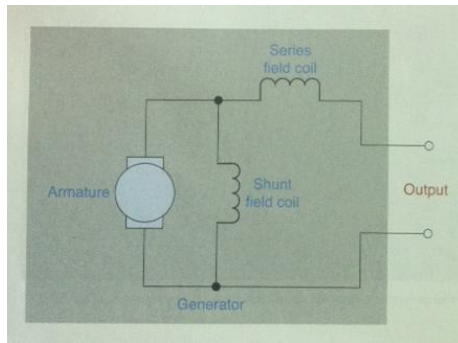
- Output Voltage Control



- The output voltage can be controlled by placing a rheostat in series
- The control rheostat ( $R_{CON}$ )
  - limits the current through the field coil
  - therefore, the voltage induced across the armature

➤ **Compound (Frog-Leg) Generators :**

Output voltage is more stable than either series or parallel generators → used more often



When no load is connected

the armature current  $I_A$  passes through the shunt field coil

with no current through series coil, the voltage output is equals the armature voltage  $E_G$

When load is connected

the armature current splits

the load current passes through the series field coil, increasing magnetic flux produced by that coil with the series and shunt field coils wrapped around the same field poles

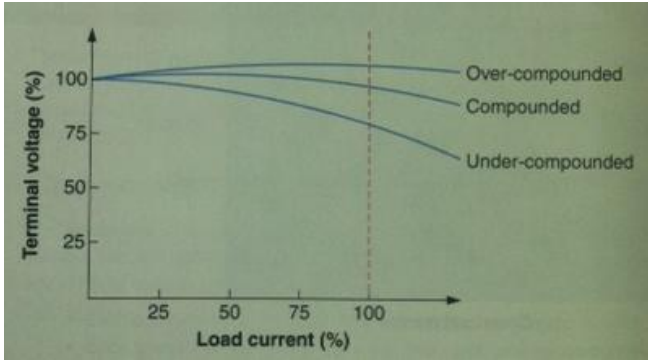
the increased flux generated by the series coil adds to flux generated by the shunt coil

the voltage induced across the armature increases

this offsets the voltage drop across series field coil, keeping output voltage stable



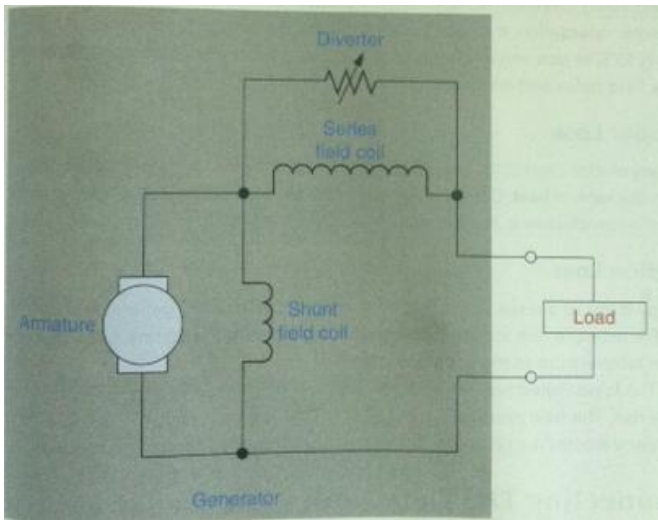
- Compounding : The process of compensating for the effects of predictable load demands on a generator



Under-Compounded : describes the condition where a generator is not adequately compensating for changes in load demand

Compounded : describes the condition where a generator is adequately compensating for changes in load demand

Over-Compounded : provides added insurance against the effects of load demands on the generator output voltage

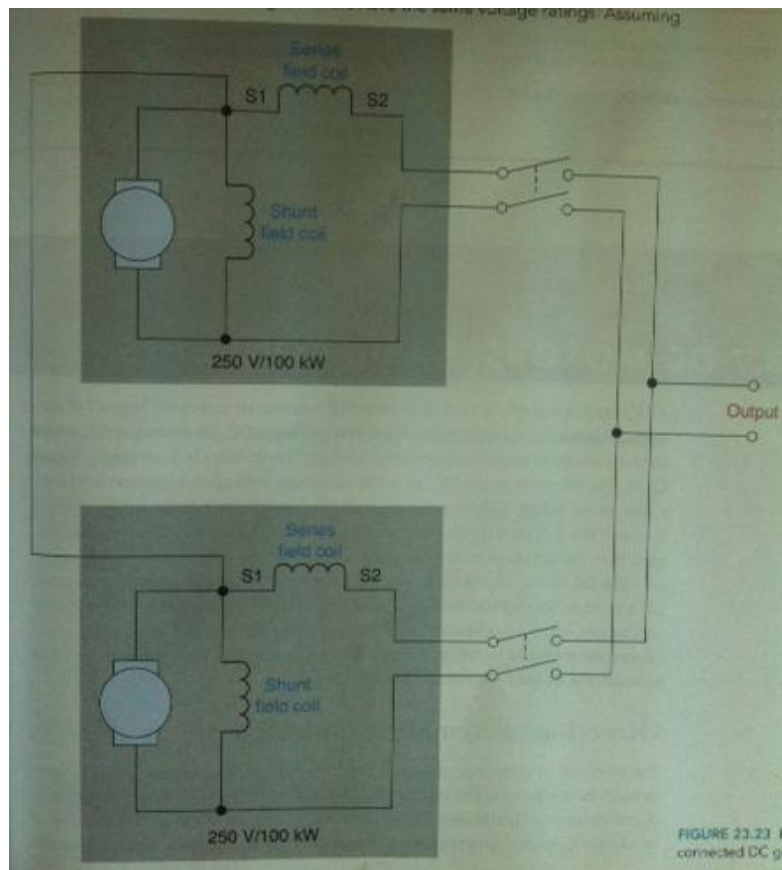


Over-Compounded is accomplished by increasing the number of turns in the series field coil

Diverter provides a path for current to bypass the field coil, thereby helping a generator to match the requirements of its load

- Eddy current power losses : armature drum DC generator is laminated
- Hysteresis Loss : occurs when energy is used to change polarity of any residual magnetic flux in iron  
as the armature rotates, armature is exposed to alternating N and S poles  
as each pole is passed, energy is used to overcome the previous magnetic orientation
- Copper Loss : power loss in the form of heat,  $I^2R$  loss, in the armature, brushes, magnetic pole windings
- Friction Loss : energy loss by the friction between brushes and commutator, rise in temperature

## Connecting DC Generators in Parallel



To provide same current capability as a larger generator

More flexible

According to current demand (high/low), generators can be increased/reduced

One generator fail, it can be repaired without disrupting other generators

Five requirements are needed:

1. Generators should have nearly identical output voltage ratings and voltage versus load current characteristics
2. Generators must be connected positive-positive and negative-negative
3. A means of disconnecting each generator must be provided
4. An equalizing connection must be made to ensure they respond equally to a change in load demand  
(the connection between S1 points alters the circuit that two series coils are in parallel with equal voltages across the field coils the currents through them are equal any change in load demand is split equally between two generators)
5. Generators must have the same prime mover



- DC motor advantages over AC motors
  - speed of DC motor can be varied by varying armature voltage
  - DC motor can provide near-constant torque over a wide range of operating speeds

- Torque : The force required to rotate an object about a point

$$T(Nm) = F \times r$$

*T = torque F = Force r = distance from the axis of rotation*

- Work : for a motor, product of the force used to move an object and the distance the object is moved

$$W(Nm \text{ or Joule}) = F \times D$$

- Full-Load Torque : The torque produced by a motor when it is operating at its rated power and at full speed

$$T = \frac{5252 \times HP}{rpm}$$

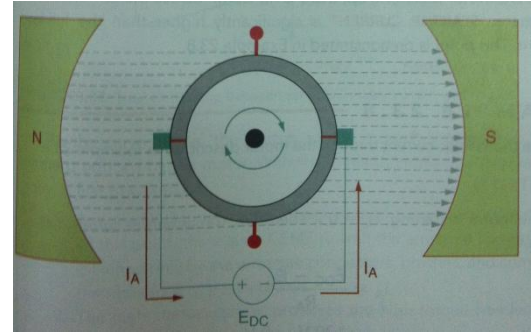
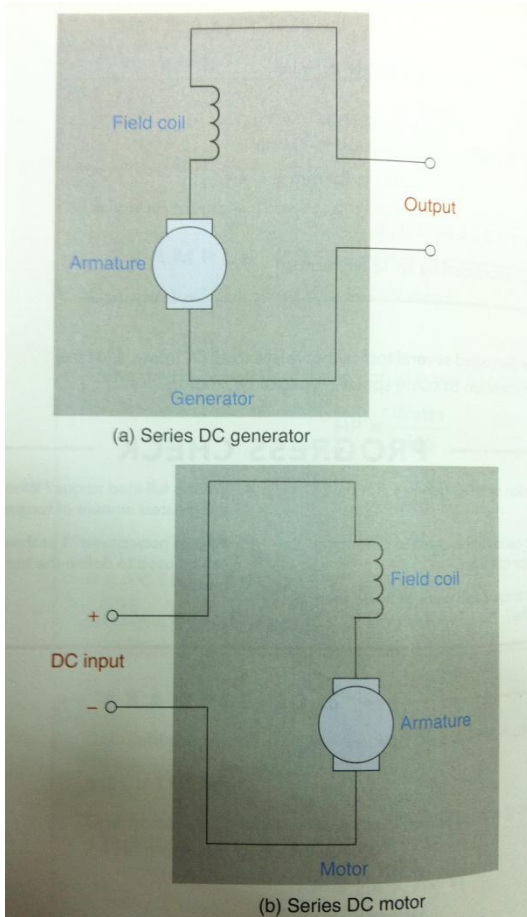
The starting torque for a DC motor can be five times its full-load torque.

- Horse Power : A unit of measure for motor power

$$1 HP = 746W$$

## ➤ Series DC Motors

DC motors and generators are nearly identical.



When a voltage source is connected to the commutator of a DC motor, a current is generated through armature.

As the armature rotates through magnetic field, a counter EMF (CEMF) is induced across the armature ( $E_G$ ) that opposes the DC input voltage ( $E_{DC}$ ).

As a result armature current is limited to:

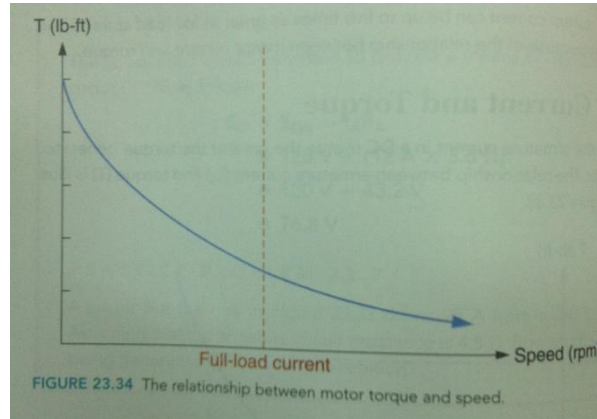
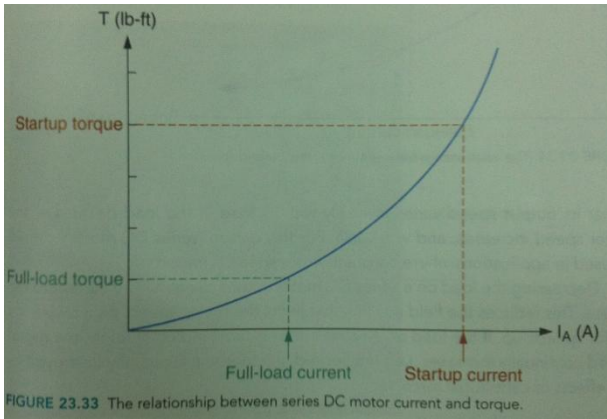
$$I_A = \frac{E_{DC} - E_G}{R_A}$$

where

- $I_A$  = the armature current
- $E_{DC}$  = the applied voltage
- $E_G$  = the CEMF generated by the armature rotating through the magnetic field
- $R_A$  = the resistance of the armature circuit (windings, brushes, and commutator)

However, when a DC motor is starting up, there is no CEMF.

So, the motor startup current is significantly higher than full-load motor current. (~five times)



What happens when the motor is first powered on:

1. A high value current (startup current) is generated in the armature.  
There is no CEMF to limit the current.  
It is only limited by the armature conductors, brushes, commutator and the resistance of field coils.
2. High startup current produces the high torque needed to increase the armature speed.
3. As the armature comes up to speed, the torque decreases.  
By the time armature is rotating at full speed, the torque has decreased to its full load value.

The primary strength of the series DC motor: it can provide high torque when heavily loaded and at startup.

The primary drawback: its output speed varies inversely with its load. → no usage where constant motor speed is important.

Decreasing load causes the armature current to decrease.

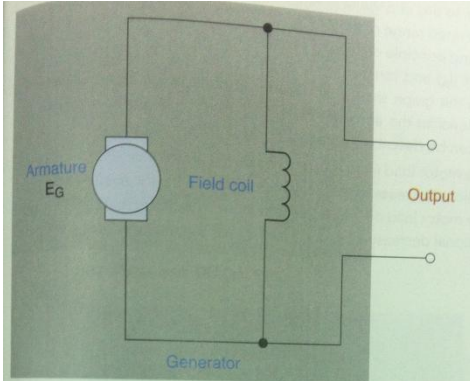
This reduces the field coil flux that limits the motor speed. As a result, motor speeds up.

If the load is removed completely, the motor speed continually increases. → Destroyed by centrifugal force.

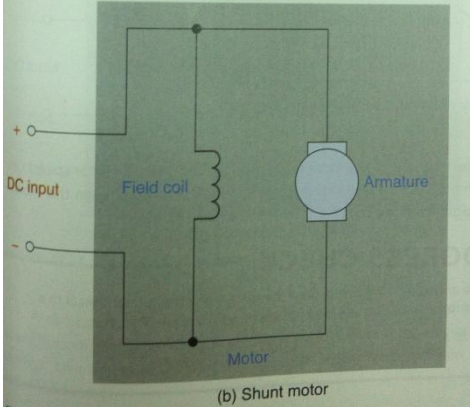
## ➤ Shunt DC Motors

Motor speed remains relatively constant despite variations in its load.

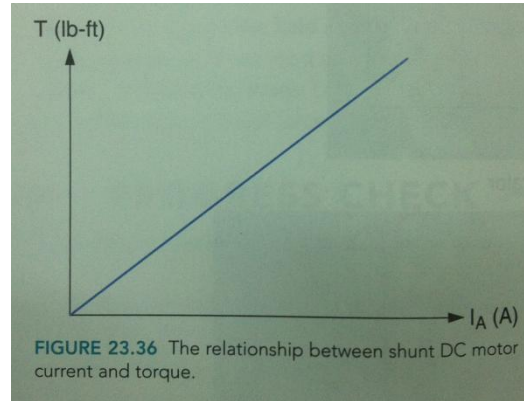
Field coil is connected : in parallel with the armature, across the DC voltage source.



(a) Shunt generator



(b) Shunt motor



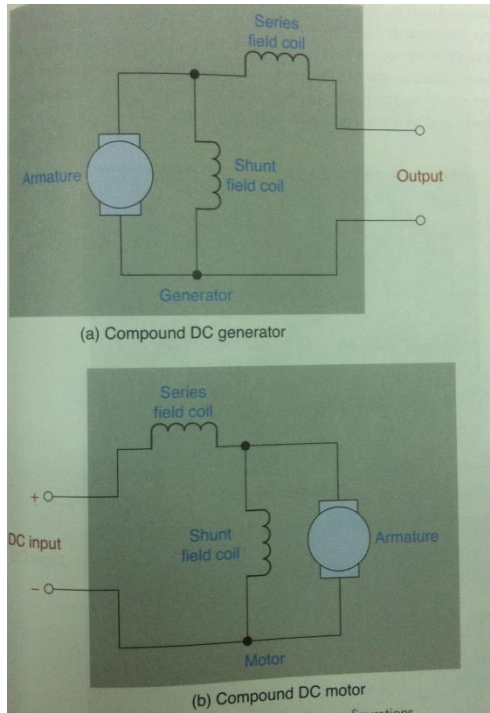
The torque of a shunt DC motor varies directly with its load.

Any change in load hold the motor speed relatively constant. (10% variation)

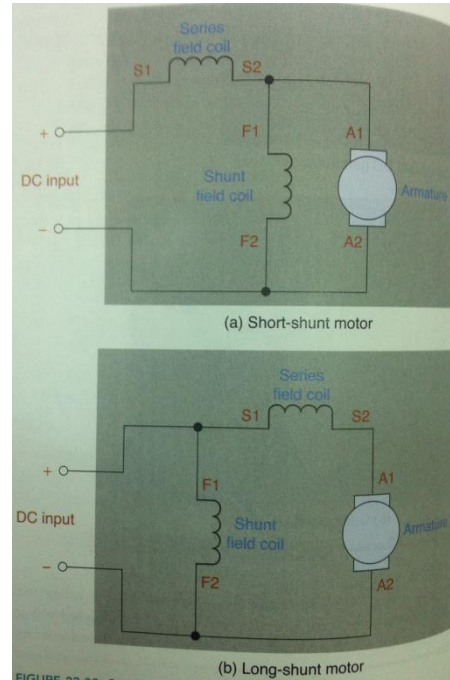
## > Compound DC Motors

Like a series motor, it can produce high torque when loaded and startup.

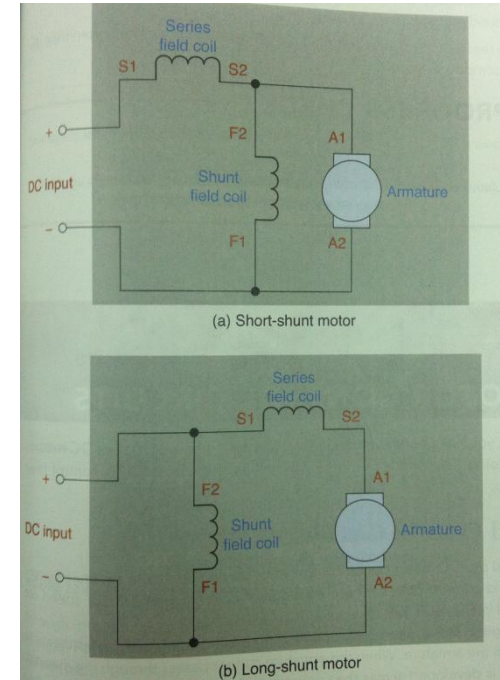
Like a shunt motor, it can maintain a relatively constant speed over its rated load range.



### Cumulative Compound Motors:



### Differential Compound Motors:



Cumulative Compound Motor: (are used far more often)

Shunt field coil : Its flux aids the flux produced by the series coil and the armature.

Long-shunt type is commonly used, because shunt current is relatively independent of the motor load, best speed stability.

Differential Compound Motor:

Shunt field coil : Its flux opposes the flux produced by the series coil and the armature.

Motor speed is very stable over a wide range of load values.

But if the load increases to where motor speed begins to increase, the speed becomes unstable, out of control.

Torque characteristics are poorer than cumulative compound motors.

> Chapter "DC motor control circuits" is skipped.



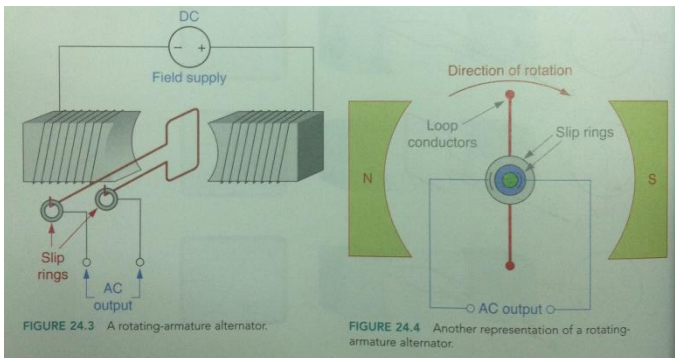
# 21. AC Machines: Alternators & Motors

Alternator: A machine that converts mechanical energy to electrical energy.

A voltage is induced across the loop conductor (armature) as it cuts through the stationary magnetic field. The magnitude and polarity depend on:

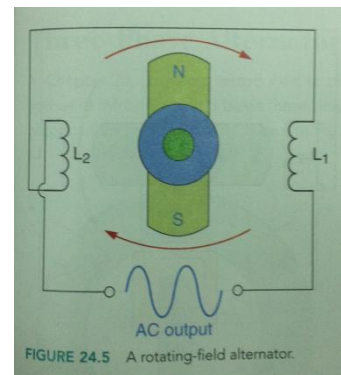
- ❑ The angle and direction of rotation of the armature
- ❑ The strength of the magnetic field (flux density)
- ❑ The speed at which armature rotates

## Rotating-Armature Alternator

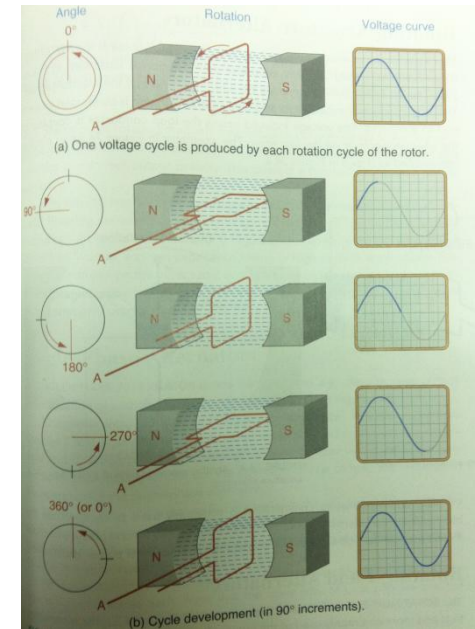


DC field supply provides the current required by the magnets. The loop conductor (armature) rotates on a central shaft and connected on each end to a slip ring. It is rarely used, because it can't provide the enough VA outputs.

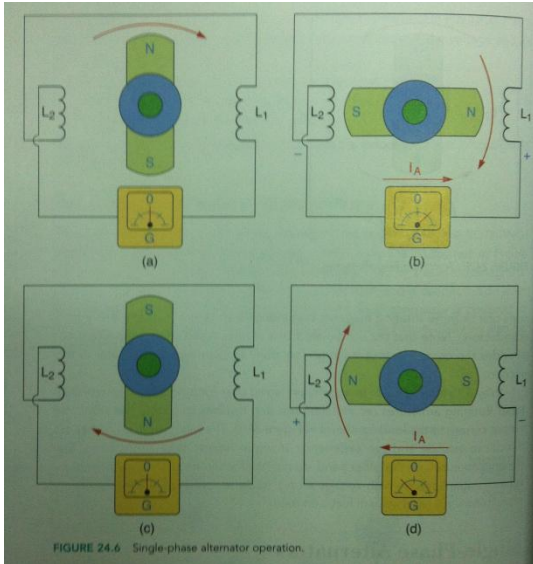
## Rotating-Field Alternator



Uses one or more stationary magnets to induce a voltage.  $L_2$  reverse wired to provide correct output polarity. No slip rings and brush, so more commonly used. 89



Rotating-Armature : Conductors  
Rotating-Field : Magnets



Single Phase Alternators: One that produces a single phase sine wave output.  
 Armature flux is  
 parallel to the windings of the stationary coil, no cut into coils  $\rightarrow 0V, 0A$   
 perpendicular to coils  $\rightarrow$  max. voltage.

Three Phase Alternators: One that provides three sinusoidal outputs.

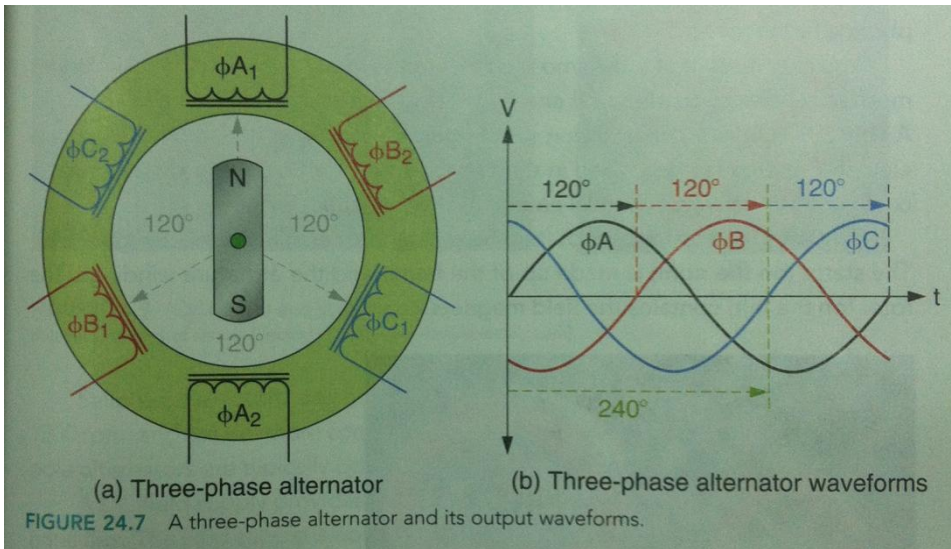


FIGURE 24.7 A three-phase alternator and its output waveforms.

➤ **Three-Phase Alternator Elements and Construction:**

Generator : A dynamo that converts mechanical energy to electrical energy.

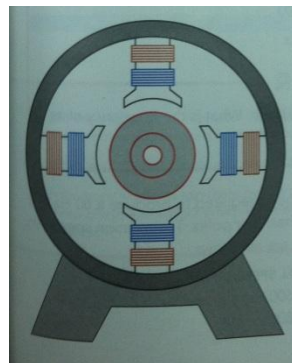
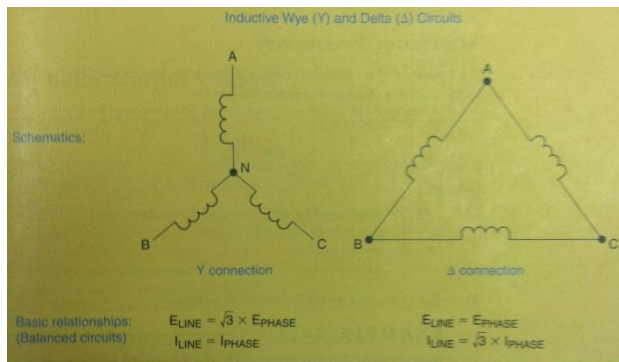
Motor : A dynamo that converts electrical energy to mechanical energy.

Cylindrical Rotor : It is similar to that in a DC generator, but containing electromagnets that generate the alternator field.  
high speed generators driven by gas or steam (turbine-driven rotors)  
speeds of 1200 rpm or more

Salient-Pole Rotor : A rotor containing electromagnets that protrude from the armature.  
more commonly used one  
low speed generators typically driven by water, wind or internal-combustion engines

A DC field supply provides the rotor to generate magnetic flux. It is normally connected via two slip rings.

Stator : Serves as the support structure for its armature windings.



Generally wired two windings per pole.

More efficient

Provides a higher output voltage than one winding per pole.

➤ Alternator Frequency

(24.1)

$$f = \frac{N_s \times P}{120}$$

where

- $f$  = the frequency of the alternator output waveform, in Hz
- $N_s$  = the rotational speed, in rpm
- $P$  = the number of poles

| # of Poles | RPM (60Hz) | RPM (50Hz) |
|------------|------------|------------|
| 2          | 3600       | 3000       |
| 4          | 1800       | 1500       |
| 6          | 1200       | 1000       |

➤ Alternator Output Voltage

(24.2)

$$E = 4.44 \times \Phi \times f \times N$$

where

- $E$  = the effective (rms) alternator output voltage
- $\Phi$  = the flux per pole, in webers (Wb)
- $f$  = the output frequency
- $N$  = the number of turns (per phase)

To adjust the output voltage:

$f$  and  $N$  are fixed. Flux can be changed by the alternator's DC field supply.

$f$  is controlled by the speed of rotation.

Output power is controlled by the torque applied to the alternator shaft by prime mover.

## ➤ Three-Phase Alternator Connections and Loading

### Voltage Regulation:

A measure of voltage source's ability to provide a constant output when the load demand varies.

(24.3)

$$\text{Regulation}(\%) = \frac{E_{NL} - E_{FL}}{E_{NL}} \times 100$$

where

$E_{NL}$  = the no-load alternator output voltage  
 $E_{FL}$  = the full-load alternator output voltage

Ideal alternator would generate the same output voltage regardless of the load value. Regulation would be 0%.  
The lower the voltage regulation of an alternator, the better.

The output voltage is usually controlled by a voltage regulator circuit (adjusts DC field supply).  
The output voltage of an alternator varies inversely with load demand.

### Connecting Alternators in Parallel:

Advantages:

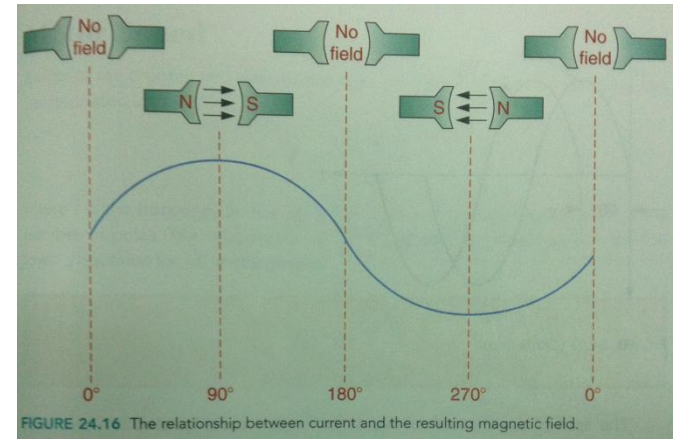
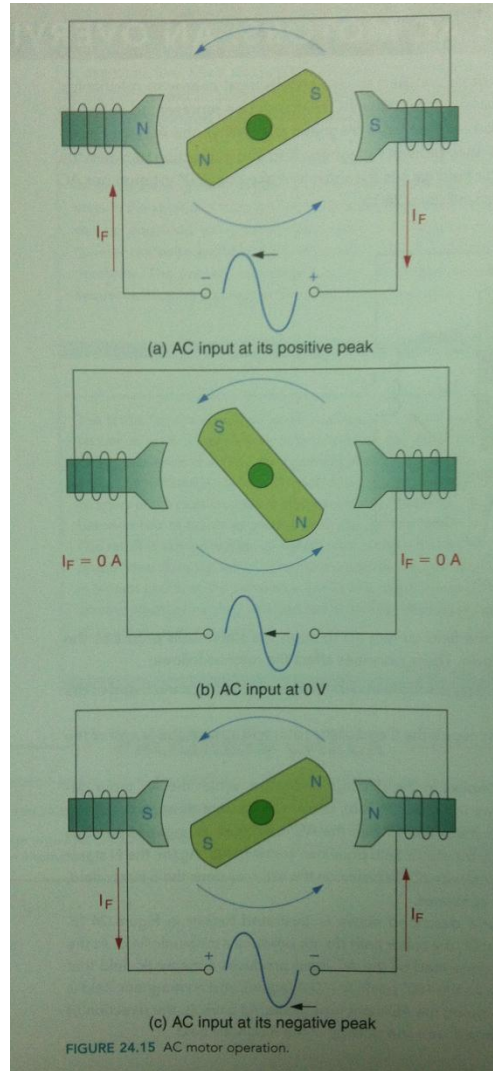
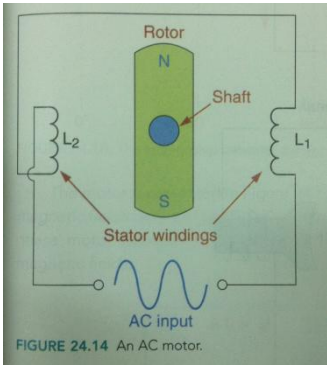
1. The max. possible output current (and therefore power) is increased.
2. The load can operate (often at reduced capacity) while one alternator is shut down.

Precautions:

1. Alternators must provide the same output frequency and voltage.
2. The motors must be synchronized to ensure that they reach their peak values at the same time.

➤ **AC Motors : An Overview**

Basic single phase AC motor:



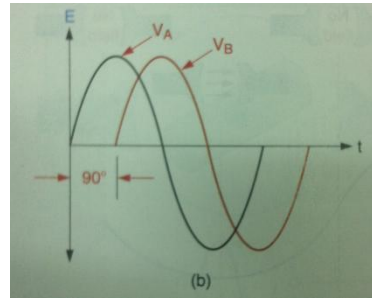
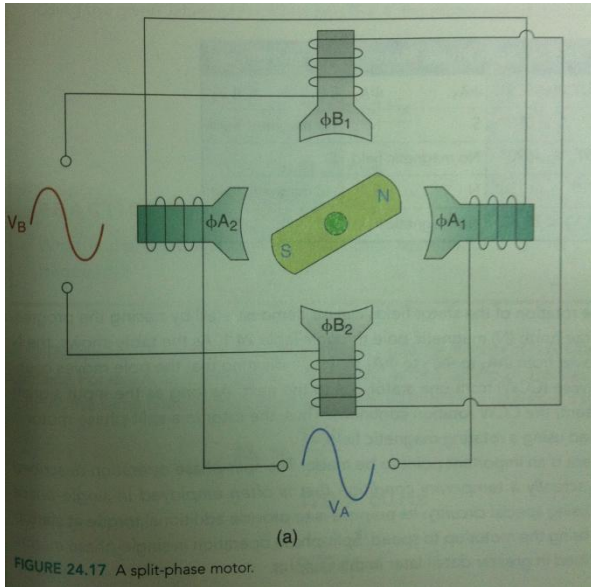
When the AC input applied to stator coils they generate magnetic flux.

The interaction between stator field and rotor field causes the rotor make one 360° rotation per AC input cycle.

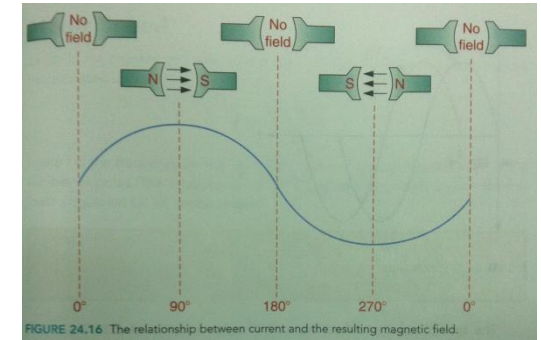
N stator field repels the rotor N end and attracts the rotor S end. S pole does the opposite. Rotor moves in the CCW direction.

This motor operates on switching magnetic fields back and forth between the stator field coils.

Split-phase motor works on the principle of rotating magnetic fields.



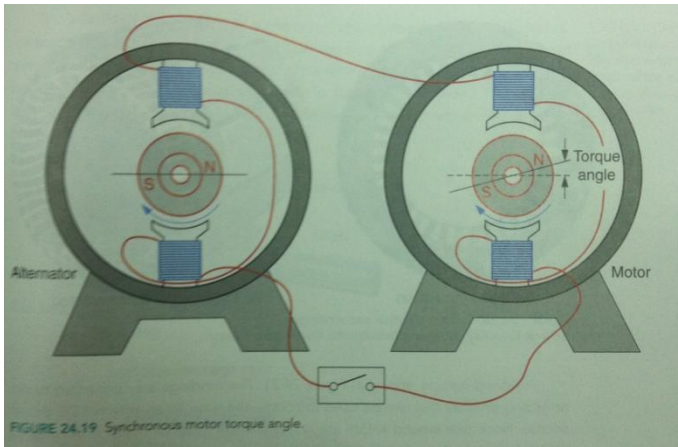
| TABLE 24.1 • Split-Phase Motor Inputs and Phases |                   |            |                   |            |
|--|-------------------|------------|-------------------|------------|
| AC INPUT PHASES                                  | $\Phi A_1$        | $\Phi A_2$ | $\Phi B_1$        | $\Phi B_2$ |
| $V_A$ at $90^\circ$ , $V_B$ at $0^\circ$         | S                 | N          | No magnetic field |            |
| $V_A$ at $180^\circ$ , $V_B$ at $90^\circ$       | No magnetic field |            | S                 | N          |
| $V_A$ at $270^\circ$ , $V_B$ at $180^\circ$      | N                 | S          | No magnetic field |            |
| $V_A$ at $0^\circ$ , $V_B$ at $270^\circ$        | No magnetic field |            | N                 | S          |



The N pole moves from  $\Phi A_2$  to  $\Phi B_2$  to  $\Phi A_1$  to  $\Phi B_1$ , pole moves CCW from one stator coil to the next.

This operation here is actually a temporary condition that is often employed in single phase motors using special circuitry. Its purpose is to provide additional torque at startup to help bring the motor up to speed.

- Motor Speed:  $N_S = \frac{120f}{P}$   
 $N_S$  rotational speed (rpm),  $P$  number of poles
- Synchronous Motor : One that is synchronized to an alternator that acts as an energy and timing source.  
 (no-load speed = full-load speed)
- Asynchronous Motor: One that does not use an alternator as an energy and timing source.
- Induction Motor : A motor with rotor current that is generated by electromagnetic induction rather than a DC field supply.  
 (no-load speed  $\neq$  full-load speed)



Ideally , the motor is perfectly in sync with the alternator rotor.

In practice, however, this is not the case.

As load increases, so does torque angle between motor and alternator rotors.

If the load on motor is sufficient, torque angle  $> 90^\circ$ , sync is lost.

Sync Motor most closely resembles an alternator with a salient-pole rotor.

The rotor electromagnets (poles) are powered by a DC field supply.

In contrast, an induction motor (async motor) does not have a DC field supply.

Rather, rotor current is generated by electromagnetic induction, like in transformer.

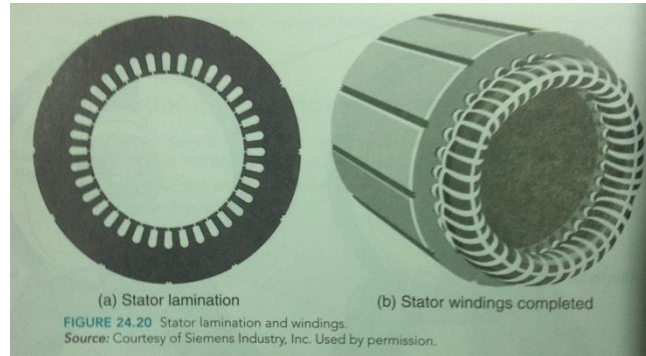
In fact, induction motor is sometimes described as a rotating transformer;

stator – primary winding, rotor – secondary winding.

Source of rotor current is the primary distinction between sync and induction motors.



- The stator of an induction motor is a cylindrical structure made of laminated (to reduce eddy current losses) steel segments.



### Two types of rotors in AC motors

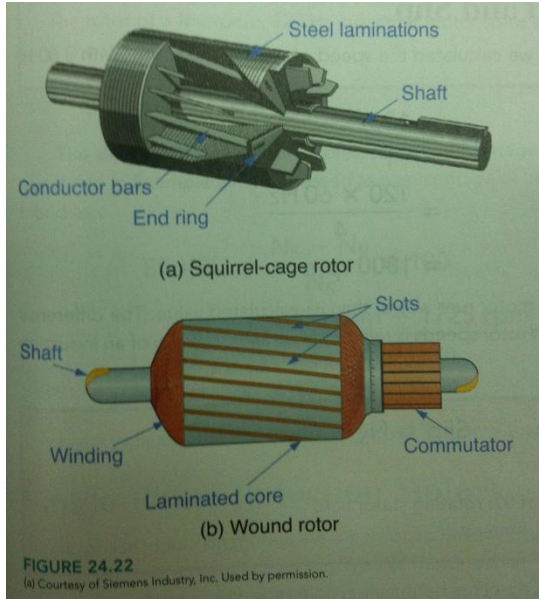
Wound : construction is similar to stator.

Windings connected to slip rings and brushes to couple rotor to an ext. DC source.

Not used very often in practice, high cost and maintenance requirements.

Squirrel-cage : most commonly used in AC motors.

contains conductor bars that extend through the length of rotor in place of the wire conductors found in wound rotors. ends by shorting rings. easier to manufacture, less maintenance, more reliable than wound motor.



➤ **Induction (Asynchronous) Motors:**

A motor with rotor current that is generated by electromagnetic induction rather than a DC field supply.

An induction motor runs slower than its calculated value: (no-load speed  $\neq$  full-load speed)

$$\text{Motor Speed: } N_S = \frac{120f}{P}$$

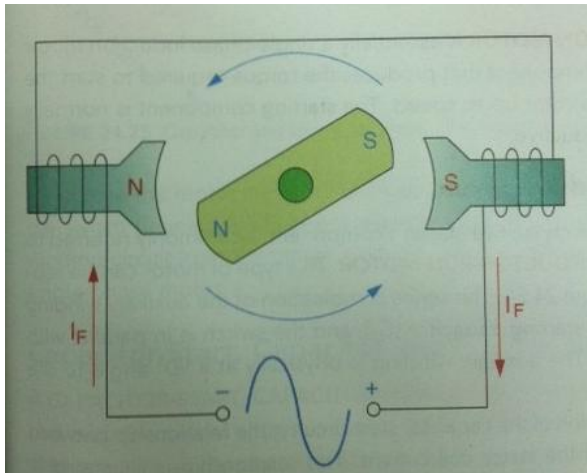
Slip: the difference between the stator and rotor speeds.

$$\text{Slip} = N_S - N_R \quad \text{Slip}(\%) = \frac{N_S - N_R}{N_S} \times 100$$

➤ **Single Phase Induction Motors:**

The most commonly used AC motors.

When power applied, each stator coil attracts one of the motor poles.



Rotor magnetic field is generated by current induced in the rotor.

To generate this rotor current, there must be relative motion between rotor conductors and stator magnetic fields (Lenz's Law).

If rotor turning in sync with stator fields, there would be no relative motion & current.

The slip provides the relative motion to generate rotor current.

Rotor is stationary when AC is applied to stator fields.

Stator fields quickly change polarity, providing relative motion.

Relative motion induces a voltage across the conductor, generates rotor magnetic field.

Rotor begins to turn, lagging the switching stator fields.

Motor slip maintains the relative motion.

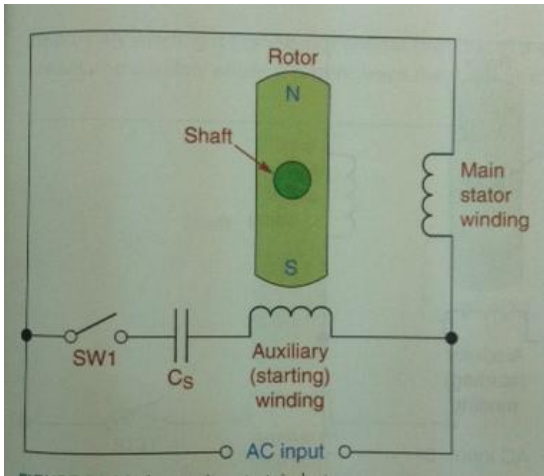
Motor slip is a result of the torque required to turn the rotor and varies with motor load.

Motor slip increases when load increases.

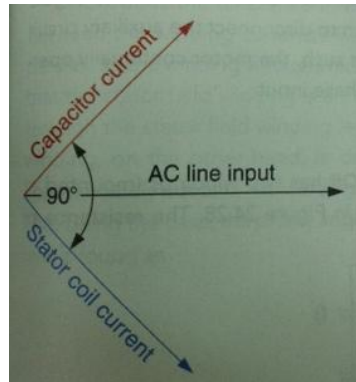
➤ **Split - Phase Induction Motors:**

A single phase induction motor with an added starting component that produces the torque required to start the motor. It brings the rotor up to speed. It normally capacitive, resistive or inductive.

➤ **Capacitor-Start, Inductor-Run**



Starting capacitor and switch is in parallel with main stator winding. Auxiliary winding is physically at 90° to main stator winding.

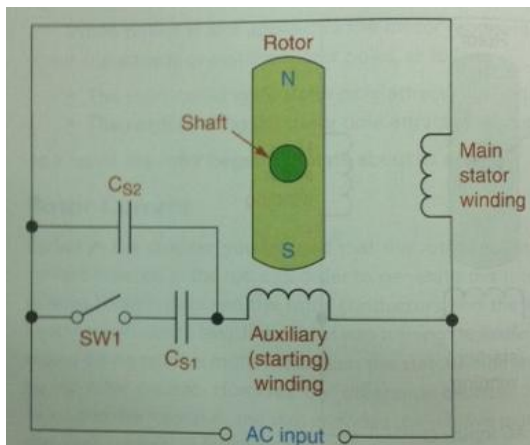


Capacitor current leads AC input 45°. Stator coil current lags AC input 45°.

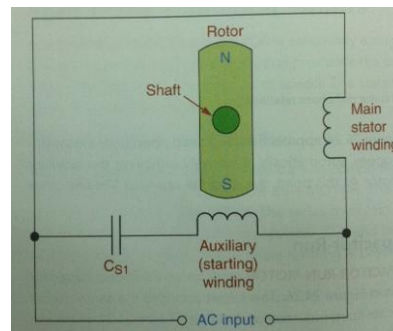
Capacitor current leads stator coil current 90°. This provides the starting torque.

When motor approaches full-speed, centrifugal switch opens automatically. Removes auxiliary winding.

➤ **Capacitor-Start, Capacitor-Run**

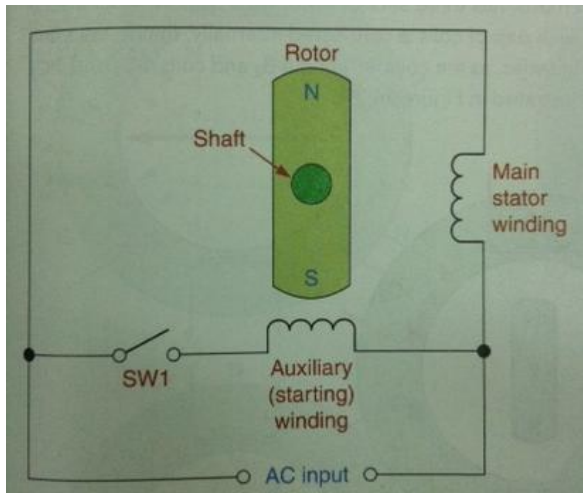


Provides same overall startup action, however after centrifugal switch opens, there still a lower-value current through auxiliary coil and  $C_{S2}$ . This current is at 90° to the higher-value current through stator field coil. The circuit continues to operate a split phase motor.



Modified version. No centrifugal switch.

➤ Inductor-Start, Inductor-Run



Two windings mounted 90° angles.

Resistance of auxiliary winding is significantly greater.

As a result, auxiliary winding current leads stator field winding.

Windings are connected in parallel. Assume stator field winding is ideal inductor. Its current lags voltage by 90°.

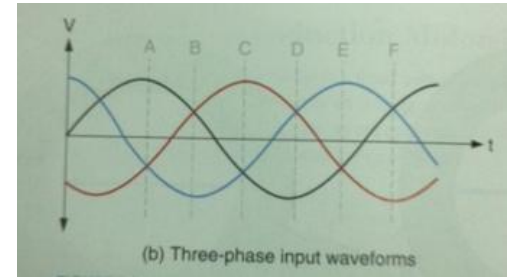
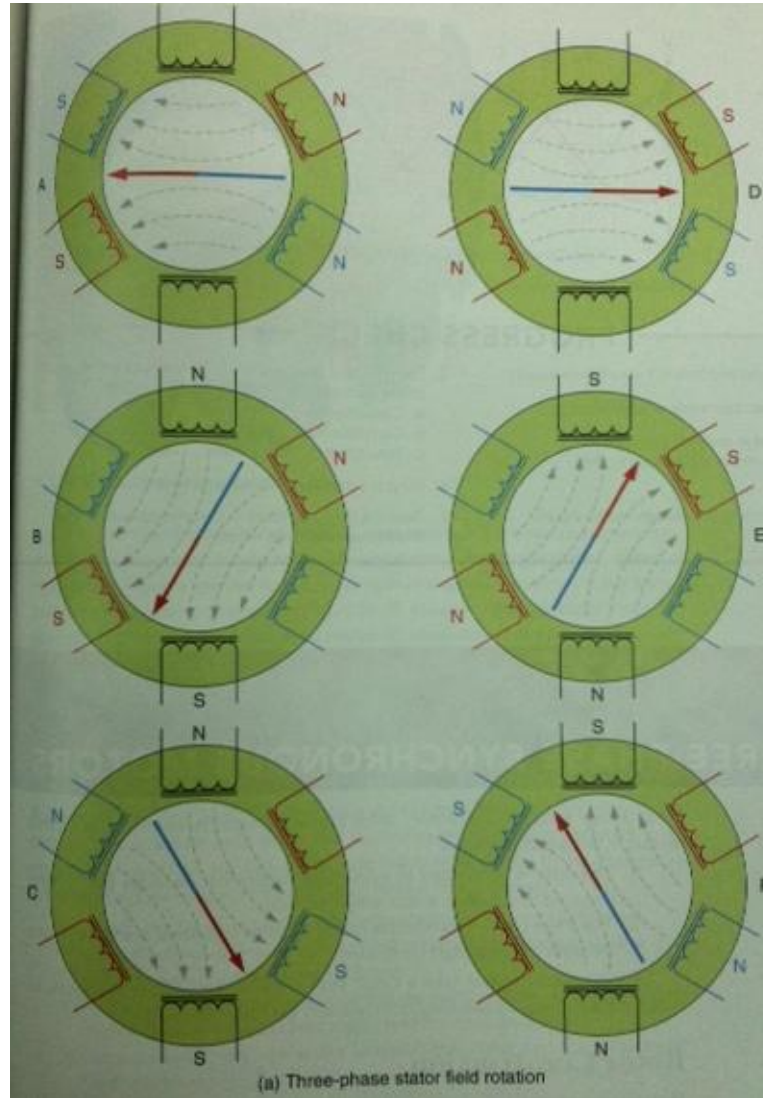
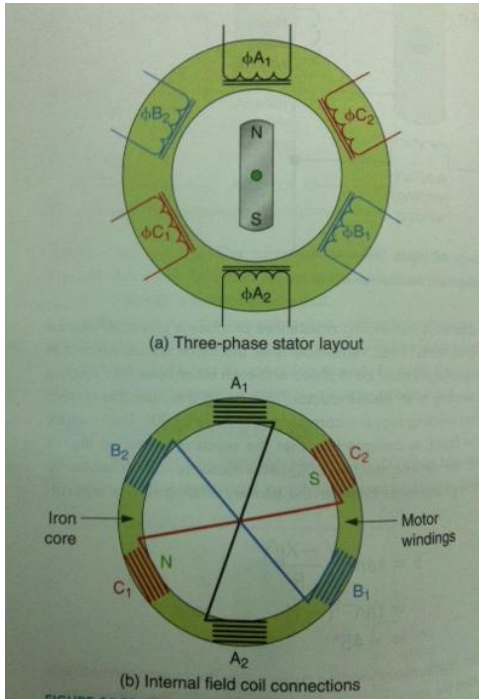
Auxiliary winding  $R_W \cong X_L$   $\theta = \tan^{-1}(-X_L/R_W) = -45^\circ$

So, auxiliary winding current leads stator field winding current 45°.

The phase difference provides the extra torque.

Lastly, centrifugal switch opens, runs as single-phase motor.

- Three-Phase Induction Motors:**  
 Has three sets of stator field coils.  
 Each coil is connected internally.

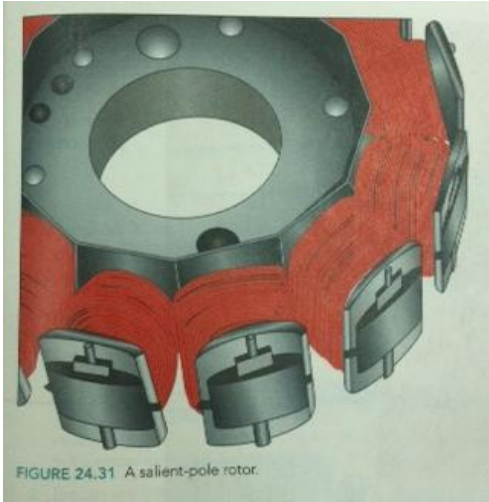


➤ **Three Phase Synchronous Motors:**

They differ physically from three-phase induction motors in two significant ways:

1. Rotor is connected to a DC field supply, generates rotor magnetic field.
2. Requires additional startup circuitry, because it cannot start on its own.

➤ The rotor of three-phase synchronous motor closely resembles a salient pole alternator rotor.



Electromagnets extend outward from the rotor.

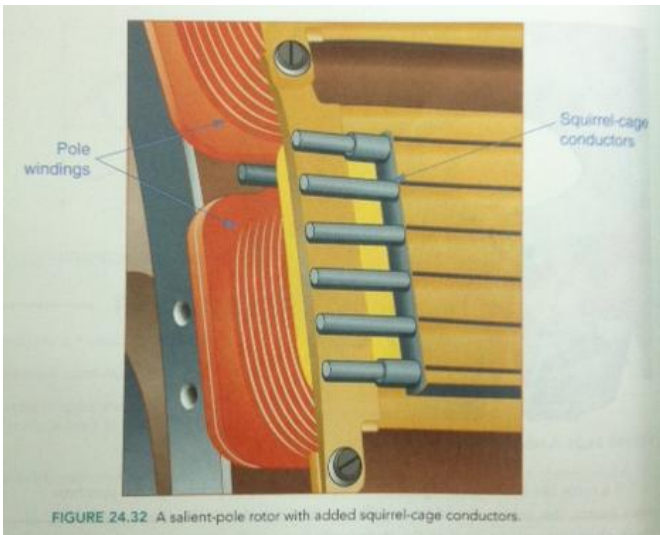
If this rotor installed in a three-phase synchronous motor, the starting would be difficult.

Because rotor can not react quickly enough to the stator field to start.

Squirrel-cage conductors are mounted around the rotor to overcome this problem.

They are referred as amortisseur windings.

They respond much more quickly to the changes in the stator field.



Initially, DC field supply is disconnected from the rotor field poles.

When 3-phase input is applied to stator,

squirrel-cage conductors cause rotor start rotating.

Rotor speed increase, centrifugal switch closes

connects DC field supply to rotor field poles.

Once powered, the interaction between rotor and stator magnetic fields causes rotor to lock in sync.

When motor is up to speed and in sync, squirrel-cage conductors become redundant.

No voltage is induced in squirrel-cage conductors.

$$N_S = \frac{120f}{P} \text{ (no-load speed = full-load speed)}$$



# 22. AC Power Transmission and Distribution

Generating and delivering electrical power

1. Power Generation : Process of converting one type of energy (mostly mechanical) into electrical energy.(2.3kV and 33kV)  
Using moving water, nuclear fuels, fossil fuels, solar, geothermal, wind
2. Power Transmission : Process of delivering generated power (over long distances) to distribution circuits that are located in populated areas. High voltage lines.  
Transformers are used to increase voltage levels to make long range power transmission feasible.
3. Power Distribution : Process of reducing transmitted power to customer-usable levels and delivering that power to local homes and industries.

Grid: Describes power generating plant, transmission lines, distribution systems and substations that make up an AC power distribution system.

Transmission Lines: High voltage lines used to transmit electrical energy over long distances.

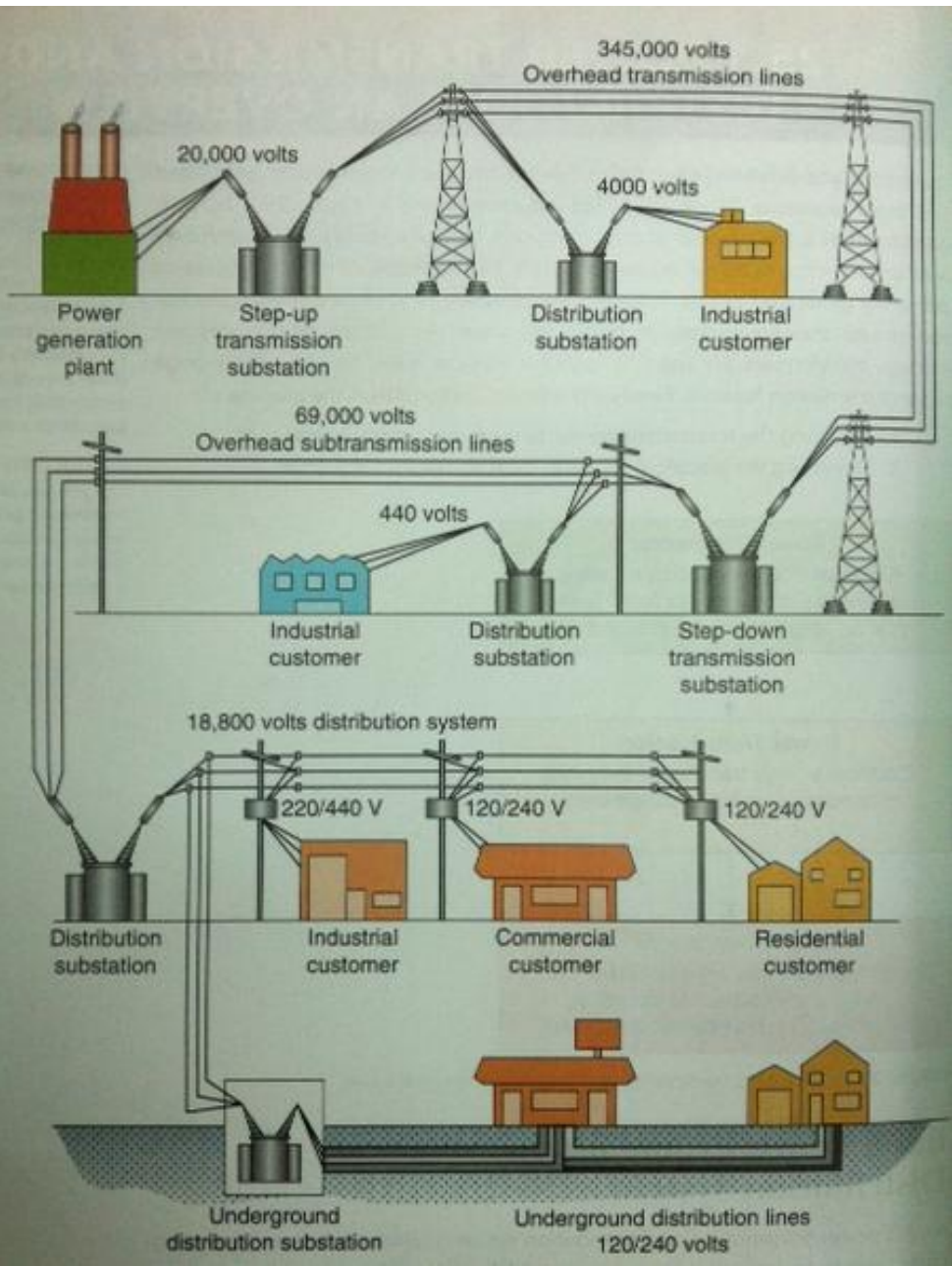
Overhead lines / Underground lines / Subtransmission lines (carries lower voltages)

Power Distribution System: Includes lines, poles, transformers, and switching and protection circuits that deliver electrical energy to customers at usable voltage levels.

Lines may be above/under ground, transformers may be pole/pad mounted.

Substations: Utility stations that contain transformers that increase or decrease voltage levels,

overload protection circuits and switching circuits (to draw from multiple sources & to direct output between loads)



To measure power generation service:

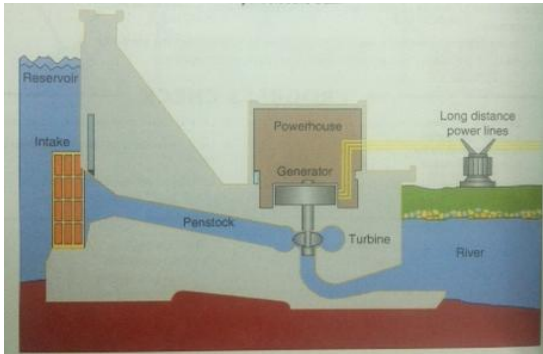
$$\text{Load Factor} = \frac{\text{average load for a given period of time}}{\text{peak load for that same period}}$$

$$\text{Capacity Factor} = \frac{\text{average load for a given period of time}}{\text{output capacity of power generation plant}}$$

Under ideal conditions both factor would be unity.



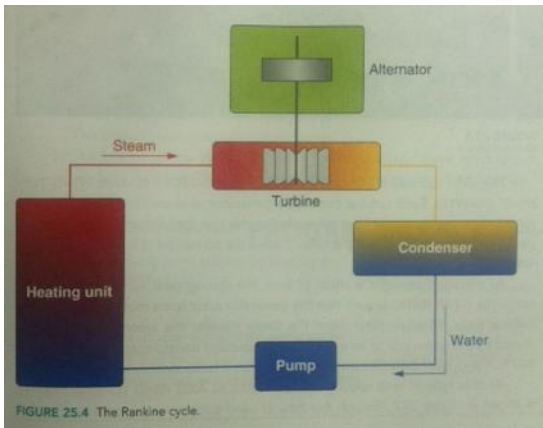
# Generating Electrical Power



**Hydroelectric Plant** : converts kinetic energy in flowing water to electrical energy.

**Impoundment Dam** : Completely blocks natural flow of water.

**Diversion Dam** : Diverts a portion of natural flowing water through its penstock and turbine.



**Thermal Power Plant** : uses heat to convert water to steam, and then uses steam as the prime mover for its turbine.

**Rankine Cycle** : Conversion of water to steam and back to water in a closed recirculating system.

**Fossil-Fuel Power Plant** : Coal, oil, natural gas.

**Nuclear Power Plant**: Mostly Uranium 235, Plutonium 239



## Wind Power

Horizontal-Axis Wind Turbines (HAWTS)    Vertical-Axis Wind Turbines (VAWTS)

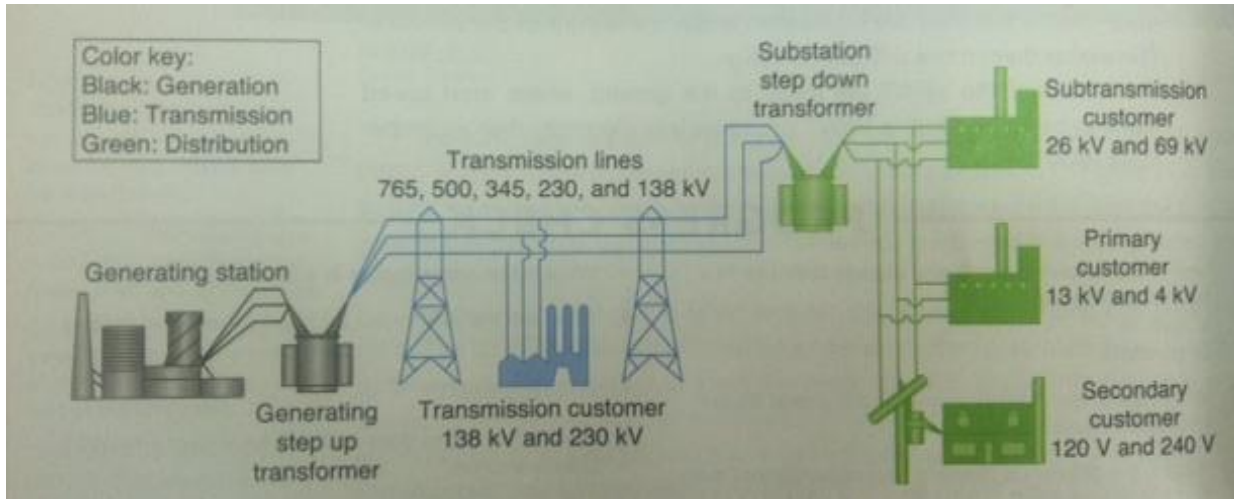
## Transmission Lines and Substations

Overhead Transmission Lines: Used to transmit electrical energy in the form of 3 phase AC.

Begins at step-up transformer and end at substation step-down transformer.

Typically 500km or less, use uninsulated aluminum conductor or aluminum conductor steel reinforced (ACSR).

345kV-465kV lines need extra precautions(increasing distance between lines) to prevent flashovers(arcing).



Corona Discharge : Power loss along transmission lines that occurs when high voltages ionize the air surrounding power lines.

Subtransmission Lines: Lines carry voltages typically between 26kV-69kV to regional substations.

Underground Transmission Lines : Where overhead transmission lines can not be used. Insulated lines.

Substations: Transformer, lightning arresters, overload protectors, voltage regulators, input/output switching circuits, control circuits

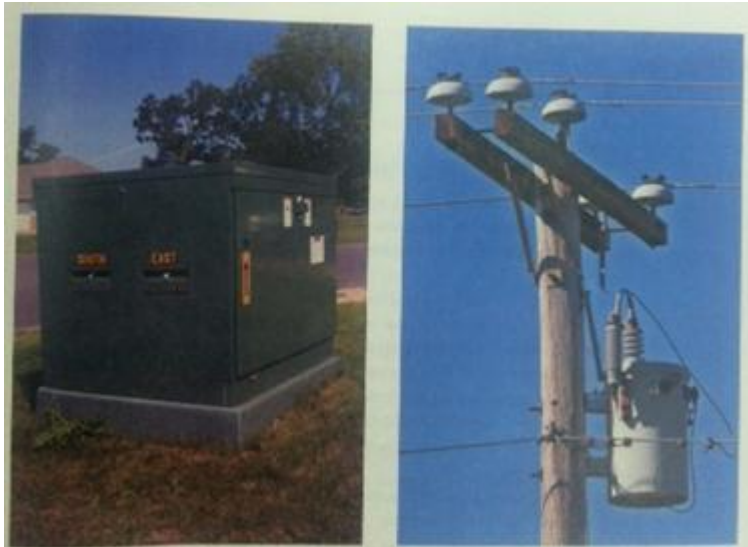
Step-Up Substation : Connects power generating plant to transmission lines. (115kV-765kV)

Step-Down Substation : Connects transmission lines and subtransmission or distribution lines. (26kV-69kV)

Distribution Substation : Connects subtransmission lines to local distribution lines. (2.4kV-33kV)

- **Distribution Grids:** Final element in the transmission system.
  - It begins at distribution substation and ends at customer's residence.
  - May be overhead or underground.
  - Includes poles, overhead wires and transformers, also underground conductors and pad transformers.
  - Distribution levels 2.4kV-33kV.
  
- **Distribution Grid Transformers**
  - They step down distribution grid voltages to levels that required by customers.
  - They provide fault isolation to prevent its effects at other points on the grid.

Distribution grids may also contain small secondary substations that are located near the area they serve.



Pad Transformers : for underground grids

Pole Transformers : for overhead grids.

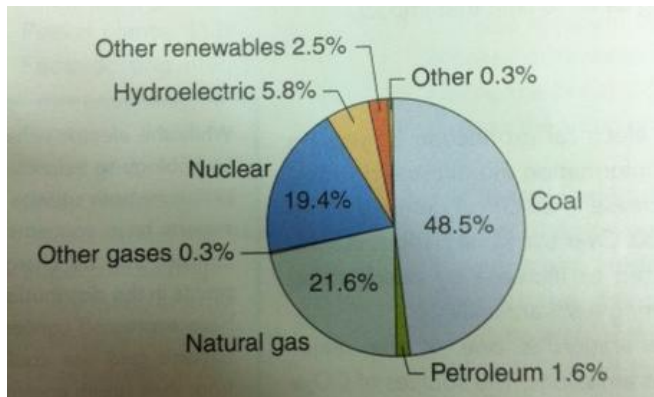
# 23. Green Power

Green: environmentally friendly products and technologies.

Greenhouse Gases: Gases that absorb and emit solar radiation in the infrared range, trapping heat in earth's atmosphere, contribute to global climate change

Carbon Dioxide Equivalent ( $CO_2e$ ) : A unit of measure for greenhouse gas emissions that indicates their global warming impact referenced to equivalent amounts of carbon dioxide.

%40 of total US  $CO_2e$  emissions (approx. %10 of the world's) is from electric power sector.



Fuels used to generate power in the US.

Carbon per unit energy : The amount of  $CO_2$  emitted per unit of energy produced. Coal contains 80% more carbon per unit energy than natural gas.

Integrated Gasification Combined Cycle (IGCC): Promising clean coal techno. Coal (biomass, petroleum, waste) converted into gas and purified before burning, improved efficiency, valuable byproducts(hydrogen-fuel cells, sulfuric acid etc.)

Drawback: carbon capture and storage (CSS), requires great energy, cost.

- Natural Gas (NG): the cleanest burning of fossil fuels, but not a renewable resource, NG is primarily methane.
- Biogas : Another form of NG, methane-rich gas that comes from the decay of organic matter.  
Produced from agricultural waste, unused plant material and animal waste.

Efficiency of power generation using NG can be increased by;

- Combined Cycle Power Generation: uses hot gases produced by burning NG to drive gas turbine, and then uses waste heat from this cycle to convert water to steam to drive a steam turbine.

Dedicated pipelines must be used to deliver NG.

Mostly NG is converted into a liquid by cooling the gas. Liquefied Natural Gas (LNG)

- Nuclear Power Production will lower greenhouse gas and particulate emissions, but radioactive waste needs to be stored for hundreds of thousands of years.
- Oil : Petroleum-fired generating plants, not a clean fuel, expensive
- Hydro : Clean and highly-efficient (90%) renewable energy source, but has impact on environment.
- Wind : Impact environment more subtly than other sources, significant clearing of forests may be necessary, bird populations.
- Solar :  
Concentrating Solar Power Technology (CSP) : uses mirrors and lenses to focus light to heat water and drive a steam turbine.  
Photovoltaic (PV) arrays : Thin-film solar cell technology.  
Concentrating Photovoltaic Technology (CPV) : Focuses sun's energy onto photovoltaic cells, increasing efficiency.  
No sign. impact when operating, but construction/disposal of solar panels is a problem (arsenic, cadmium), and requires land.
- Wave : Uses constant rise and fall of surface waves or deep water waves. The first became operational in 2008.
- Tidal : Since mid 1960s.
- Ultimate Power Plant – Vision 21 Project : Multifuel power plant, extremely efficient, no greenhouse gas or pollutants.

## Small-Scale Power Generation:

Distributed Generation (DG) : Production of small-scale power near or at a customer's site.

Lower greenhouse gas emissions, result of using more efficient and/or renewable energy sources.

Reduced power distribution infrastructure.

Peak shaving: leveling out of power consumption over time.

Fuel flexibility

Reciprocating Internal Combustion Engines: low cost, low maintenance requirements, high reliability; Diesel, NG.

Cogeneration: Capture and use of waste heat produced by a generator for space and/or water heating.

Gas Turbines: Based on the same technology as a jet engine. Consists of a compressor, combustion chamber and turbine.

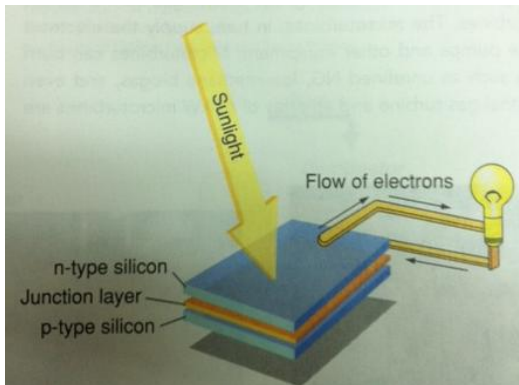
Can burn a variety of fuels (NG, methane produced by biomass)

Compared to internal combustion engines: lighter, less time for maintenance, lower emissions, wide range of fuels take longer to power up and down, less efficient for <2MW, suitable for large cogeneration applications.

Biomass: Production of methane from the decay of vegetation, plant matter or agricultural waste.

Brayton Cycle: Process of burning fuel with compressed air and then using the expanding gasses to drive a turbine.

Microturbine: A much smaller version of industrial gas turbine, tens of kilowatts to a few hundreds.



Photovoltaic Cells: no greenhouse gasses, quiet and reliable, little maintenance, expensive, works only sun shines

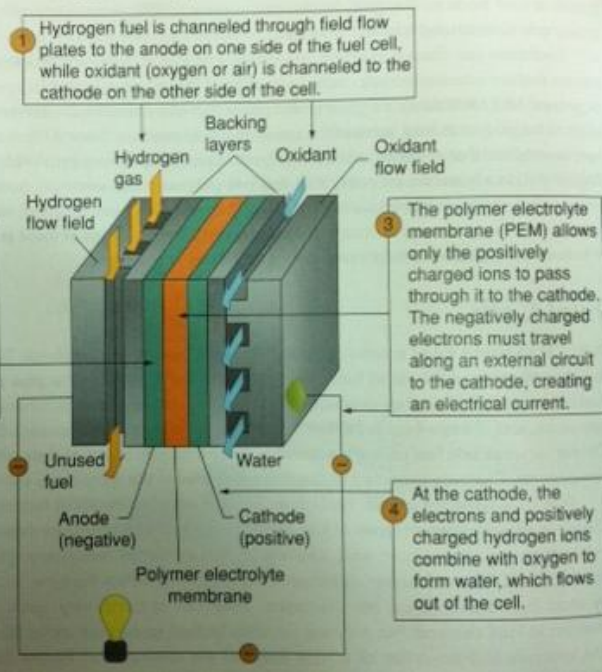
base material is silicon, a semiconductor has four valance electrons

impurities : n-type has excess free electrons, p-type has excess valance-band holes

crystalline silicon modules, newer types are thin-film PV

produces DC, inverter required.

### Proton exchange membrane fuel cell



Fuel Cells: generates power through chemical reaction involving hydrogen.

Quiet, almost no greenhouse gases,

expensive since platinum is one critical components

Several types (based on electrolyte they use): phosphoric acid, alkaline, proton exchange membrane (PEM), solid oxide (SOFC), and molten carbonate (MCFC)

hybrid electric car applications, quick respond to load demand, limited <10kW, (SOFC,MCFC tens of megawatts)

There are three subsystems in every DG installation:

generator, load and **BOS** (balance of system - rest of the equipment require to make the whole thing work)

BOS requirements:

inverter (if PV is used), voltage regulator, switching systems (if grid connected),

power conditioning (to keep AC pure), power storage (if required), safety equipment (surge, overvoltage protectors) and many more...

- **Smart grid:** An interactive grid in which the power producer, distributor and end user are in constant real-time communication with each other.
- **Cold-Rolled Grain-Oriented (CRGO):** A type of silicon steel that is used in transformer cores.
- **Amorphous-Core Transformers (ACTs):** Use silicon steel cores that manufactured to reduce core-related losses.
  - When molten silicon steel is cooled very quickly, it retains a chemical structure resembling glass. This structure reduce eddy current and hysteresis losses.
  - Rather stacked laminations, ribbons of steel wound into a rectangular toroid-shaped core is used.
  - On market since mid 1980s, 70% less no-load core losses than CRGO.
- **Superconductors:** Man-made alloys that can pass electric current with virtually zero resistance when operated at extremely low temperatures. ( $\sim -150^\circ$ )
  - current capacity is great and higher than critical current rating it becomes resistive.
- **Superconducting Magnetic Energy Storage (SMES):**
  - Storing electrical energy in the massive magnetic field of a closed superconducting inductor.
- **Peaker Plants:** Power plants that generate electricity only in response to peak load demands.
- **Smart Meters:** Two way communication devices that allow provider to monitor and price the consumption in real time and cost.
- **Islanding :** The ability of distributed generation to continue to generate power even when power from a utility is absent.

