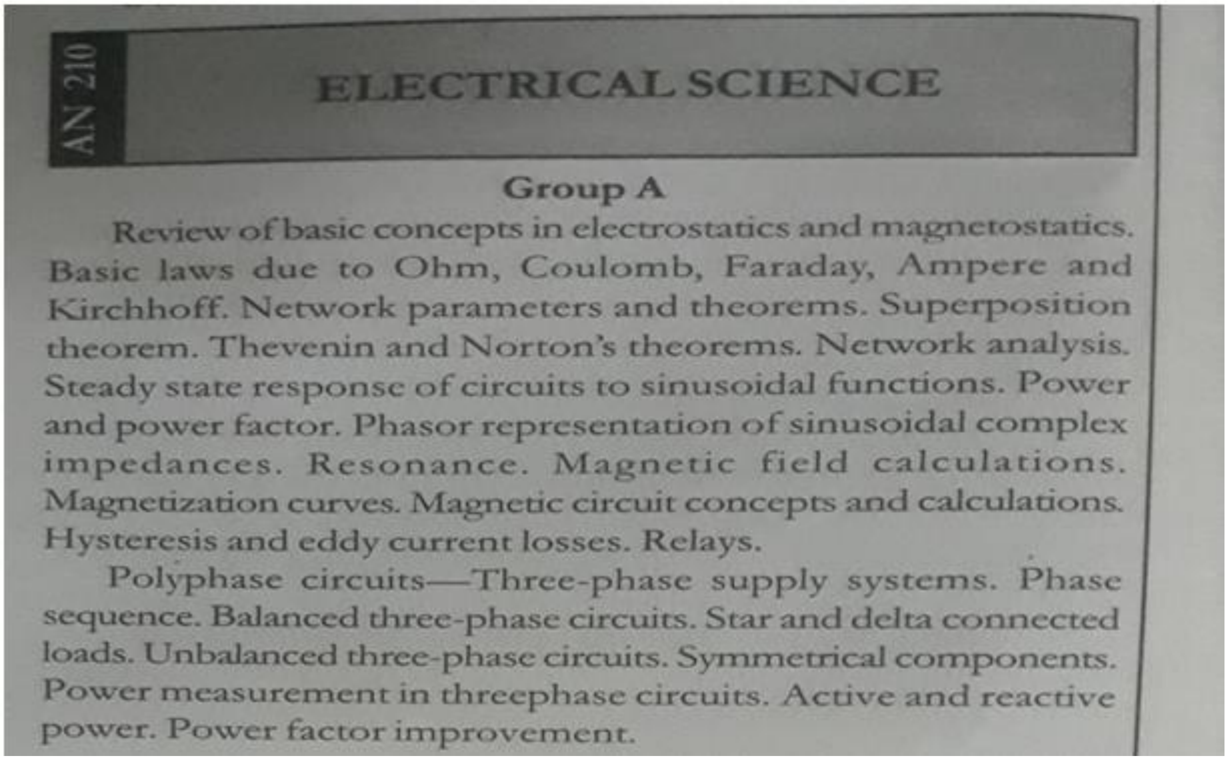
Electrical Science



AN 210

ELECTRICAL SCIENCE

Group A

Review of basic concepts in electrostatics and magnetostatics. Basic laws due to Ohm, Coulomb, Faraday, Ampere and Kirchhoff. Network parameters and theorems. Superposition theorem. Thevenin and Norton's theorems. Network analysis. Steady state response of circuits to sinusoidal functions. Power and power factor. Phasor representation of sinusoidal complex impedances. Resonance. Magnetic field calculations. Magnetization curves. Magnetic circuit concepts and calculations. Hysteresis and eddy current losses. Relays.

Polyphase circuits—Three-phase supply systems. Phase sequence. Balanced three-phase circuits. Star and delta connected loads. Unbalanced three-phase circuits. Symmetrical components. Power measurement in threephase circuits. Active and reactive power. Power factor improvement.

Group A

REVIEW OF BASIC CONCEPTS IN ELECTROSTATICS AND MAGNETO STATICS
ELECTROSTATICS

Electric charge is the **physical property** of matter that causes it to experience a **force** when placed in an **electromagnetic field.**

Two types of electric charges

1. Positive.   2. Negative (commonly carried by **protons** and **electrons** respectively). Like charges repel and unlike attract. An object with an absence of net charge is referred to as **neutral**.

The SI derived unit of electric charge is the **coulomb**(C). It is also common to use the ampere-hour (Ah); in physics and chemistry, it is common to use the elementary charge (e as a unit).

Electric charge is a **conserved property**; the net charge of an **isolated system**, the amount of positive charge minus the amount of negative charge, cannot change. Electric charge is carried **by subatomic particles**. In ordinary matter, negative charge is carried by electrons, and positive charge is carried by the protons in the **nuclei** of atoms. If there are more electrons than protons in a piece of matter, it will have a negative charge, if there are less it will have a positive charge, and if there are equal numbers it will be neutral. Charge is quantized; it comes in integer multiples of individual small units called the **elementary charge**, e, about 1.602×10^{-19} coulombs,[1] which is the smallest charge which can exist free (particles called **quarks** have smaller charges, multiples of 1/3e but they are only found in combination). The **proton** has a charge of +e, and the electron has a charge of −e.

Electric Field

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Electric charges create an **electric field**, if they are moving they also generate a **magnetic field.** The combination of the electric and magnetic field is called the electromagnetic field, and its interaction with charges is the source of the electromagnetic force, which is one of the four fundamental forces in physics. The study of charged particles, and how their interactions are mediated by **photons**, is called quantum electrodynamics.

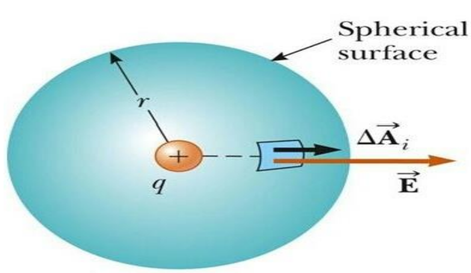
Electric flux

In electromagnetism, **electric flux** is the measure of flow of the electric field through a given area. Generally speaking flux is a flow, such as the flow of charge, or current. The electric field E is analogous to a force, since qE is a force. The electric field is proportional to the gradient of the voltage. The electric field drives charge.

Gauss law

The Gauss' law of electrostatics is one of the most fundamental theorems in Electrostatics. It states that the Electric flux ϕ through a closed surface is $\frac{1}{\epsilon_0}$ times the charge enclosed by that surface.

Suppose if I consider a sphere having a point charge q situated at its centre. The electric field due to the point charge should be directed radially outward. At each and every point on the surface of the sphere, the electric field intensity E and the normal to the surface $\hat{n}$ is in the same direction. So the angle θ between them must be 0°.



Let the radius of the spherical surface be r. By the very definition of electric flux over a curved surface, the electric flux due to a small area element dS would be

$$d\phi = EdScos\theta$$

But we know that θ is 0°

Applying the surface integral we get

$$\phi = \oint EdScos\theta$$

$$\phi = \oint EdScos0^\circ$$

$$\phi = E\oint dS$$

The area of the sphere is $4\pi r^2$ and by coulomb's law, $E = \frac{1}{4\pi\epsilon_0}\frac{q}{r^2}$

$$\implies \phi = \frac{1}{4\pi\epsilon_0}\frac{q}{r^2}4\pi r^2$$

Therefore

$$\phi = \frac{q}{\epsilon_0}$$

It should be noted that the charge q represents the charge enclosed by the surface. Any charge located outside the surface is not included in the above formula. Therefore, the above formula for convenience is modified as

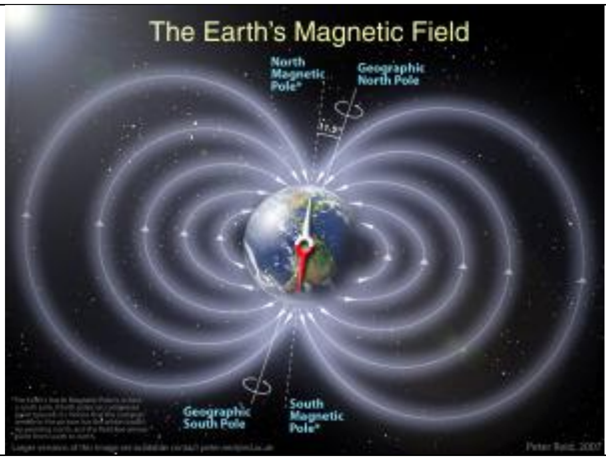
$$\phi = \frac{q_{enc}}{\epsilon_0}$$

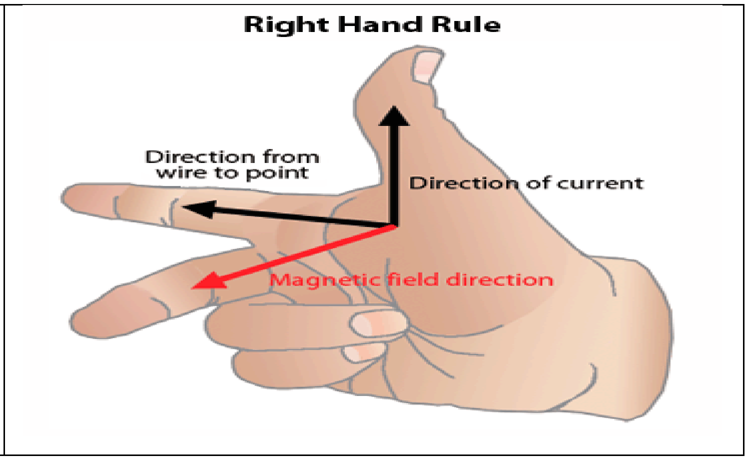
Suppose if we were to shift the point charge q a bit to the left, the integration would be much more complicated. In order to get over that issue, the Gauss' law of electrostatics is generalised for any closed surface. The same formula would work for the above case.

$$\phi = \frac{q_{enc}}{\epsilon_0}.$$

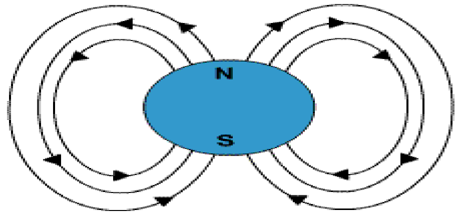
There are many applications which use the above formula.

BASIC CONCEPTS
MAGNETIC FIELD





• The magnetic field is the central concept used in describing magnetic phenomena.
• A region or a space surrounding a magnetized body or current-carrying circuit in which resulting magnetic force can be detected.
• A magnetic field consists of imaginary lines of flux coming from moving or spinning electrically charged particles. Examples include the spin of a proton and the motion of electrons through a wire in an electric circuit.

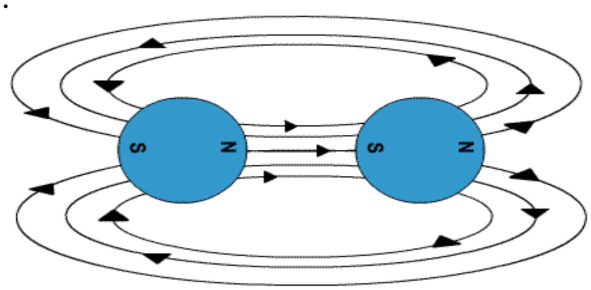


Magnetic field or lines of flux of a moving charged particle

MAGNETIC FORCE

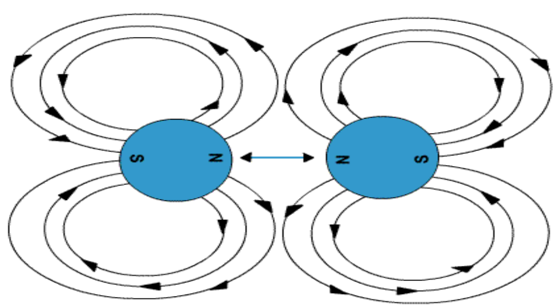
The magnetic field of an object can create a magnetic force on other objects with magnetic fields. That force is what we call magnetism.
When a magnetic field is applied to a moving electric charge, such as a moving proton or the electrical current in a wire, the force on the charge is called a Lorentz force.

Attraction: When two magnets or magnetic objects are close to each other, there is a force that attracts the poles together.



Force attracts N to S

Magnets also strongly attract ferromagnetic materials such as iron, nickel and cobalt.
Repulsion: When two magnetic objects have like poles facing each other, the magnetic force pushes them apart.



Force pushes magnetic objects apart

Magnetic and electric fields

The magnetic and electric fields are both similar and different. They are also inter-related.

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Electric charges and magnetism similar
Just as the positive (+) and negative (−) electrical charges attract each other; the N and S poles of a magnet attract each other. In electricity like charges repel, and in magnetism like poles repel.

Electric charges and magnetism different
The magnetic field is a dipole field. That means that every magnet must have two poles.
On the other hand, a positive (+) or negative (−) electrical charge can stand alone. Electrical charges are called monopoles, since they can exist without the opposite charge.

- Monopole – a single magnetic pole or electric charge
- Dipole – a pair of opposite poles
- The so-called magnetic moment is the measure of the strength of the dipole.

The magnetic moments are expressed as multiples of Bohr Magnetons. A Bohr magneton has a value of 9.27 x 10-24 joules/tesla.

FORMS OF MAGNETISM

Ferromagnetic ↓ ↓ ↓ ↓ ↓ ↓	Magnetic moments are aligned.
Antiferromagnetic ↓ ↑ ↓ ↑ ↓ ↑	Zero net magnetic moment at sufficiently low temperatures.
Ferrimagnetic ↓ ↑ ↓ ↑ ↓ ↑	Magnetic moments oppose but do not cancel.
Paramagnetic ↓ ↑ ↑ ↓ ↓ ↑	Random magnetic moments. Magnetic moments will align with an applied magnetic field. Occurs above Curie temperature.

MAGNETIC FIELDS and FORCES
The same situations which create magnetic fields (charge moving in a current or in an atom, and intrinsic magnetic dipoles) are also the situations in which a magnetic field has an effect, creating a force. Following is the formula for moving charge; for the forces on an intrinsic dipole, see magnetic dipole. When a charged particle moves through a magnetic field B, it feels a force F given by the cross product: where is the electric charge of the particle, is the velocity vector of the particle, and is the magnetic field. Because this is a cross product, the force is perpendicular to both the motion of the particle and the magnetic field. It follows that the magnetic force does no work on the particle; it may change the direction of the particle's movement, but it cannot cause it to speed up or slow down. The magnitude of the force is where is the angle between the and vectors. One tool for determining the direction of the velocity vector of a moving charge, the magnetic field, and the force exerted is labeling the index finger "V", the middle finger "B", and the thumb "F" with your right hand. When making a gun-like configuration (with the middle finger crossing under the index finger), the fingers represent the velocity vector, magnetic field vector, and force vector, respectively. See also right hand rule.

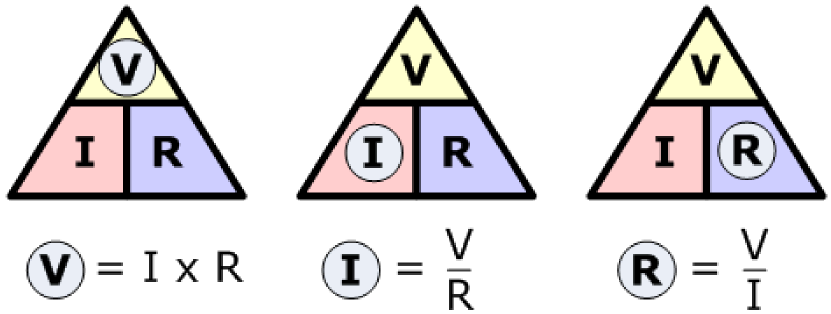
Lenz's law gives the direction of the induced electromotive force (emf) and current resulting from electromagnetic induction. German physicist Heinrich Lenz formulated it in 1834.

Electrical Science

OHMS LAW

At constant temperature, the electrical current flowing through a fixed linear resistance is directly proportional to the voltage applied across it, and also inversely proportional to the resistance.

$$Current, (I) = \frac{Voltage, (V)}{Resistance, (R)} \text{ in Amperes, (A)}$$



Ohmic

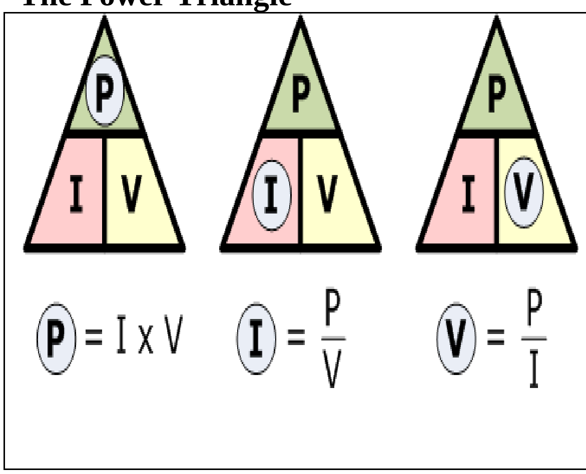
Any Electrical device or component that obeys "Ohms Law" said to be "**Ohmic**" in nature, and devices that do not, such as transistors or diodes, are said to be "**Non-ohmic**" devices.

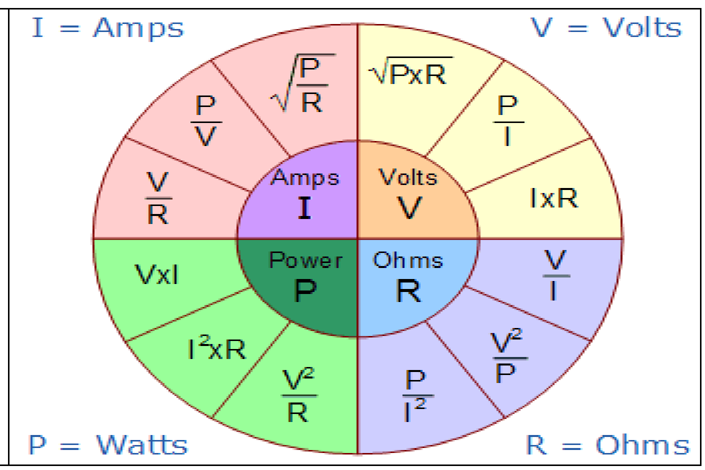
Electrical Power in Circuits (P)

It is the rate at which energy is absorbed or produced within a circuit

[P = V x I= V2 ÷ R= I2 x R]   P (watts) = V (volts) x I (amps)

The Power Triangle





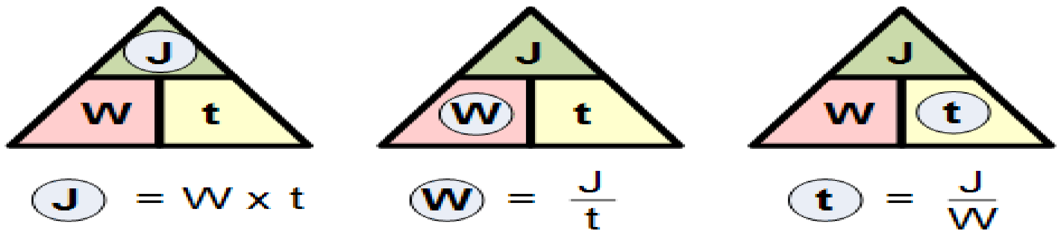
Electrical Power Rating

It indicates the **maximum rate at which the component converts the electrical power into other forms of energy** such as heat, light or motion. For example, a 1/4W resistor, a 100W light bulb etc.

Electrical Energy is the capacity to do work, and the unit of work or energy is the **joule**(J). Electrical energy is the product of power multiplied by the length of time it was consumed. So if unit: watt-seconds or joules.

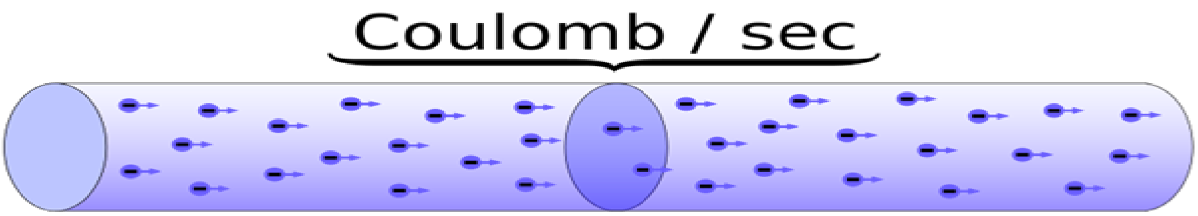
$$\text{Electrical Energy} = \text{Power (W)} \times \text{Time (s)}$$

Electrical Power and Energy Triangle



COULOMB

It is equal to the quantity of charge that passes through a cross-section of a conductor in one second, given a current of one ampere. The SI derived unit used to measure electric charge .Named for the 18th–19th-century French physicist Charles-Augustin de Coulomb, it is approximately equivalent to 6.24 × 1018 electrons.



Coulomb's law: The magnitude of the electrostatic force of **attraction or repulsion** between two point charges is directly proportional to the product of the magnitudes of charges and inversely proportional to the square of the distance between them. The force is along the straight line joining them.

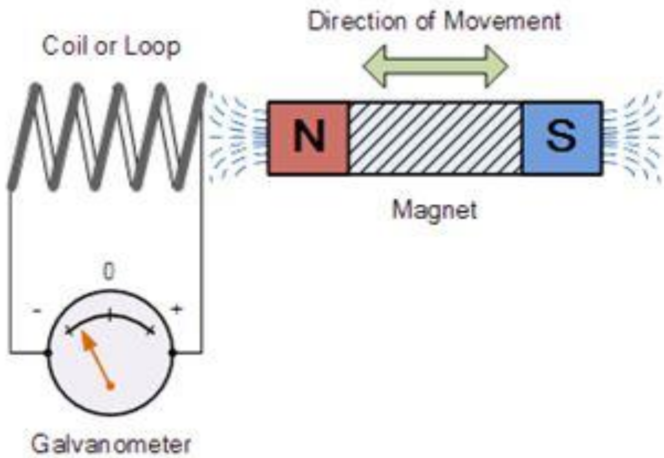
FARADAY'S LAWS OF ELECTROMAGNETIC INDUCTION

Faraday performs an experiment with a **magnet and a coil**. During his experiment, he found how **emf is induced in the coil when flux linked with it changes.**

Faraday's Experiment

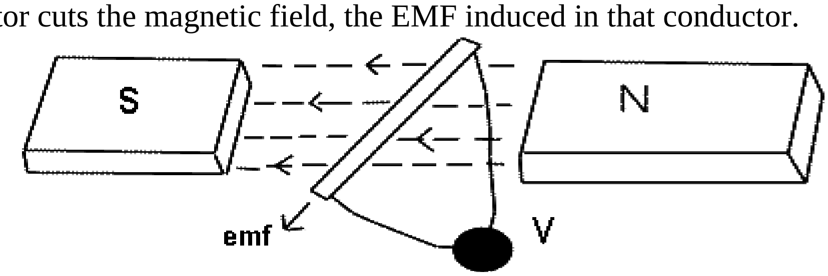
Here **magnet and a coil** and **connects a galvanometer across the coil**. At starting, the magnet is at rest, so there is no deflection in the galvanometer i.e needle of galvanometer is at the center or zero position. When the magnet is moved towards the coil, the needle of galvanometer deflects in one direction.

When the magnet is held stationary at that position, the needle of galvanometer returns to zero position. Now when the magnet moves away from the coil, there is some deflection in the needle but opposite direction, and again when the magnet becomes stationary, at that point respect to the coil, the needle of the galvanometer returns to the zero position. Similarly, if the magnet is held stationary and the coil moves away, and towards the magnet, the galvanometer similarly shows deflection. It is also seen that, the faster the change in the **magnetic field**, the greater will be the **induced emf** or **voltage** in the coil.



Position of magnet	Deflection in galvanometer
Magnet at rest	No deflection in galvanometer
Magnet moves towards the coil	Deflection in galvanometer in one direction
Magnet is held stationary at same position (near the coil)	No deflection in galvanometer
Magnet moves away from the coil	Deflection in galvanometer but in opposite direction
Magnet is held stationary at same position (away from the coil)	No deflection in galvanometer

Faraday's First Law
When a conductor cuts the magnetic field, the EMF induced in that conductor.



Faraday's Second Law
The magnitude of EMF induced in any conductor is equal to the rate of change of flux linkages with it.

Faraday Law Formula
Consider, a magnet is approaching towards a coil. Here we consider two instants at time T_1 and time T_2.

Flux linkage with the coil at time	$T_1 = N\phi_1 \ wb$
Flux linkage with the coil at time	$T_2 = N\phi_2 \ wb$
Change in flux linkage	$N(\phi_2 - \phi_1)$
Let this change in flux linkage be	$\phi = (\phi_2 - \phi_1)$
So, the Change in flux linkage	$N\phi$

Now the rate of change of flux linkage	$\frac{N\phi}{t}$
Take derivative on right hand side we will get The rate of change of flux linkage	$N\frac{d\phi}{dt}$
Faraday's law of electromagnetic induction, the rate of change of flux linkage is equal to induced emf	$E = N\frac{d\phi}{dt}$
Lenz's Law	$E = -N\frac{d\phi}{dt}$

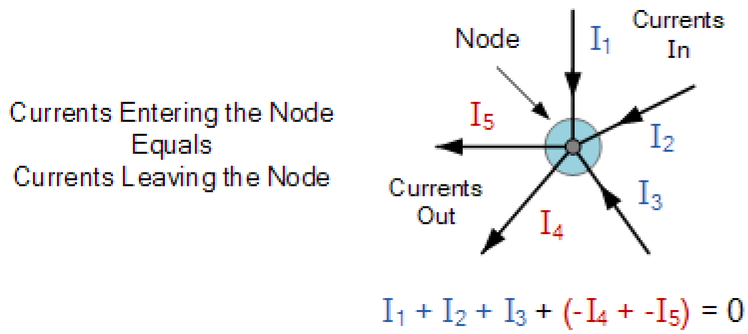
Where, flux Φ in Wb = B.A B = magnetic field strength A = area of the coil

Applications of Faraday's Law
Faraday law is one of the most basic and important laws of electromagnetism. This law finds its application in most of the electrical machines, industries and medical field etc.
Electrical Transformers, **electrical generator, Induction cooker, Electromagnetic Flow Meter** (Measure velocity of certain fluids), used in musical instruments like electric guitar, electric violin etc.

AMPERE AND KIRCHOFF
Ampere: a unit of electric current equal to a flow of one coulomb per second.

KIRCHHOFFS CIRCUIT LAW
It has 2 basic laws.
1. Kirchhoff's Current Law, (KCL). **2. Kirchhoff's Voltage Law, (KVL).**

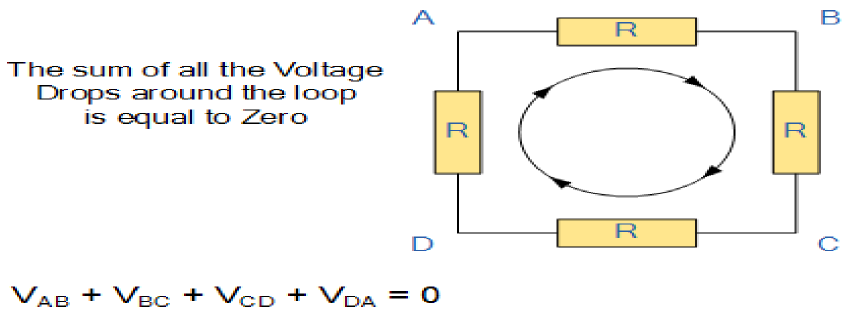
Kirchhoff's Current Law, (KCL)
the "total current or charge entering a junction or node is exactly equal to the charge leaving the node as it has no other place to go except to leave, as no charge is lost within the node". In other words the algebraic sum of ALL the currents entering and leaving a node must be equal to zero, $\mathbf{I_{(exiting)} + I_{(entering)} = 0}$. This idea by Kirchhoff is commonly known as the **Conservation of Charge**.



Node in an electrical circuit generally refers to a connection or junction of two or more current carrying paths or elements such as cables and components. Also for current to flow either in or out of a node a closed circuit path must exist. We can use Kirchhoff's current law when analysing parallel circuits.

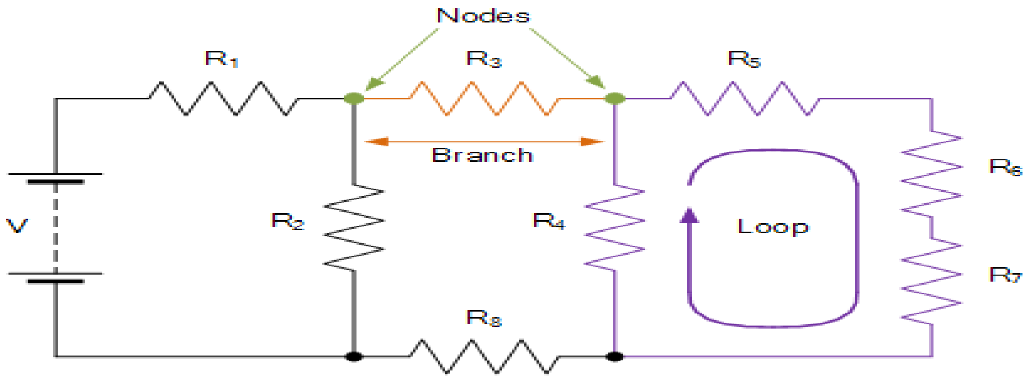
Kirchhoff's 2nd Law / Voltage Law, (KVL) / Conservation of Energy
It states that "in any closed loop network, the **total voltage around the loop is equal to the sum of all the voltage drops within the same loop"** which is also equal to zero.

In other words the **algebraic sum of all voltages within the loop must be equal to zero.** This idea by Kirchhoff is known as the

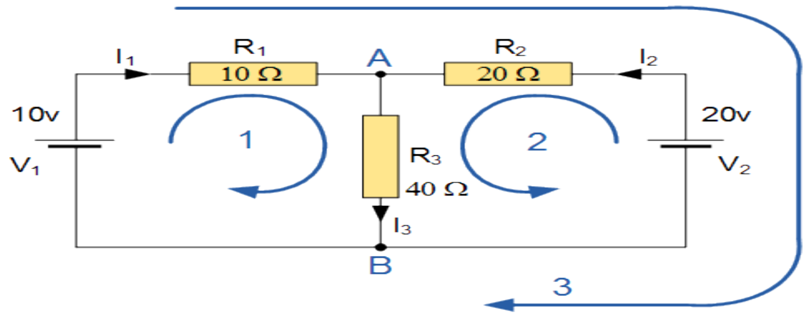


Common DC Circuit Theory Terms:
Circuit – a circuit is a closed loop conducting path in which an electrical current flows.
Path – a single line of connecting elements or sources.
Node – a node is a junction, connection or terminal within a circuit were two or more circuit elements are connected or joined together giving a connection point between two or more branches. A node is indicated by a dot.
Branch – a branch is a single or group of components such as resistors or a source which are connected between two nodes.
Loop – a loop is a simple closed path in a circuit in which no circuit element or node is encountered more than once.
Mesh – a mesh is a single open loop that does not have a closed path. There are no components inside a mesh.

Note
Components are said to be connected together in Series if the same current value flows through all the components. Components are said to be connected together in Parallel if they have the same voltage applied across them.



Law Example No1
Find the current flowing in the 40Ω Resistor, R_3



The circuit has 3 branches, 2 nodes (A and B) and 2 independent loops.
Using **Kirchhoff's Current Law**, **KCL** the equations are given as:
At node A : $I_1 + I_2 = I_3$
At node B : $I_3 = I_1 + I_2$

Using **Kirchhoff's Voltage Law**, **KVL** the equations are given as:
Loop 1: $10 = R_1 I_1 + R_3 I_3 = 10I_1 + 40I_3$
Loop 2: $20 = R_2 I_2 + R_3 I_3 = 20I_2 + 40I_3$
Loop 3: $10 – 20 = 10I_1 – 20I_2$

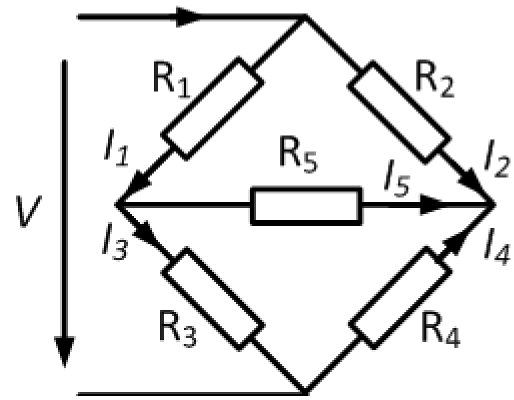
As I_3 is the sum of $I_1 + I_2$ we can rewrite the equations as;
Eq. No 1 : $10 = 10I_1 + 40(I_1 + I_2) = 50I_1 + 40I_2$
Eq. No 2 : $20 = 20I_2 + 40(I_1 + I_2) = 40I_1 + 60I_2$

We now have two "**Simultaneous Equations**" that can be reduced to give us the values of I_1 and I_2
Substitution of I_1 in terms of I_2 gives us the value of I_1 as -0.143 Amps
Substitution of I_2 in terms of I_1 gives us the value of I_2 as +0.429 Amps
As : $I_3 = I_1 + I_2$

The current flowing in resistor R_3 is given as : -0.143 + 0.429 = 0.286 Amps
and the voltage across the resistor R_3 is given as : 0.286 x 40 = 11.44 volts

The negative sign for I_1 means that the direction of current flow initially chosen was wrong, but never the less still valid. In fact, the 20v battery is charging the 10v battery.

Kirchhoff law example
The Kirchhoff laws form the basis of network theory. Combined with Ohm's law and the equations for resistors in series and parallel, more complex networks can be solved. Several examples of resistor circuits are given to illustrate how Kirchhoff can be used.
Example 1: the bridge circuit
Bridge circuits are a very common tool in electronics. They are used in measurement, transducer and switching circuits. Consider the bridge circuit below. In this example will be shown, how to use Kirchhoff's laws to determine the cross current I_5. The circuit has four bridge sections with resistors R1 – R4. There is one cross bridge connection with resistor R5. The bridge is subject to a constant voltage V and I.



The first Kirchhoff law states that the sum of all currents in one node is zero. This results in:

$$I = I_1 + I_2$$
$$I = I_3 + I_4$$
$$I_1 = I_3 + I_5$$

The second Kirchhoff law states the sum of all voltages across all elements in a loop is zero. This leads to:

$$0 = R_1 I_1 + R_3 I_3 - V$$
$$0 = R_1 I_1 + R_5 I_5 - R_2 I_2$$
$$0 = R_3 I_3 + R_5 I_5 - R_4 I_4$$

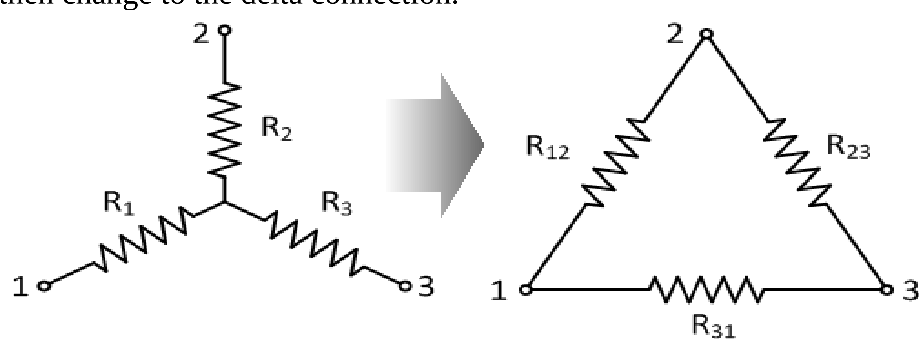
The six sets of equations above can be rewritten using normal algebra to find the expression for I_5 (the current in the cross branch):

The equation shows that the bridge current is equal to zero the bridge is balanced:

$$0 = R_1 R_4 = R_2 R_3$$

Example 2: the star delta connection

Kirchhoff's laws can be used to convert a star connection to a delta connection. This is often done to solve complex networks. A widely used application for star delta connections is to limit the starting current of electric motors. The high starting current causes high voltage drops in the power system. As a solution, the motor windings are connected in the star configuration during starting and then change to the delta connection.



The star connection as shown in the figure above, has the same voltage drops and currents as the delta connection shown on the right side, only when the following equations are valid:

$$R_1 = \frac{R_{31} R_{12}}{R_{12} + R_{23} + R_{31}}$$

$$R_{12} = R_1 + R_2 + \frac{R_1 R_2}{R_3}$$

$$R_2 = \frac{R_{12} R_{23}}{R_{12} + R_{23} + R_{31}}$$

$$R_{23} = R_2 + R_3 + \frac{R_2 R_3}{R_1}$$

$$R_3 = \frac{R_{23} R_{31}}{R_{12} + R_{23} + R_{31}}$$

$$R_{31} = R_3 + R_1 + \frac{R_3 R_1}{R_2}$$

NETWORK PARAMETERS AND THEOREMS

Theorems and laws: The electrical circuit theorems can also be applied to A.C systems, with only one difference: replacing the ohmic resistance of the D.C system with impedance.

Common Terms used in Circuit Theory

1. A **circuit** is a closed conducting path through which an electrical current either flows or is intended to flow. A circuit consists of active and passive elements.
2. Parameters are the various elements of an electrical circuit (for example, resistance, capacitance, and inductance).
3. Linear circuit – Circuits in which the parameters are constant with time, do not change with voltage or current, and obey Ohm's law. In a **non-linear circuit** the parameters change with voltage and current.
4. A **passive network** is a one which contains no source of EMF.
5. An **active network** is a one which contains one or more sources of EMF.
6. A **bilateral circuit** is one whose properties or characteristics are same in either direction of current. Example: the usual transmission line is bilateral.
7. A **unilateral circuit** is that circuit in which properties or characteristics change with the direction of operation. Example: a diode rectifier can rectify only in one direction.
8. A **Node** is a point in a circuit where two or more circuit elements are connected together.
9. Branch is a part of a network which lies between two nodes.
10. Loop is a closed path in a circuit in which no element or node is encountered more than once.
11. Mesh is a loop that contains no other loop within it.

E		voltage source		[volts, V]		**V**		voltage drop	[volts, V]
G		conductance		[siemens, S]		**X**		reactance	[ohms, W]
I		current		[amps, A]		**Y**		admittance	[siemens, S]
R		resistance		[ohms, W]		**Z**		impedance	[ohms, W]
P		power		[watts]					

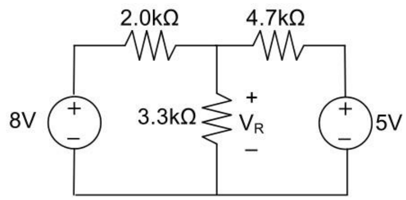
Laws

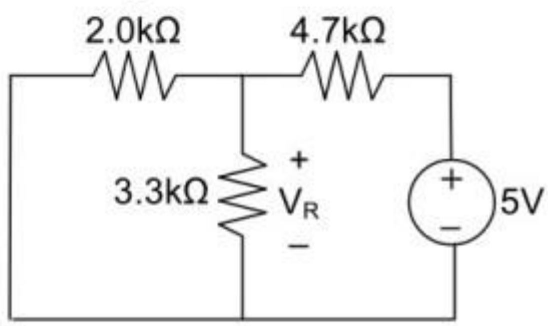
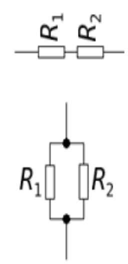
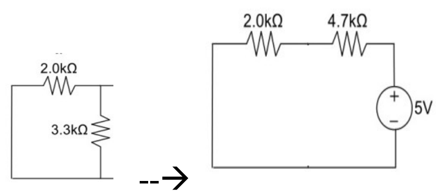
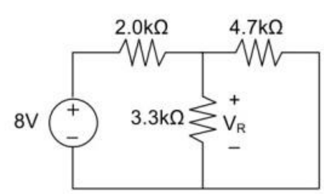
Electrical Science

1. Ohm's Law 2. Kirchhoff's Laws 3. Thévenin's Theorem 4. Norton's Theorem 5. Norton Theorem 6. Superposition Theorem 7. Reciprocity Theorem	8. Compensation Theorem 9. Millman's Theorem 10. Joule's Law 11. Maximum Power Transfer Theorem 12. Star-Delta Transformation 13. Delta-Star Transformation

Superposition theorem

Using the superposition theorem, determine the voltage drop and current across the resistor 3.3K as shown in the figure below.

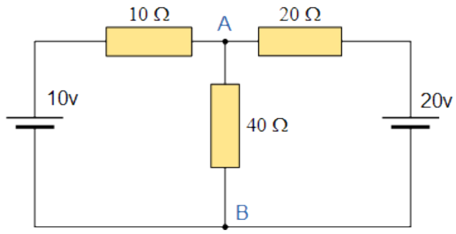


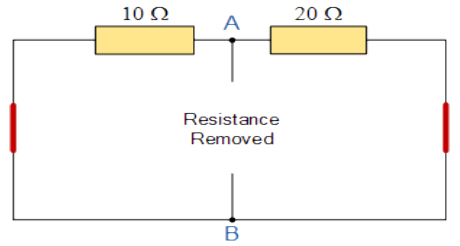
	$R_{TOTAL} = R_1 + R_2 \dots R_n$ $\frac{1}{R_{TOTAL}} = \frac{1}{R_1} + \frac{1}{R_2} \dots \frac{1}{R_n}$ 
Here 3.3K and 2K are in parallel; therefore resultant resistance will be 1.245K. **1/R=1/3.3+1/2 =➔ 1/R=0.3+ 0.5 = 0.8 ==> R=1/0.8=** **R= 1.25k**	
Using **voltage divider rule** voltage across 1.245K will be V=IR V1= [1.245/(1.245+4.7)]*5 = 1.047V	VOLTAGE — Series: Voltages add to total circuit voltage; Parallel: Same voltage across all parallel branches
Remove the 5V power supplies from the original circuit such that the new circuit becomes as the following and then measure the voltage across a resistor.	
Here 3.3K and 4.7K are in parallel, therefore	

resultant resistance will be 1.938K. Using voltage divider rule voltage across 1.938K will be V2= [1.938/(1.938+2)]*8 = 3.9377V Therefore voltage drop across a 3.3K resistor is V1+V2 = 1.047+3.9377=4.9847	

Thévenin's Theorem

Thevenin's Theorem.(https://www.electronics-tutorials.ws/dccircuits/dcp_7.html)





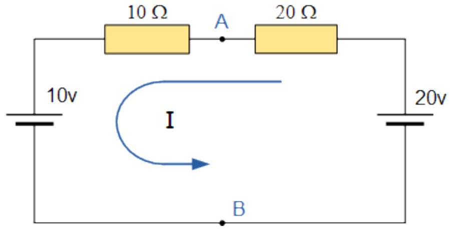
Find the Equivalent Resistance (Rs)

10Ω Resistor in Parallel with the 20Ω Resistor

$$R_T = \frac{R_1 \times R_2}{R_1 + R_2} = \frac{20 \times 10}{20 + 10} = 6.67\Omega$$

The voltage Vs is defined as the total voltage across the terminals A and B when there is an open circuit between them. That is without the load resistor RL connected.

Find the Equivalent Voltage (Vs)



We now need to reconnect the two voltages back into the circuit, and as VS = VAB the current flowing around the loop is calculated as:

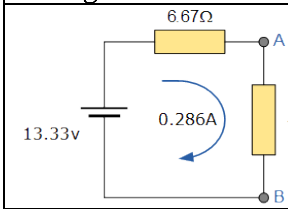
$$I = \frac{V}{R} = \frac{20v - 10v}{20\Omega + 10\Omega} = 0.33\ amps$$

This current of 0.33 amperes (330mA) is common to both resistors so the voltage drop across the 20Ω resistor or the 10Ω resistor can be calculated as:

VAB = 20 – (20Ω x 0.33amps) = 13.33 volts.or

VAB = 10 + (10Ω x 0.33amps) = 13.33 volts, the same.

Then the The venin's Equivalent circuit would consist or a series resistance of 6.67Ω and a voltage source of 13.33v. With the 40Ω resistor connected back into the circuit we get:



and from this the current flowing around the circuit is given as:

$$I = \frac{V}{R} = \frac{13.33v}{6.67\Omega + 40\Omega} = 0.286\ amps$$

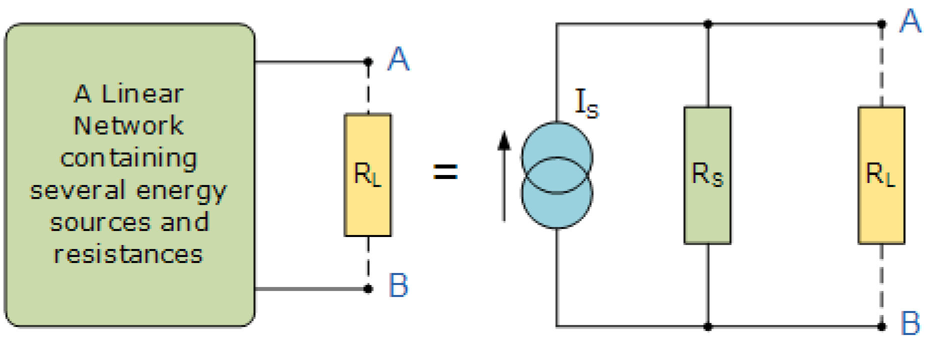
Which again, is the same value of 0.286 amps, we found using Kirchhoff's circuit law in the previous circuit analysis tutorial.

Norton's Theorem

It states that "Any linear circuit containing several energy sources and resistances can be replaced by a single Constant Current generator in parallel with a Single Resistor".

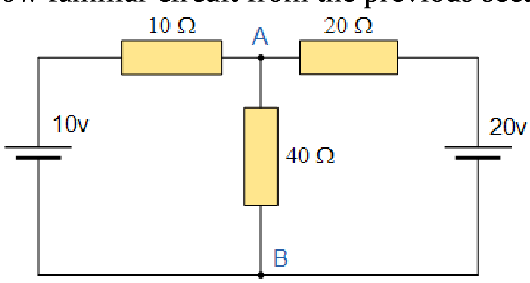
As far as the load resistance, R_L is concerned this single resistance, R_S is the value of the resistance looking back into the network with all the current sources open circuited and $I_S$is the short circuit current at the output terminals as shown below.

Nortons equivalent circuit

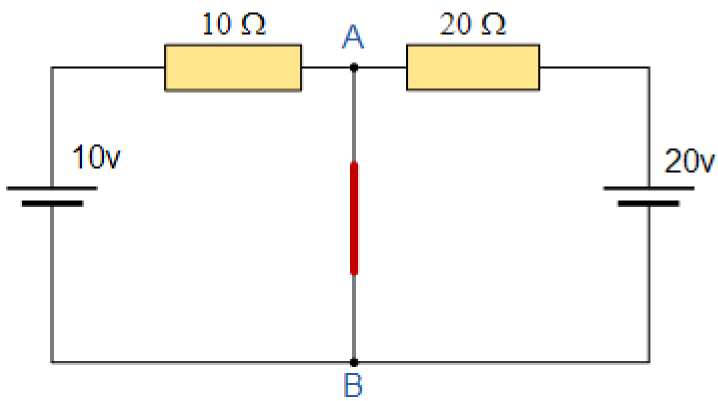


The value of this "constant current" is one which would flow if the two output terminals where shorted together while the source resistance would be measured looking back into the terminals, (the same as Thevenin).

For example, consider our now familiar circuit from the previous section.



To find the Nortons equivalent of the above circuit we firstly have to remove the centre 40Ω load resistor and short out the terminals A and B to give us the following circuit.



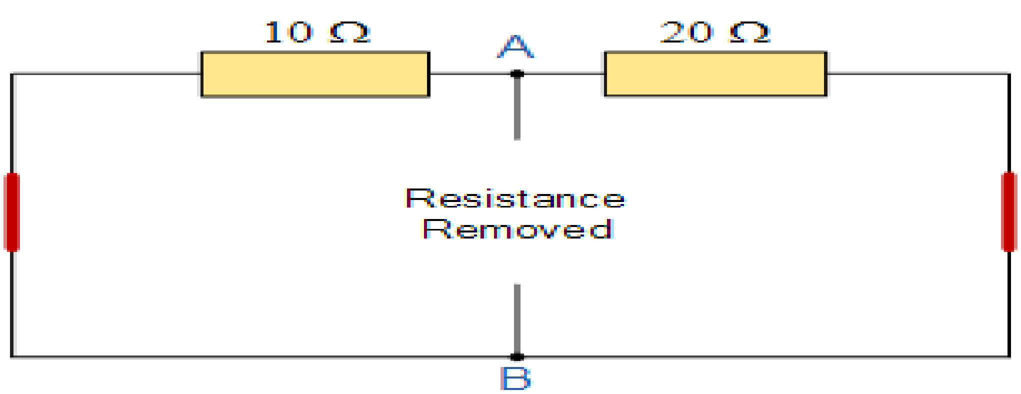
When the terminals A and B are shorted together the two resistors are connected in parallel across their two respective voltage sources and the currents flowing through each resistor as well as the total short circuit current can now be calculated as:

with A-B Shorted Out

$$I_1 = \frac{10v}{10\Omega} = 1amp, \quad I_2 = \frac{20v}{20\Omega} = 1amp$$

$$\text{therefore,} \quad I_{short\text{-}circuit} = I_1 + I_2 = 2amps$$

If we short-out the two voltage sources and open circuit terminals A and B, the two resistors are now effectively connected together in parallel. The value of the internal resistor Rs is found by calculating the total resistance at the terminals A and B giving us the following circuit.



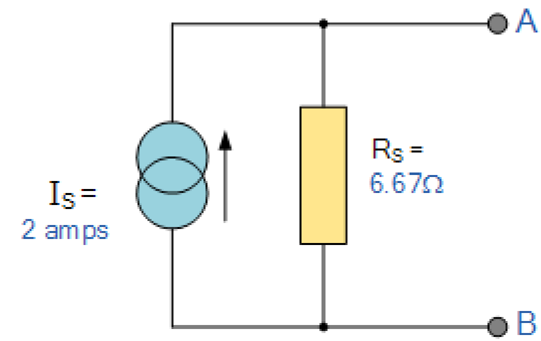
Find the Equivalent Resistance (Rs)

10Ω Resistor in Parallel with the 20Ω Resistor

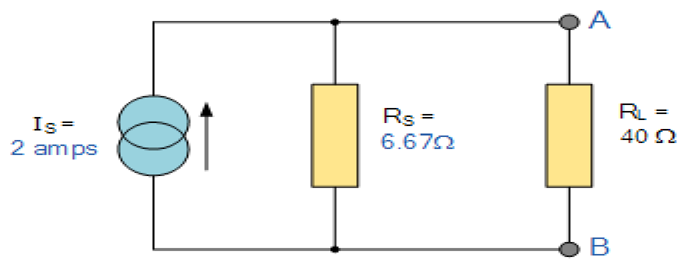
$$R_T = \frac{R_1 \times R_2}{R_1 + R_2} = \frac{20 \times 10}{20 + 10} = 6.67\Omega$$

Having found both the short circuit current, Is and equivalent internal resistance, Rs this then gives us the following Nortons equivalent circuit.

Nortons equivalent circuit



Ok, so far so good, but we now have to solve with the original 40Ω load resistor connected across terminals A and B as shown below.



Again, the two resistors are connected in parallel across the terminals A and B which gives us a total resistance of:

$$R_T = \frac{R_1 \times R_2}{R_1 + R_2} = \frac{6.67 \times 40}{6.67 + 40} = 5.72\Omega$$

The voltage across the terminals A and B with the load resistor connected is given as:

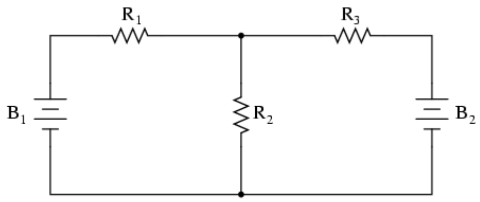
$$V_{A\text{-}B} = I \times R = 2 \times 5.72 = 11.44\text{v}$$

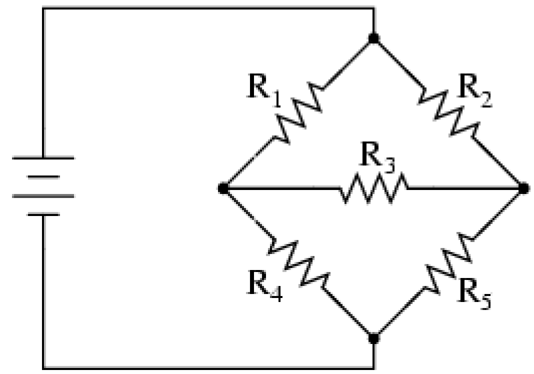
Then the current flowing in the 40Ω load resistor can be found as:

$$I = \frac{V}{R} = \frac{11.44}{40} = 0.286 \text{ amps}$$

which again, is the same value of 0.286 amps, we found using **Kirchhoff**´s circuit law in the previous tutorials.

NETWORK ANALYSIS (Find R, I, V and E)





$$E = I\,R \quad (E \text{ is unknown; } I \text{ and } R \text{ are known})$$

. . . or . . .

$$I = \frac{E}{R} \quad (I \text{ is unknown; } E \text{ and } R \text{ are known})$$

. . . or . . .

$$R = \frac{E}{I} \quad (R \text{ is unknown; } E \text{ and } I \text{ are known})$$

STEADY STATE RESPONSE OF CIRCUITS TO SINUSOIDAL FUNCTIONS

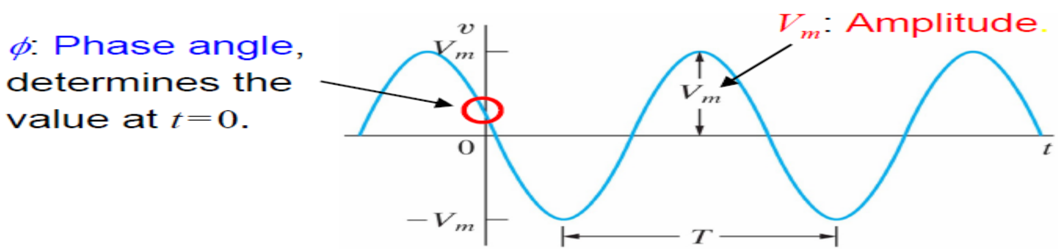
We will generalize circuit analysis from constant to time-varying sources Sinusoidal sources are particularly important because:

(1) Generation, transmission, consumption of electric energy occur under sinusoidal conditions.
(2) It can be used to predict the behaviors of circuits with non- sinusoidal sources.

The Sinusoidal Source and Response

Definition

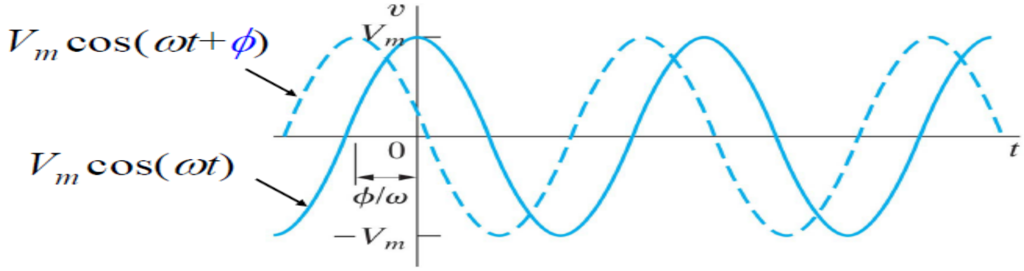
- A source producing a voltage varying sinusoidally with time: $v(t) = V_m \cos(\omega t + \phi)$.



ω: Angular frequency, related to period T via $\omega = 2\pi/T$.
The argument ωt changes 2π radians (360°) in one period.

More on phase angle

- Change of phase angle shifts the curve along the time axis without changing the shape (amplitude, angular frequency).
- Positive phase ($\phi > 0$), $\Rightarrow$ the curve is shifted to the left by ϕ/ω in time, and vice versa.



Characteristics of steady-state response

- $i_{ss}(t)$ of this example exhibits the following characteristics of steady-state response:

$$i_{ss}(t) \equiv \frac{V_m}{\sqrt{R^2 + \omega^2 L^2}} \cos(\omega t + \phi - \theta)$$

1. It remains sinusoidal of the same frequency as the driving source if the circuit is linear (with constant R, L, C values).
2. The amplitude differs from that of the source.
3. The phase angle differs from that of the source.

Purpose of Chapter 9

- Directly finding the steady-state response without solving the differential equation.
- According to the characteristics of steady-state response, the task is reduced to finding two real numbers, i.e. amplitude and phase angle, of the response. The waveform and frequency of the response are already known.
- Transient response matters in switching. It will be dealt with in Chapters 7, 8, 12, 13.

Solve steady-state response by phasor

- The phasor is a constant complex number that carries the amplitude and phase angle information of a sinusoidal function.
- The concept of phasor is rooted in Euler's identity, which relates the (complex) exponential function to the trigonometric functions: $e^{\pm j\theta} = \cos\theta \pm j\sin\theta$.

$$\Rightarrow \cos\theta = \mathrm{Re}\{e^{j\theta}\}, \quad \sin\theta = \mathrm{Im}\{e^{j\theta}\}.$$

Phasor representation

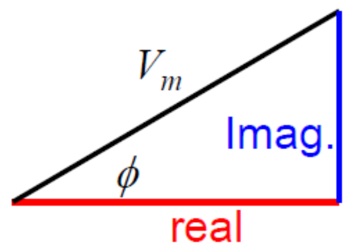
- A sinusoidal function can be represented by the real part of a phasor times the "complex carrier".

$$V_m \cos(\omega t + \phi) = V_m \,\mathrm{Re}\left\{e^{j(\omega t + \phi)}\right\}$$
$$= \mathrm{Re}\left\{\left(V_m e^{j\phi}\right) e^{j\omega t}\right\} = \mathrm{Re}\left\{\mathbf{V} \times e^{j\omega t}\right\}$$

phasor carrier

- A phasor can be represented in two forms:

1. Polar form (good for ×, ÷):
   $\mathbf{V} \equiv V_m e^{j\phi} = V_m \angle \phi,$
2. Rectangular form (good for +, -):
   $\mathbf{V} \equiv V_m \cos\phi + jV_m \sin\phi.$



Phasor transformation

- A phasor can be regarded as the "phasor transform" of a sinusoidal function from the time domain to the frequency domain:

$$\mathbf{V} = P\{V_m \cos(\omega t + \phi)\} = V_m e^{j\phi}.$$

time domain freq. domain

- The "inverse phasor transform" of a phasor is a sinusoidal function in the time domain:

$$P^{-1}\{\mathbf{V}\} = \mathrm{Re}\left\{\mathbf{V} e^{j\omega t}\right\} = V_m \cos(\omega t + \phi).$$

Time derivative ↔ Multiplication of constant

Time domain:

$$\frac{d}{dt}V_m\cos(\omega t+\phi)=-\omega V_m\sin(\omega t+\phi)$$

$$=\omega V_m\cos(\omega t+\phi+90^\circ),$$

$$\frac{d^2}{dt^2}V_m\cos(\omega t+\phi)=-\omega^2 V_m\cos(\omega t+\phi).$$

Frequency domain:

$$\mathrm{P}\left\{\frac{d}{dt}V_m\cos(\omega t+\phi)\right\}=\omega V_m e^{j(\phi+90^\circ)}$$

$$=\omega\left(V_m e^{j\phi}\right)e^{j90^\circ}=\boxed{j\omega\mathbf{V},}$$

$$\mathrm{P}\left\{\frac{d^2}{dt^2}V_m\cos(\omega t+\phi)\right\}=\boxed{(j\omega)^2\mathbf{V}}=-\omega^2\mathbf{V}.$$

How to calculate steady-state solution by phasor?

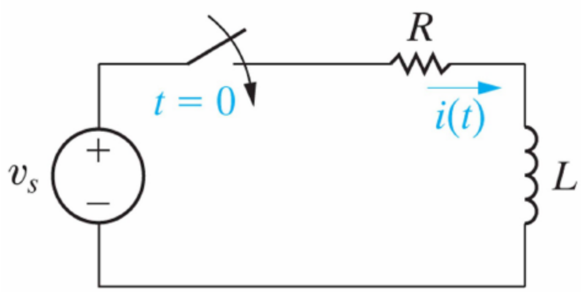
- Step 1: Assume that the solution is of the form:

$$\mathrm{Re}\left\{\left(Ae^{j\beta}\right)e^{j\omega t}\right\}$$

- Step 2: Substitute the proposed solution into the differential equation. The common time-varying factor $e^{j\omega t}$ of all terms will cancel out, resulting in two algebraic equations to solve for the two unknown constants $\{A,\ \beta\}$.

Example: RL circuit (1)

- Q: Given $v_s(t) = V_m \cos(\omega t + \phi)$, calculate $i_{ss}(t)$.



Assume

$i_{ss}(t) = I_m \cos(\omega t + \beta)$.

$$\Rightarrow L\frac{d}{dt}i_{ss}(t) + Ri_{ss}(t) = V_m \cos(\omega t + \phi),$$

$$\Rightarrow L\frac{d}{dt}[I_m \cos(\omega t + \beta)] + R[I_m \cos(\omega t + \beta)] = V_m \cos(\omega t + \phi),$$

$$\Rightarrow -\omega L I_m \sin(\omega t + \beta) + RI_m \cos(\omega t + \beta) = V_m \cos(\omega t + \phi),$$

Power and power factor

Electric power is the rate, per unit time, at which **electrical** energy is transferred by an **electric** circuit. The SI unit of **power** is the watt, one joule per second. **Electric power** is usually produced by **electric** generators, but can also be supplied by sources such as **electric** batteries.

Electrical energy	Electric power
(*i*) The work done or energy supplied by the source in maintaining the flow of electric current is called electrical energy. It appears in the form of heat given by $H = VIt = \frac{V^2 t}{R} = I^2RT$	(*i*) The time rate at which electric energy is consumed or dissipated by an electrical device is called electric power and is given by $P = VI = \frac{V^2}{R} = I^2R$
(*ii*) It is equal to the product of power and time $E = P \times t$	(*ii*) it equal to the rate of doing work by an energy source. $P = \frac{W}{t}$
(*iii*) Its SI unit is jule (J) $1\ J = 1\ W \times 1s$	(*iii*) Its SI unit is watt (W) $1\ W = 1\ J\ s^{-1}$

For the same applied voltage, $P \propto \frac{1}{R}$

P = true power $P = I^2R$ $P = \frac{E^2}{R}$

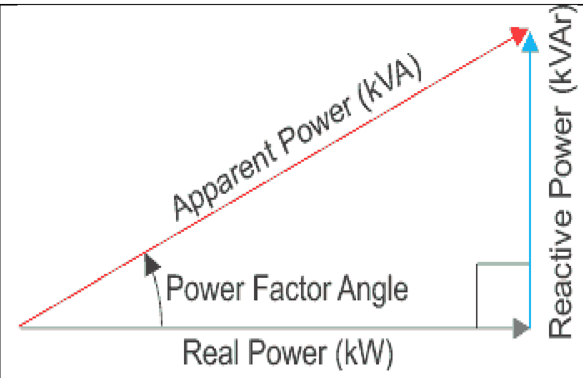
Measured in units of ***Watts***

Q = reactive power $Q = I^2X$ $Q = \frac{E^2}{X}$

Measured in units of ***Volt-Amps-Reactive (VAR)***

S = apparent power $S = I^2Z$ $S = \frac{E^2}{Z}$ $S = IE$

Measured in units of ***Volt-Amps (VA)***



Active Power (P) / Real Power / True Power, Watt-full Power/ Useful Power, Real Power
In a DC Circuit, power supply to the DC load is simply the product of Voltage across the load and Current flowing through it i.e., P = V I. because in DC Circuits, there is no concept of phase angle between current and voltage.

Reactive Power: (Q) /Use-less Power/ Watt less Power
The powers that continuously bounce back and forth between source and load is known as reactive Power (Q) .Power merely absorbed and returned in load due to its reactive properties is referred to as reactive power The unit of Active or Real power is Watt where 1W = 1V x 1 A.

Apparent Power: (S) The product of voltage and current if and only if the phase angle differences between current and voltage are ignored. Total power in an AC circuit, both dissipated and absorbed/returned is referred to as apparent power .
Apparent power = reactive power + true power
AC circuit is the product of the r.m.s voltage and the r.m.s current.

Power Factor Improvement
Mathematically it is the cosine of the phase difference between the source voltage and current. It refers to the fraction of total power (apparent power) which is utilised to do the useful work called active power. $\cos\phi = \frac{Active\ power}{Apparent\ power}$

Methods of Power Factor Improvement
Capacitors, Synchronous Condenser and Phase Advancer.

Power Factor Calculation

$$From\ this\ cos\phi = \frac{P}{VI}\ or\ \frac{Wattmeter\ reading}{Voltmeter\ reading \times\ Ammeter\ reading}$$

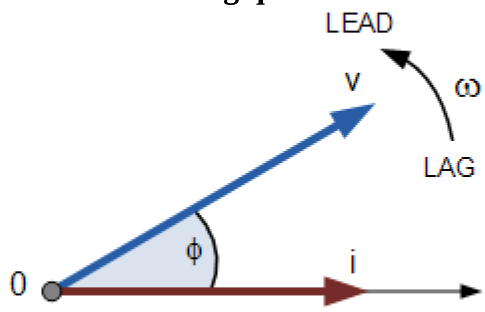
Reactive power Q = VIsinφ VAR .Value of capacitor is calculated as per following formula:

$$Q = \frac{V^2}{X_C} \Rightarrow C = \frac{Q}{2\pi f V^2}\ farad$$

PHASOR REPRESENTATION OF SINUSOIDAL FUCTIONS

Phasor Diagrams and Phasor Algebra

Phasor Diagrams are a graphical way of representing the **magnitude and directional relationship between two or more alternating quantities**



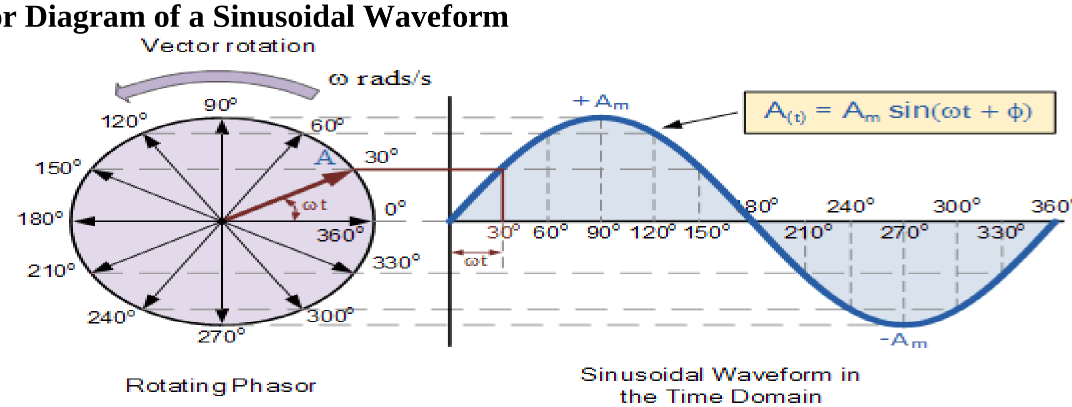
Sinusoidal waveforms of the same frequency can have a Phase Difference between themselves which represents the angular difference of the two sinusoidal waveforms. Also the terms "lead" and "lag" as well as "in-phase" and "out-of-phase" are commonly used to indicate the relationship of one waveform to the other with the generalized sinusoidal expression given as: $A_{(t)} = A_m \sin(\omega t \pm \Phi)$ representing the sinusoid in the time-domain form.

Basically a rotating vector, simply called a "**Phasor**" is a scaled line whose length represents an AC quantity that has both magnitude ("peak amplitude") and direction ("phase") which is "frozen" at some point in time.

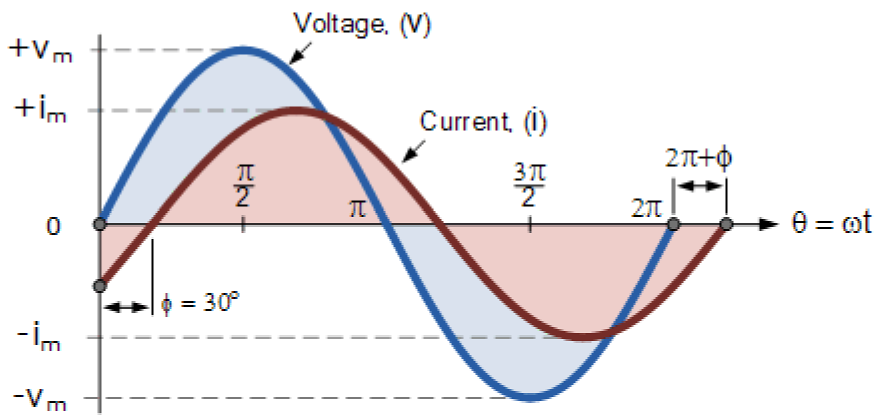
Although the both the terms vectors and phasors are used to describe a rotating line that itself has both magnitude and direction, the main difference between the two is that a vectors magnitude is the "peak value" of the sinusoid while a phasors magnitude is the "rms value" of the sinusoid. In both cases the phase angle and direction remains the same.

The phase of an alternating quantity at any instant in time can be represented by a phasor diagram, so phasor diagrams can be thought of as "functions of time". A complete sine wave can be constructed by a single vector rotating at an angular velocity of $\omega = 2\pi f$, where f is the frequency of the waveform. Then a **Phasor** is a quantity that has both "Magnitude" and "Direction".

Phasor Diagram of a Sinusoidal Waveform



Phase Difference of a Sinusoidal Waveform



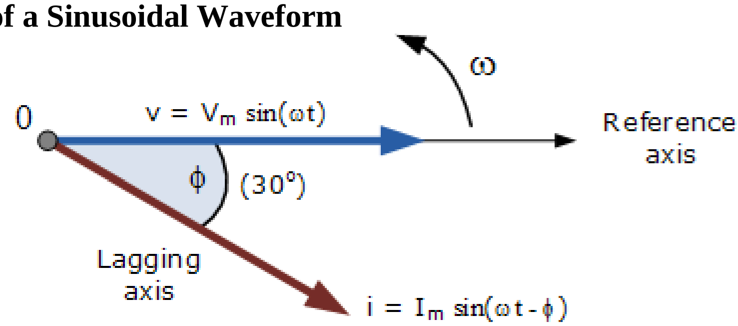
The generalised mathematical expression to define these two sinusoidal quantities will be written as:

$$v_{(t)} = V_m \sin(\omega t)$$

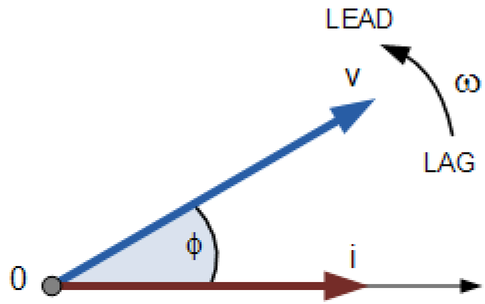
$$i_{(t)} = I_m \sin(\omega t - \phi)$$

The current, i is lagging the voltage, v by angle Φ and in our example above this is 30°. So the difference between the two phasors representing the two sinusoidal quantities is angle Φ and the resulting phasor diagram will be.

Phasor Diagram of a Sinusoidal Waveform



The phasor diagram is drawn corresponding to time zero (t = 0) on the horizontal axis. The lengths of the phasors are proportional to the values of the voltage, (V) and the current, (I) at the instant in time that the phasor diagram is drawn. The current phasor lags the voltage phasor by the angle, Φ, as the two phasors rotate in an *anticlockwise*direction as stated earlier, therefore the angle, Φ is also measured in the same anticlockwise direction.



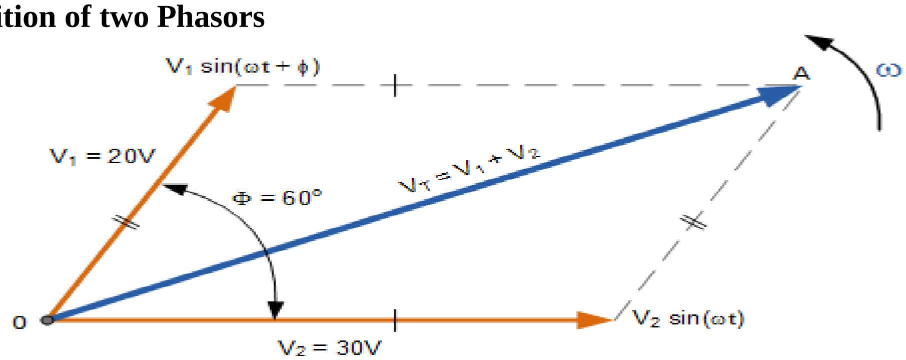
If however, the waveforms are frozen at time, t = 30°, the corresponding phasor diagram would look like the one shown on the right. Once again the current phasor lags behind the voltage phasor as the two waveforms are of the same frequency.

Phasor Addition

Sometimes it is necessary when studying sinusoids to add together two alternating waveforms, for example in an AC series circuit, that are not in-phase with each other. using phasor diagrams to determine their **Resultant Phasor** or **Vector Sum** by using the *parallelogram law*.

Consider two AC voltages, V_1 having a peak voltage of 20 volts, and V_2 having a peak voltage of 30 volts where V_1 leads V_2 by 60°. The total voltage, V_T of the two voltages can be found by firstly drawing a phasor diagram representing the two vectors and then constructing a parallelogram in which two of the sides are the voltages, V_1 and V_2 as shown below.

Phasor Addition of two Phasors



By drawing out the two phasors to scale onto graph paper, their phasor sum $V_1 + V_2$ can be easily found by measuring the length of the diagonal line, known as the "resultant r-vector", from the zero point to the intersection of the construction lines 0-A. The downside of this graphical method is that it is time consuming when drawing the phasors to scale.

Mathematically we can add the two voltages together by firstly finding their "vertical" and "horizontal" directions, and from this we can then calculate both the "vertical" and "horizontal" components for the resultant "r vector", V_T. This analytical method which uses the cosine and sine rule to find this resultant value is commonly called the **Rectangular Form**.

In the rectangular form, the phasor is divided up into a real part, x and an imaginary part, yforming the generalised expression $Z = x \pm jy$. (we will discuss this in more detail in the next tutorial). This then gives us a mathematical expression that represents both the magnitude and the phase of the sinusoidal voltage as:

Phasor Addition using Rectangular Form

The resultant voltage, V_T is found by adding together the horizontal and vertical components as follows.

- $V_{Horizontal}$ = sum of real parts of V_1 and V_2 = 30 + 10 = 40 volts
- $V_{Vertical}$ = sum of imaginary parts of V_1 and V_2 = 0 + 17.32 = 17.32 volts

Now that both the real and imaginary values have been found the magnitude of voltage, V_T is determined by simply using **Pythagoras's Theorem** for a 90° triangle as follows.

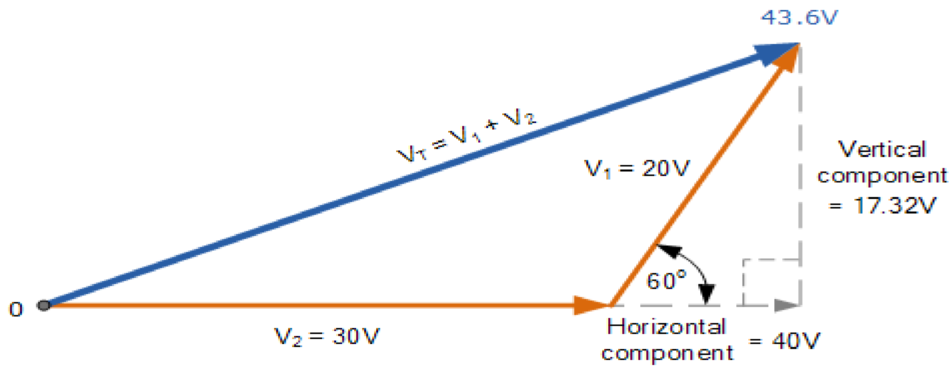
$$V_T = \sqrt{\left(\text{Real or Horizontal Component}\right)^2 + \left(\text{Imaginary or Vertical Component}\right)^2}$$

$$V_T = \sqrt{40^2 + 17.32^2}$$

$$\therefore V_T = 43.6\text{volts}$$

Then the resulting phasor diagram will be:

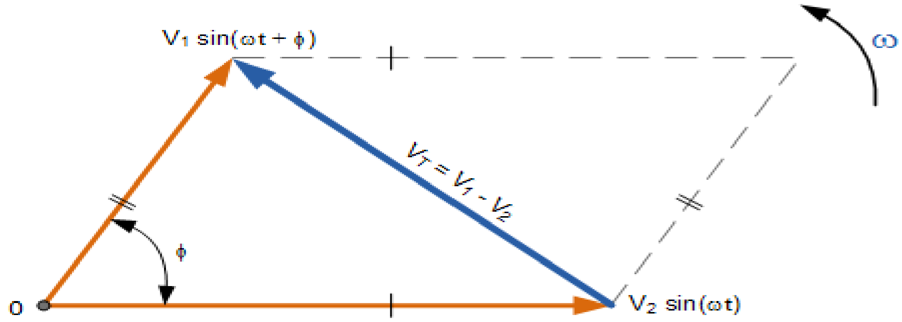
Resultant Value of V_T



Phasor Subtraction

Phasor subtraction is very similar to the above rectangular method of addition, except this time the vector difference is the other diagonal of the parallelogram between the two voltages of V_1 and V_2 as shown.

Vector Subtraction of two Phasors



This time instead of "adding" together both the horizontal and vertical components we take them away, subtraction.

$$A = x + jy \qquad B = w + jz$$

$$A - B = (x - w) + j(y - z)$$

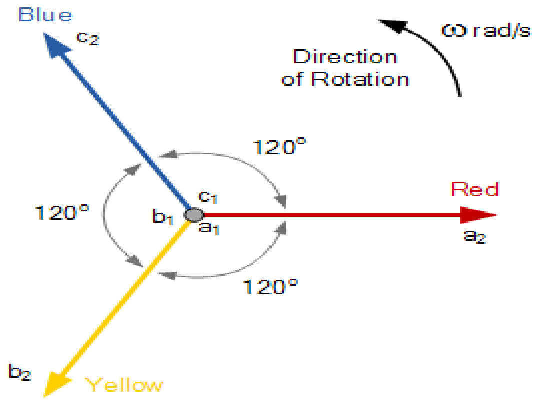
The 3-Phase Phasor Diagram

A balanced three-phase voltage supply consists of three individual sinusoidal voltages that are all equal in magnitude and frequency but are out-of-phase with each other by exactly 120^o electrical degrees.

Standard practice is to colour code the three phases as Red, Yellow and Blue to identify each individual phase with the red phase as the reference phase. The normal sequence of rotation for a three phase supply is Red followed by Yellow followed by Blue, (R, Y, B).

As with the single-phase phasors above, the phasors representing a three-phase system also rotate in an anti-clockwise direction around a central point as indicated by the arrow marked ω in rad/s. The phasors for a three-phase balanced star or delta connected system are shown below.

Three-phase Phasor Diagram



The phase voltages are all equal in magnitude but only differ in their phase angle. The three windings of the coils are connected together at points, a_1, b_1 and c_1 to produce a common neutral connection for the three individual phases. Then if the red phase is taken as the reference phase each individual phase voltage can be defined with respect to the common neutral as.

RESONANCE

In an electrical circuit, the condition that exists when the inductive reactance and the capacitive reactance are of equal magnitude, causing electrical energy to oscillate between the magnetic field of the inductor and the electric field of the capacitor.

Note 1: Resonance occurs because the collapsing magnetic field of the inductor generates an electric current in its windings that charges the capacitor and the discharging capacitor provides an electric current that builds the magnetic field in the inductor, and the process is repeated.

Note 2: At resonance, the series **impedance** of the two elements is at a minimum and the parallel impedance is a maximum. Resonance is used for **tuning** and filtering, because resonance occurs at a particular **frequency** for given values of inductance and capacitance. Resonance can be detrimental to the **operation** of **communications** circuits by causing unwanted sustained and transient oscillations that may cause **noise**, **signal distortion**, and damage to circuit elements. *Note 3:* At resonance the inductive reactance and the capacitive reactance are of equal magnitude. Therefore,

$$\omega L = 1/\omega C \text{, where } \omega = 2\pi f,$$

in which f is the resonant frequency in **hertz**, *L* is the inductance in henrys, and *C* is the capacity in farads when **standard** SI units are used. Thus,

$$f = \frac{\pi}{2\sqrt{LC}}.$$

Magnetic field calculations

When electric current is carried in a wire, a magnetic field is formed around it. The magnetic field lines form concentric circles around the wire. The magnetic field direction depends on the direction of the current. It can be determined using the "right hand rule", by pointing the thumb of your right hand in the direction of the current. The direction of the magnetic field lines is the direction of your curled fingers. The magnitude of the magnetic field depends on the amount of current, and the distance from the charge-carrying wire. The formula includes the constant μ_0. This is called the permeability of free space, and has a value $\mu_0 = 4\pi \times 10^{-7}\ (\mathrm{T}\cdot m)/A$. The unit of magnetic field is the Tesla, T.

$$magnetic\ field\ magnitude = \frac{(permeabilty\ of\ free\ space)(current\ magnitude)}{2\pi(distance)}$$

$$B = \frac{\mu_0 I}{2\pi r}$$

B = magnetic field magnitude (Tesla, T)

μ_0 = permeability of free space ($4\pi \times 10^{-7}\ \mathrm{T}\cdot m/\mathrm{A}$)

I = magnitude of the electric current (Amperes, A)

r = distance (m)

Magnetic Field Formula Questions:

1) What is the magnitude of the magnetic field 0.10 m away from a wire carrying a 3.00 A current? If the current has a vector direction out of the page (or screen), what is the direction of the magnetic field?

Answer: The magnitude of the magnetic field can be calculated using the formula:

$$B = \frac{\mu_0 I}{2\pi r}$$

$$B = \frac{(4\pi \times 10^{-7}\ \mathrm{T}\cdot m/\mathrm{A})(3.00\ \mathrm{A})}{2\pi(0.10\ m)}$$

$$B = \frac{(4\pi \times 10^{-7}\ \mathrm{T}\cdot \cancel{m}/\cancel{\mathrm{A}})(3.00\ \cancel{\mathrm{A}})}{2\pi(0.10\ \cancel{m})}$$

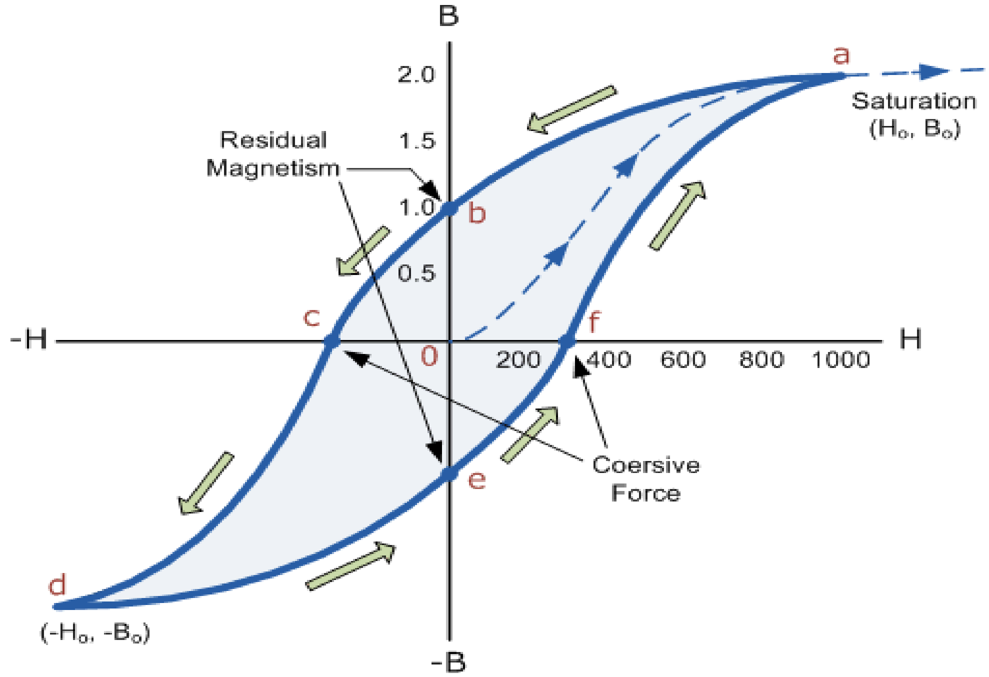
$$B = \frac{(4\pi \times 10^{-7})(3.00)}{2\pi(0.10)}\ \mathrm{T}$$

$$B = \frac{4\pi}{2\pi}\frac{(3.00)}{(0.10)} \times 10^{-7}\ \mathrm{T}$$
$$B = 2(30.0) \times 10^{-7}\ \mathrm{T}$$
$$B = 60.0 \times 10^{-7}\ \mathrm{T}$$
$$B = 6.00 \times 10^{1-7}\ \mathrm{T}$$
$$B = 6.00 \times 10^{-6}\ \mathrm{T}$$
$$B = 6.00\ \mu\mathrm{T}$$

The magnitude of the magnetic field is 6.00 x 10^{-6} T, which can also be written as $6.00\ \mu\mathrm{T}$ (micro-Tesla).
The direction of the magnetic field can be determined using the "right hand rule", by pointing the thumb of your right hand in the direction of the current. The direction of the magnetic field lines is the direction of your curled fingers. The current has a vector direction out of the page, and so your fingers will curl in the counter-clockwise direction. Therefore, the magnetic field lines point in the counter-clockwise direction, forming circles around the wire.

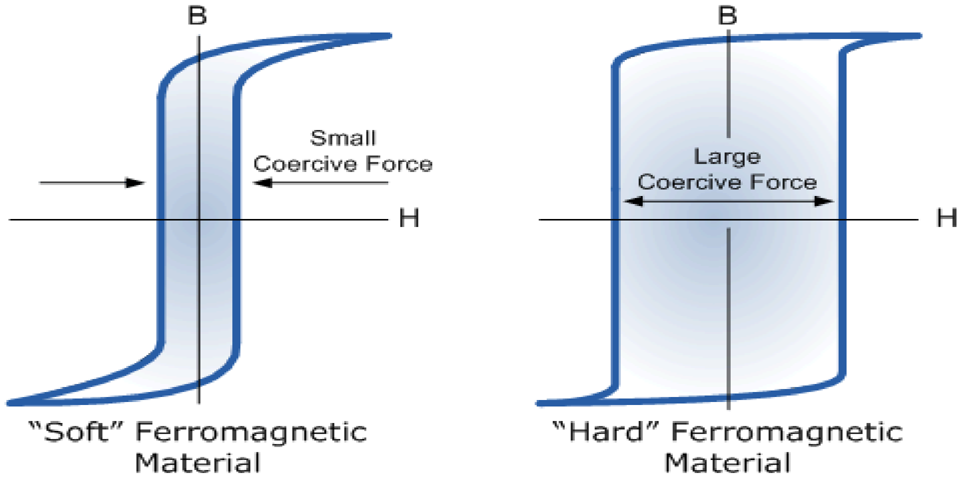
Magnetization curve

A magnetisation curve/hysteresis loop/B-H loop plots the relationship between the induced magnetic flux density (B) and the magnetizing force (H).



The underlying principle of a magnetising curve is the fact that the flux density of a material is not just a property of magnetising force applied, but also its history of magnetisation.

Magnetic Hysteresis
The lag or delay of a magnetic material known commonly as **Magnetic Hysteresis**, relates to the magnetisation properties of a material by which it firstly becomes magnetised and then de-magnetised.



We know that the magnetic flux generated by an electromagnetic coil is the amount of magnetic field or lines of force produced within a given area and that it is more commonly called "Flux Density". Given the symbol B with the unit of flux density being the Tesla, T.

We also know that the magnetic strength of an electromagnet depends upon the number of turns of the coil, the current flowing through the coil or the type of core material being used, and if we increase either the current or the number of turns we can increase the magnetic field strength, symbol H.

Previously, the relative permeability, symbol μ_r was defined as the ratio of the absolute permeability μ and the permeability of free space μ_o (a vacuum) and this was given as a constant. However, the relationship between the flux density, B and the magnetic field strength, H can be defined by the fact that the relative permeability, μ_r is not a constant but a function of the magnetic field intensity thereby giving magnetic flux density as: $B = \mu H$.

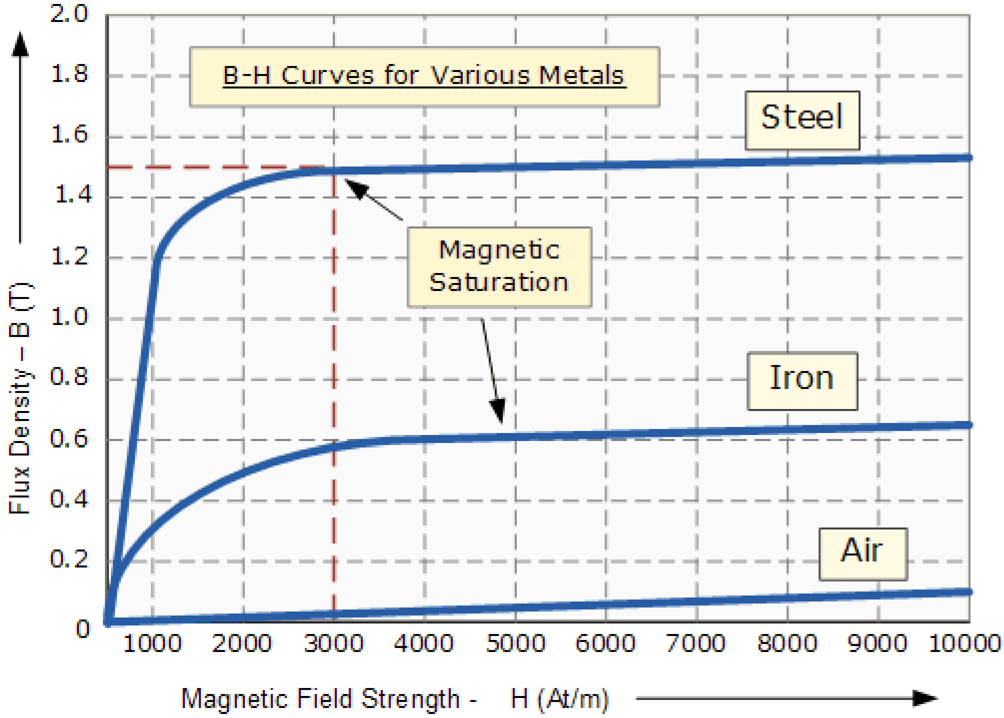
Then the magnetic flux density in the material will be increased by a larger factor as a result of its relative permeability for the material compared to the magnetic flux density in vacuum, $\mu_o H$ and for an air-cored coil this relationship is given as:

$$B = \frac{\Phi}{A} \quad \text{and} \quad \frac{B}{H} = \mu_0$$

So for ferromagnetic materials the ratio of flux density to field strength (B/H) is not constant but varies with flux density. However, for air cored coils or any non-magnetic medium core such as woods or plastics, this ratio can be considered as a constant and this constant is known as μ_o, the permeability of free space, ($\mu_o = 4.\pi.10^{-7}$ H/m).

By plotting values of flux density, (B) against the field strength, (H) we can produce a set of curves called **Magnetisation Curves**, **Magnetic Hysteresis Curves** or more commonly **B-H Curves** for each type of core material used as shown below.

Magnetisation or B-H Curve



The set of magnetisation curves, M above represents an example of the relationship between B and H for soft-iron and steel cores but every type of core material will have its own set of magnetic hysteresis curves. You may notice that the flux density increases in proportion to the field strength until it reaches a certain value were it can not increase any more becoming almost level and constant as the field strength continues to increase.

This is because there is a limit to the amount of flux density that can be generated by the core as all the domains in the iron are perfectly aligned. Any further increase will have no effect on the value of M, and the point on the graph where the flux density reaches its limit is called **Magnetic Saturation** also known as **Saturation of the Core** and in our simple example above the saturation point of the steel curve begins at about 3000 ampere-turns per metre.

Saturation occurs because as we remember from the previous Magnetism tutorial which included Weber's theory, the random haphazard arrangement of the molecule structure within the core material changes as the tiny molecular magnets within the material become "lined-up".

As the magnetic field strength, (H) increases these molecular magnets become more and more aligned until they reach perfect alignment producing maximum flux density and any increase in the magnetic field strength due to an increase in the electrical current flowing through the coil will have little or no effect.

Retentivity
Lets assume that we have an electromagnetic coil with a high field strength due to the current flowing through it, and that the ferromagnetic core material has reached its saturation point, maximum flux density. If we now open a switch and remove the magnetising current flowing through the coil we would expect the magnetic field around the coil to disappear as the magnetic flux reduced to zero.

However, the magnetic flux does not completely disappear as the electromagnetic core material still retains some of its magnetism even when the current has stopped flowing in the coil. This ability for a coil to retain some of its magnetism within the core after the magnetisation process has stopped is called **Retentivity** or remanence, while the amount of flux density still remaining in the core is called **Residual Magnetism**, B_R .

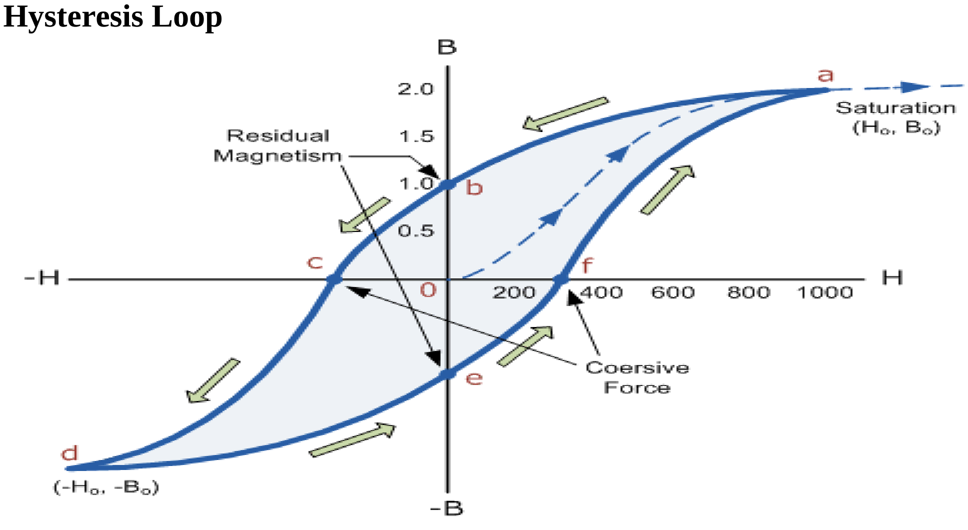
The reason for this that some of the tiny molecular magnets do not return to a completely random pattern and still point in the direction of the original magnetising field giving them a sort of "memory". Some ferromagnetic materials have a high retentivity (magnetically hard) making them excellent for producing permanent magnets.

While other ferromagnetic materials have low retentivity (magnetically soft) making them ideal for use in electromagnets, solenoids or relays. One way to reduce this residual flux density to zero is by reversing the direction of the current flowing through the coil, thereby making the value of H, the magnetic field strength negative. This effect is called a **Coercive Force**, H_C .

If this reverse current is increased further the flux density will also increase in the reverse direction until the ferromagnetic core reaches saturation again but in the reverse direction from before. Reducing the magnetising current, i once again to zero will produce a similar amount of residual magnetism but in the reverse direction.

Then by constantly changing the direction of the magnetising current through the coil from a positive direction to a negative direction, as would be the case in an AC supply, a **Magnetic Hysteresis** loop of the ferromagnetic core can be produced.

Magnetic Hysteresis Loop



The **Magnetic Hysteresis** loop above, shows the behaviour of a ferromagnetic core graphically as the relationship between B and H is non-linear. Starting with an unmagnetised core both B and H will be at zero, point 0 on the magnetisation curve.

If the magnetisation current, i is increased in a positive direction to some value the magnetic field strength H increases linearly with i and the flux density B will also increase as shown by the curve from point 0 to point **a** as it heads towards saturation.

Now if the magnetising current in the coil is reduced to zero, the magnetic field circulating around the core also reduces to zero. However, the coils magnetic flux will not reach zero due to the residual magnetism present within the core and this is shown on the curve from point **a** to point **b**.

To reduce the flux density at point b to zero we need to reverse the current flowing through the coil. The magnetising force which must be applied to null the residual flux density is called a "Coercive Force". This coercive force reverses the magnetic field re-arranging the molecular magnets until the core becomes unmagnetised at point **c**.

An increase in this reverse current causes the core to be magnetised in the opposite direction and increasing this magnetisation current further will cause the core to reach its saturation point but in the opposite direction, point **d** on the curve.

This point is symmetrical to point **b**. If the magnetising current is reduced again to zero the residual magnetism present in the core will be equal to the previous value but in reverse at point **e**.

Again reversing the magnetising current flowing through the coil this time into a positive direction will cause the magnetic flux to reach zero, point **f** on the curve and as before increasing the magnetisation current further in a positive direction will cause the core to reach saturation at point **a**.

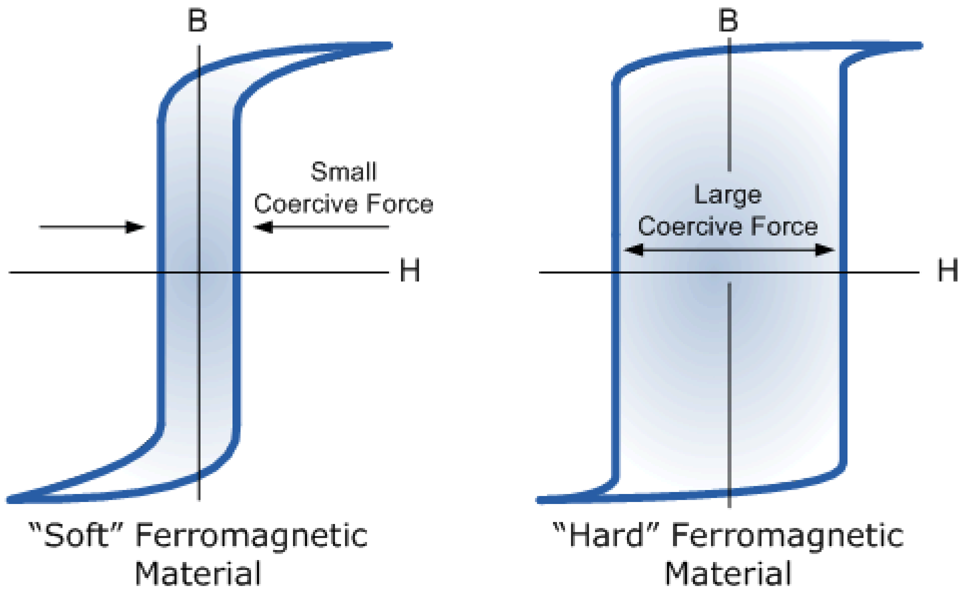
Then the B-H curve follows the path of **a-b-c-d-e-f-a** as the magnetising current flowing through the coil alternates between a positive and negative value such as the cycle of an AC voltage. This path is called a **Magnetic Hysteresis Loop**.

The effect of magnetic hysteresis shows that the magnetisation process of a ferromagnetic core and therefore the flux density depends on which part of the curve the ferromagnetic core is magnetised on as this depends upon the circuits past history giving the core a form of "memory". Then ferromagnetic materials have memory because they remain magnetised after the external magnetic field has been removed.

However, soft ferromagnetic materials such as iron or silicon steel have very narrow magnetic hysteresis loops resulting in very small amounts of residual magnetism making them ideal for use in relays, solenoids and transformers as they can be easily magnetised and demagnetised. Since a coercive force must be applied to overcome this residual magnetism, work must be done in closing the hysteresis loop with the energy being used being dissipated as heat in the magnetic material. This heat is known as hysteresis loss, the amount of loss depends on the material's value of coercive force.

By adding additive's to the iron metal such as silicon, materials with a very small coercive force can be made that have a very narrow hysteresis loop. Materials with narrow hysteresis loops are easily magnetised and demagnetised and known as soft magnetic materials.

Magnetic Hysteresis Loops for Soft and Hard Materials



Magnetic Hysteresis results in the dissipation of wasted energy in the form of heat with the energy wasted being in proportion to the area of the magnetic hysteresis loop. Hysteresis losses will always be a problem in AC transformers where the current is constantly changing direction and thus the magnetic poles in the core will cause losses because they constantly reverse direction.

Rotating coils in DC machines will also incur hysteresis losses as they are alternately passing north the south magnetic poles. As said previously, the shape of the hysteresis loop depends upon the nature of the iron or steel used and in the case of iron which is subjected to massive reversals of magnetism, for example transformer cores, it is important that the B-H hysteresis loop is as small as possible.

In the next tutorial about Electromagnetism, we will look at Faraday's Law of Electromagnetic Induction and see that by moving a wire conductor within a stationary magnetic field it is possible to induce an electric current in the conductor producing a simple generator.

Magnetic circuit concepts and calculations

A **magnetic circuit** is made up of one or more closed loop paths containing a magnetic flux. The flux is usually generated by permanent magnets or electromagnets and confined to the path by magnetic cores consisting of ferromagnetic materials like iron, although there may be air gaps or other materials in the path. Magnetic circuits are employed to efficiently channel magnetic fields in many devices such as electric motors, generators, transformers, relays, lifting electromagnets, SQUIDs, galvanometers, and magnetic recording heads.

The concept of a "magnetic circuit" exploits a one-to-one correspondence between the equations of the magnetic field in an unsaturated ferromagnetic material to that of an **electrical circuit.** Using this concept the magnetic fields of complex devices such as **transformers** can be quickly solved using the methods and techniques developed for electrical circuits.
Some examples of magnetic circuits are:

- **horseshoe magnet** with iron keeper (low-reluctance circuit)
- horseshoe magnet with no keeper (high-reluctance circuit)
- electric motor (variable-reluctance circuit)

When the electric flux is moving, there will be generated magneto motive force. The magneto motive force in the magnetic circuit is similar to the electro motive force in the electric circuit.

In a magnetic circuit, the current is the ratio of the magneto motive force to the reluctance, which is similar to an electric circuit, that is, in an electric circuit the current is the ratio of the electro motive force to the resistance.

In a magnetic circuit, if all the magnetic paths are connected in series, the equivalent reluctance will be the arithmetic sum of all the reluctances which is also the same for a series connection of an electrical circuit. And for parallel connection of the magnetic circuit, the equivalent reluctance is the sum of the reciprocal of the reluctance that is connected in parallel connection, which is also the same as the electrical circuit.

The voltage drop, which is known as magneto motive force drop in a magnetic circuit is the product of magnetic flux and the reluctance.
Thus, in almost all the properties, the electric and the magnetic circuits are similar.

MAGNETIC CIRCUIT DESIGN 1. MAGNETIC CIRCUIT ANALYSIS 1-1. Basic calculation method The basic calculation method of a magnetic circuit is the same as is used in a basic electrical analysis using Ohm’s Law. The total magnetic flux ø (analogous to electric current), magnetomotive force F (analogous to voltage), and magnetic reluctance R (analogous to electrical resistance) are related as shown in below.

$$\text{Total magnetic flux } ø = \frac{\text{Magnetomotive force } F}{\text{Magnetic reluctance } R} \quad \text{............(1)}$$

In magnetic circuit calculations, it is more common to use the magnetic permeance P, which is the reciprocal to reluctance R. Using permeance instead of reluctance, the total flux equation is changed as shown in below.

$$\text{Total magnetic flux } \o = \text{Magnetomotive force F} \bullet \text{Permeance P} \quad ....(2)$$

The permeance P is a function of the magnetic circuit length L, magnetic circuit cross sectional area A, and magnetic permeability μ.

$$\text{Permeance P} = \frac{\text{Permeability } \mu \bullet \text{Cross sectional area A}}{\text{Magnetic circuit length L}} \quad ....(3)$$

The total magnetic circuit permeance Pt is considered as a total of any air gap permeance Pg defined as a reciprocal of magnetic reluctance in the air gap, and the sum of leakage permeance Pf, defined as the reciprocal of the magnetic reluctance of the leakage flux paths at the poles.
Pt = Pg+Pf = Pg+Pf1+Pf2+ .... +Pfn ....(4)

Magnetomotive force loss coefficient f The magnetomotive force loss coefficient f is the ratio of the total magnetomotive force Ft and the magnetomotive force in the air gap Fg for a given magnetic circuit.

$$\text{Magnetomotive force loss coefficient f} = \frac{Ft}{Fg} \quad ....(5)$$

Leakage coefficient σ: Itis the ratio of the total magnetic flux øt generated from the magnet in a given circuit and the flux found in the air gap øg.

$$\text{Leakage coefficient } \sigma = \frac{\o t}{\o g} \quad ....(7)$$

Permeance coefficient Pc The permeance coefficient is used to design a permanent magnet application with a B-H curve. This is defined as the ratio of flux density Bd and magnetic field strength Hd of the operating point, and equation (11) becomes:

$$\text{Permeance coefficient Pc} = \frac{Bd}{Hd} \quad ....(11)$$

Magnetic		
Name	**Symbol**	**Units**
Magnetomotive force (MMF)	$\mathcal{F} = \int \mathbf{H} \cdot \mathrm{d}\mathbf{l}$	ampere-turn
Magnetic field	*H*	ampere/meter
Magnetic flux	Φ	weber
Hopkinson's law or Rowland's law	$\mathcal{F} = \Phi \mathcal{R}_m$	ampere-turn
Reluctance	$\mathcal{R}_m$	1/henry
Permeance	$\mathcal{P} = \frac{1}{\mathcal{R}_m}$	henry
Relation between *B* and *H*	$\mathbf{B} = \mu \mathbf{H}$	
Magnetic flux density *B*	*B*	tesla
Permeability	*μ*	henry/meter

Hysteresis and eddy current losses
Hysteresis Eddy Current Iron or Core Losses and Copper Loss in Transformer
Copper Loss in Transformer
Copper loss is I^2R loss, in primary side it is $I_1^2R_1$ and in secondary side it is $I_2^2R_2$ loss, where I_1 and I_2 are primary and secondary **current** of transformer and R_1 and R_2 are **resistances** of primary and secondary winding. As the both primary & secondary currents depend upon load of transformer, **copper loss in transformer** vary with load.
Core Losses in Transformer
Hysteresis loss and **eddy current loss**, both depend upon magnetic properties of the materials used to construct the **core of transformer** and its design. So these **losses in transformer** are fixed and do not depend upon the load current. So **core losses in transformer** which is alternatively known as **iron loss in transformer** can be considered as constant for all range of load. **Hysteresis loss in transformer** is denoted as, $W_h = K_h f (B_m)^{1.6} \; watts$ **Eddy current loss in transformer** is denoted as, $W_e = K_e f^2 K_f^2 B_m^2 \; watts$ Where, K_h = Hysteresis constant. K_e = Eddy current constant. K_f = form constant.
Copper loss can simply be denoted as,

$$I_L^2 R_2' + \text{Stray loss}$$

Where, $I_L = I_2$ = load of transformer, and R_2' is the **resistance** of transformer referred to secondary. Now we will discuss Hysteresis loss and Eddy current loss in little bit more details for better understanding the topic of losses in transformer.

Hysteresis Loss in Transformer

Hysteresis loss in transformer can be explained in different ways. We will discuss two of them, one is physical explanation and the other is mathematical explanation.

What is Eddy Current Loss?

In **transformer**, we supply alternating current in the primary, this alternating current produces alternating magnetizing flux in the core and as this flux links with secondary winding, there will be induced **voltage** in secondary, resulting current to flow through the load connected with it. Some of the alternating fluxes of transformer; may also link with other conducting parts like steel core or iron body of transformer etc. As alternating flux links with these parts of transformer, there would be a locally induced emf. Due to these emfs, there would be currents which will circulate locally at that parts of the transformer. These circulating current will not contribute in output of the transformer and dissipated as heat. This type of energy loss is called eddy current loss of transformer. This was a broad and simple explanation of eddy current loss. The detail explanation of this loss is not in the scope of discussion in that chapter.

There are two types of Losses in an Electrical Machine. They are

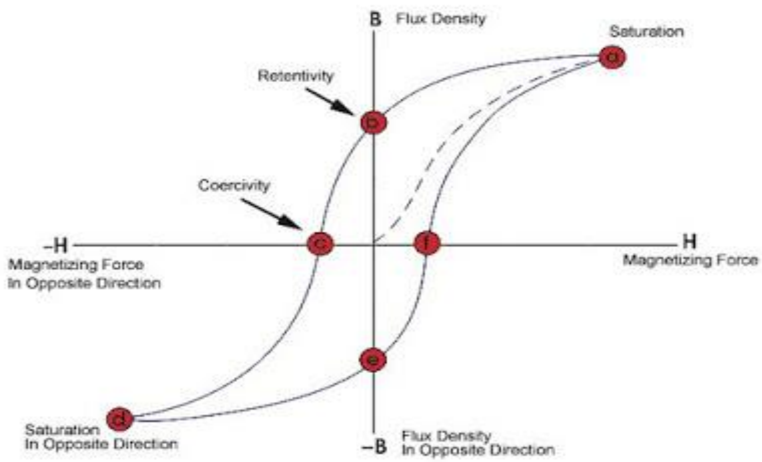
Core Loss or Iron Loss	Core Loss is again classified into two types: • Hysteresis Loss • Eddy Current Loss
Ohmic Loss or Copper Loss	

First we will have a look at how the core of a Transformer looks like. But the Core Loss take place in any electrical machine which face changing magnetic flux.

Hysteresis Loss:

This loss is due to magnetic properties of iron part or core.

When the magnetic field strength or the current is increased the flux increase, after a point when we further increase current the flux gets saturated. When we reduce the current from saturation to zero side the flux density starts to decrease. But when the current value reaches zero the flux density should also be zero but it is not zero. For zero current there is still some flux present in the material, this is known as ***Residual Magnetic Flux or Remnant Magnetic Flux***. Hence the amount of power is never recovered back. The power which gets trapped in the core of the material is lost in the form of heat.



Now we will consider the mathematical part of Hysteresis Loss. The Hysteris Loss in core is given as

$\mathbf{P_h = K_h f B_m^x}$

Where Kh = Constant which depends on the volume and quality of core material.

B_m = Maximum flux density in the core

f = Frequency of Supply

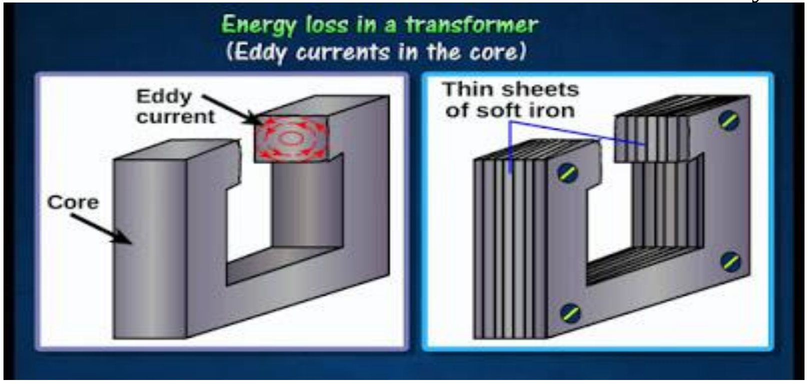
x = Steinmetz's constant whose value varies from 1.5 to 2.5.

Thus we see that Core Loss depend on Voltage as well as Frequency of Supply.

Eddy Current Loss:

Eddy Current Loss takes place when a coil is wrapped around a core and alternating ac supply is applied to it. As the supply to the coil is alternating, the flux produced in the coil is also alternating.

By **faradays law** of electromagnetic induction, the change in flux through the core causes emf induction inside the core. Due to induction of emf eddy current starts to flow in the core. Due to this eddy current there will be an associated Ohmic loss which is called Eddy Current Loss.



Eddy current losses can be reduced by lamination in the core. Thin sheet steels must be used which are insulated from each other. Due to insulated sheets the amount of current which flows get reduced and hence the eddy current losses also reduces.

Now we will take a look at the mathematical part of Eddy Current Loss. Eddy Current Loss is given as

$\mathbf{P_e = K_e f^2 B_m^2}$

Where Ke = constant whose value depends on the volume and resistivity of the core material.
Bm = Maximum flux density in the core
f = Frequency of Supply

It shall be noted that, from the equation of Eddy Current Loss it seems that Eddy Current Loss depends on the frequency of supply but it is not so rather it only depends on the Supply Voltage. **How?**

As $P_e = K_e f^2 B_m^2$

But we know that

$$V = \sqrt{2}\,\pi f N \text{Ø}m$$

$$V = \sqrt{2}\,\pi f N B m A$$

where B isMagnetic Flux Density and A is Cross sectional area of Core

So,

$\mathbf{B_m^2 f^2 = KE^2}$ where K is constant

Thus Eddy Current Loss $\mathbf{Pe = KV^2}$

Therefore, Eddy Current Loss only depends on the applied Voltage.

RELAYS

Relays involve two circuits: the **energizing circuit and the contact circuit**. The coil is on the energizing side; and the relays contacts are on the contact side. When a relays coil is energized, current flow through the coil creates a magnetic field. Whether in a DC unit where the polarity is fixed, or in an AC unit where the polarity changes 120 times per second, the basic function remains the same: the magnetic coil attracts a ferrous plate, which is part of the armature. One end of the armature is attached to the metal frame, which is formed so that the armature can pivot, while the other end opens and closes the contacts. Contacts come in a number of different configurations, depending on the number of Breaks, poles and Throws that make up the relay. For instance, relays might be described as Single-Pole, Single-Throw (SPST), or Double-Pole, Single-Throw (DPST). These terms will give an instant indication of the design and function of different types of relays.

1. Break -This is the number of separate places or contacts that a switch uses to open or close a single electrical circuit. All contacts are either single break or double break. A single break (SB) contact breaks an electrical circuit in one place, while a double break (DB) contact breaks it in two places. Single break contacts are normally used when switching lower power devices such as indicating lights. Double break contacts are used when switching high-power devices such as solenoids.

2. Pole -This is the number of completely isolated circuits that relays can pass through a switch. A single-pole contact (SP) can carry current through only one circuit at a time. A double-pole contact (DP) can carry current through two isolated circuits simultaneously. The maximum number of poles is 12, depending upon a relays design.

3. Throw -This is the number of closed contact positions per pole that are available on a switch. A switch with a single throw contact can control only one circuit, while a double-throw contact can control two.

Types of Relyas: Electromechanical

1. General Purpose Relays are electromechanical switches, usually operated by a magnetic coil. General purpose relays operate with AC or DC current, at common voltages such as 12V, 24V, 48V, 120V and 230V, and they can control currents ranging from 2A-30A. These relays are economical, easy to replace and allow a wide range of switch configuration.

2. Machine Control Relays are also operated by a magnetic coil. They are heavy-duty relays used to control starters and other industrial components. Although they are more expensive than general purpose relays, they are generally more durable. The biggest advantage of machine control relays over general purpose relays is the expandable functionality of Machine Control Relays by the adding of accessories. A wide selection of accessories is available for machine control relays, including additional poles, convertible contacts, transient suppression of electrical noise, latching control and timing attachments.

3. Reed Relays are a small, compact, fast operating switch design with one contact, which is NO. Reed Relays are hermetically sealed in a glass envelope, which makes the contacts unaffected by contaminants, fumes or humidity, allows reliable switching, and gives contacts a higher life expectancy. The ends of the contact, which are often plated with gold or another low resistance material to increase conductivity, are drawn together and closed by a magnet. Reed relays are capable of switching industrial components such as solenoids, contactors and starter motors. Reed relays consists of two reeds. When a magnetic force is applied, such as an electromagnet or coil, it sets up a magnetic field in which the end of the reeds assume opposite polarity. When the magnetic field is strong enough, the attracting force of the opposite poles overcomes the stiffness of the reeds and draws them together. When the magnetic force is removed, the reeds spring back to their original, open position. These relays work very quickly because of the short distance between the reeds.

Solid State Relays

Solid state relays consist of an **input circuit**, a **control circuit** and an **output circuit**. The Input Circuit is the portion of a relays frame to which the control component is connected. The input circuit performs the same function as the coil of electromechanical relays. The circuit is activated when a voltage higher than the relays specified Pickup Voltage is applied to the relays input. The input circuit is deactivated when the voltage applied is less than the specified minimum Dropout voltage of the relay. The voltage range of 3 VDC to 32 VDC, commonly used with most solid-state relays, makes it useful for most electronic circuits. The Control Circuit is the part of the relay that determines when the output component is energized or de-energized. The control circuit functions as the coupling between the input and output circuits. In electromechanical relays, the coil accomplishes this function. A relays Output Circuit is the portion of the relay that switches on the load and performs the same function as the mechanical contacts of electromechanical relays. Solid-state relays, however, normally have only one output contact.

Solid State Relays, like the one pictured above, are capable of switching high voltages up to 600 VACrms. These relays are designed to switch various loads such as heating elements, motors, and transformers.

Types of Relays: Solid State

1. Zero-Switching Relays - relays turns ON the load when the control (minimum operating) voltage is applied and the voltage of the load is close to zero. Zero-Switching relays turn OFF the load when the control voltage is removed and the current in the load is close to zero. Zero-Switching relays are the most widely used.

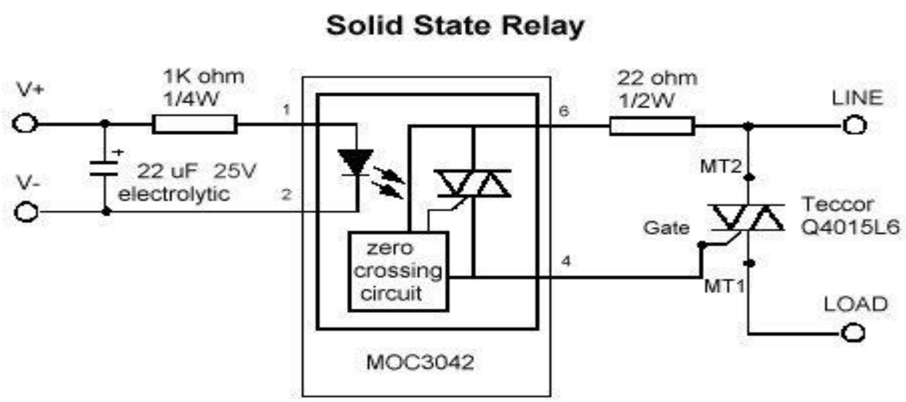
2. Instant ON Relays - turns ON the load immediately when the pickup voltage is present. Instant ON Relays allow the load to be turned ON at any point in it's up and down wave.

3. Peak Switching Relays - turns ON the load when the control voltage is present, and the voltage of the load is at its peak. Peak Switching relays turn OFF when the control voltage is removed and the current in the load is close to zero.

4. Analog Switching Relays - has an infinite number of possible output voltages within the relays rated range. Analog switching relays have a built in synchronizing circuit that controls the amount of output voltage as a function of the input voltage. This allows a Ramp-Up function of time to be on the load. Analog Switching relays turn OFF when the control voltage is removed and current in the load is near zero.

A Relays Contact Life

A relays useful life depends upon its contacts. Once contacts burn out, the relays contacts or the entire relay has to be replaced. Mechanical Life is the number of operations (openings and closings) a contact can perform without electrical current. A relays mechanical life is relatively long, offering up to 1,000,000 operations. A relays Electrical life is the number of operations (openings and closings) the contacts can perform with electrical current at a given current rating. A relays Contact electrical life ratings range from 100,000 to 500,000 cycles.

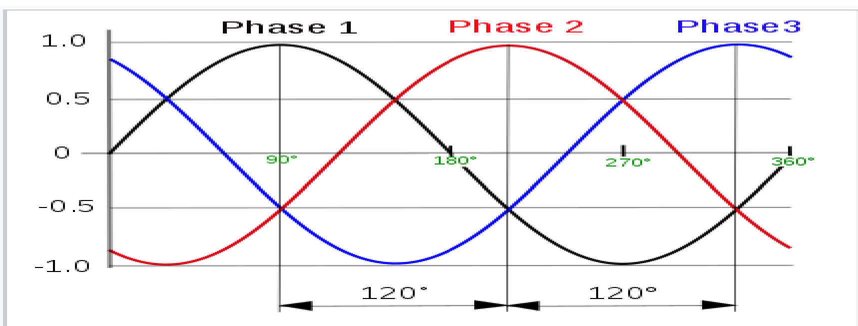


This diagram represents the basic circuit of Solid State Relays.

POLYPHASE SYSTEM

A **polyphase system** is a means of **distributing alternating-current electrical power**. Polyphase systems have three or more energized **electrical conductors** carrying alternating currents with a **defined phase angle** between the voltage waves in each conductor; for three-phase voltage, the phase angle is 120° or ~2.09 radians. Polyphase systems are particularly useful for transmitting power to **electric motors.** The most common example is the **three-phase power** system used for industrial applications and for **power transmission.**

AC power generation and distribution in higher phase orders than three is still in the theoretical and modeling stages.



One voltage cycle of a three-phase system

Phases

In the very early days of commercial electric power, some installations used two-phase four-wire systems for motors. The chief advantage of these was that the winding configuration was the same as for a single-phase capacitor-start motor and, by using a four-wire system, conceptually the phases were independent and easy to analyse with mathematical tools available at the time.

Two-phase systems can also be implemented using three wires (two "hot" plus a common neutral). However this introduces asymmetry; the voltage drop in the neutral makes the phases not exactly 90 degrees apart.

Two-phase systems have been replaced with three-phase systems. A two-phase supply with 90 degrees between phases can be derived from a three-phase system using a **Scott-connected transformer**. A polyphase system must provide a defined direction of phase rotation, so mirror image voltages do not count towards the phase order. A 3-wire system with two phase conductors 180 degrees apart is still only single phase. Such systems are sometimes described as **split-phase**.

Motors

Polyphase power is particularly useful in **AC** motors, such as the **induction motor**, where it generates a **rotating magnetic field.** When a three-or-more-phase supply completes one full cycle, the magnetic field of a two-poles-per-phase motor has rotated through 360° in physical space; motors with more than two poles per phase require more power supply cycles to complete one physical revolution of the magnetic field and so these motors run slower. Induction motors using a rotating magnetic field were independently invented by **Galileo Ferraris** and **Nikola Tesla** and developed in a three-phase form by **Mikhail Dolivo-Dobrovolsky** in 1889. Previously all commercial motors were DC, with expensive **commutators**, high-maintenance brushes and characteristics unsuitable for operation on an alternating current network. Polyphase motors are simple to construct, are self-starting and have little vibration compared with single-phase motors.

Higher phase order

Once polyphase power is available, it may be converted to any desired number of phases with a suitable arrangement of transformers. Thus, the need for more than three phases is unusual, but higher phase numbers than three have been used.

Between 1992 and 1995, New York State Electric & Gas operated a 1.5Mi. converted double-circuit 3-phase 115KV transmission line as a 93KV 6-phase transmission line. The primary result was that it is economically favorable to operate an existing double-circuit 115KV 3-phase line as a 6-phase line for distances greater than 23-28 miles.

Multi-phase power generation designs with 5, 7, 9, 12, and 15 phases in conjunction with multi-phase **induction generators** (MPIGs) driven by wind turbines have been proposed. An induction generator produces electrical power when its rotor is turned faster than the **synchronous speed**. A multi-phase induction generator has more poles, and therefore a lower synchronous speed. Since the rotation speed of a wind turbine may be too slow for a substantial portion of its operation to generate single-phase or even three-phase AC power, higher phase orders allow the system to capture a larger portion of the rotational energy as electric power.

High-phase-order (HPO) power transmission has been frequently proposed as a way to increase transmission capacity within a limited-width **right of way**. The required conductor spacing is determined by the phase-to-phase voltages, and six-phase power has the same voltage between adjacent phases as between phase and neutral. Three-phase power has phase-to-phase voltages equal to $\sqrt{3}$ = 1.732 times the phase-to-neutral voltage. This lets an existing **double-circuit transmission line** carry more power with minimal change to the existing cable plant. This is particularly economical when the alternative is upgrading an existing **extra high voltage** (EHV, more than 345 kV phase-to-phase) transmission line to ultra-high voltage (UHV, more than 800 kV) standards.

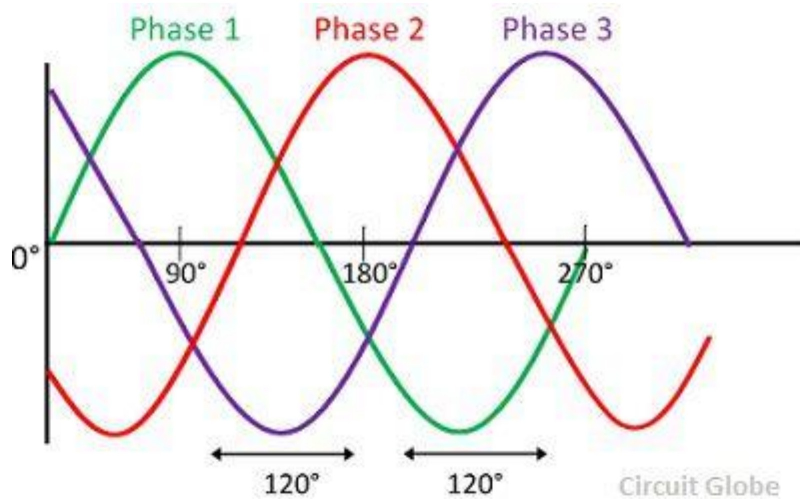
THREE PHASE SYSTEM

The system which has three phases, i.e., the current will pass through the three wires, and there will be one neutral wire for passing the fault current to the earth is known as the three phase system. In other words, the system which uses three wires for generation, transmission and distribution is known as the three phase system. The three phase system is also used as a single phase system if one of their phase and the neutral wire is taken out from it. The sum of the line currents in the 3-phase system is equal to zero, and their phases are differentiated at an angle of 120º

The three-phase system has four wire, i.e., the three current carrying conductors and the one neutral. The cross section area of the neutral conductor is half of the live wire. The current in the neutral wire is equal to the sum of the line current of the three wires and consequently equal to √3 times the zero phase sequence components of current.

The three-phase system has several advantages like it requires fewer conductors as compared to the single phase system. It also gives the continuous supply to the load. The three-phase system has higher efficiency and minimum losses.

The three phase system induces in the generator which gives the three phase voltage of equal magnitude and frequency. It provides an uninterruptible power, i.e., if one phase of the system is disturbed, then the remaining two phases of the system continue supplies the power.The magnitude of the current in one phase is equal to the sum of the current in the other two phases of the system.



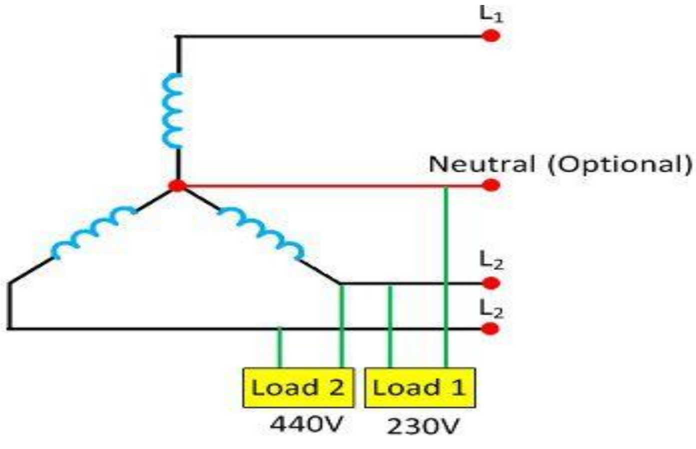
The 120º phase difference of the three phases is must for the proper working of the system. Otherwise, the system becomes damaged

Types of Connections in Three-Phase System

The three-phase systems are connected in two ways, i.e., the star connection and the delta connection. Their detail explanation is shown below.

Star Connection

The star connection requires four wires in which there are three phase conductors and one neutral conductor. Such type of connection is mainly used for long distance transmission because it has a neutral point. The neutral point passes the unbalanced current to the earth and hence make the system balance.

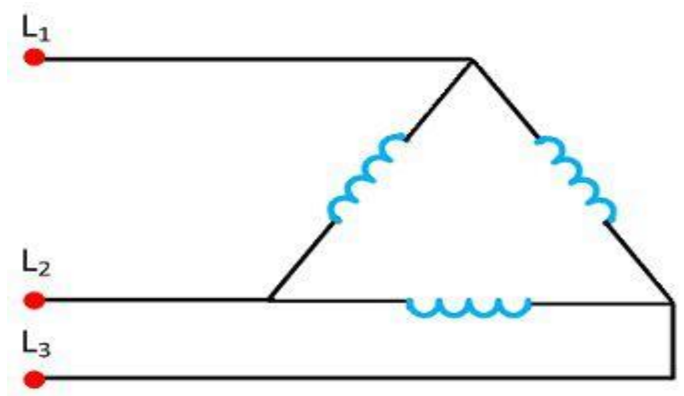


3 - phase Star Connected System

The star connected three phase systems gives two different voltages, i.e., the 230 V and 440V. The voltage between the single phase and the neutral is 230V, and the voltage between the two phases is equal to the 440V.

Delta Connection

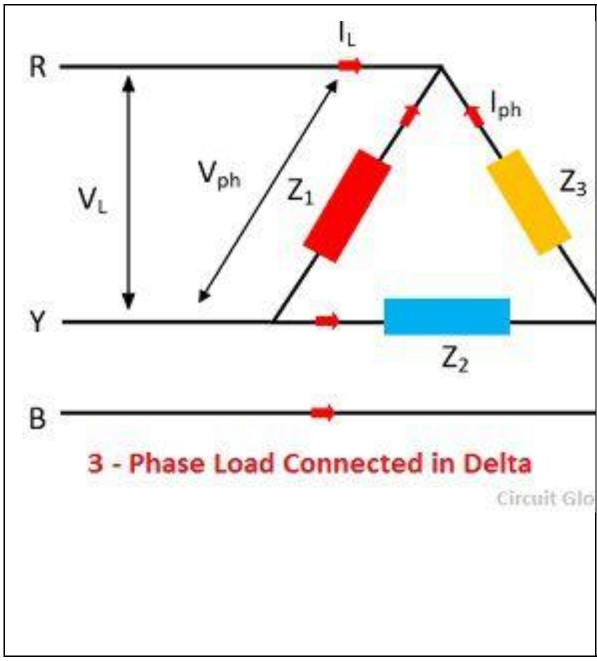
The delta connection has three wires, and there is a no neutral point. The delta connection is shown in the figure below. The line voltage of the delta connection is equal to the phase voltage.

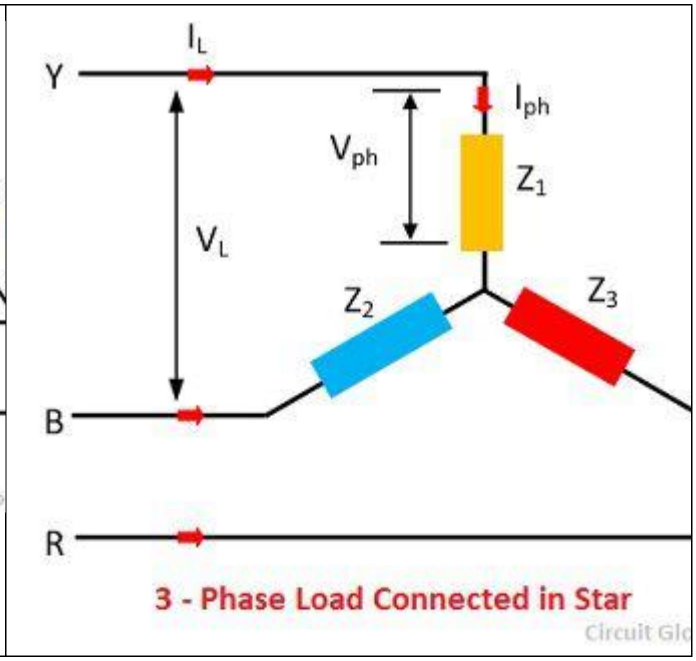


3 - Phase Delta Connection

Connection of Loads in Three Phase System

The loads in the three-phase system may also connect in the star or delta. The three phase loads connected in the delta and star is shown in the figure below.



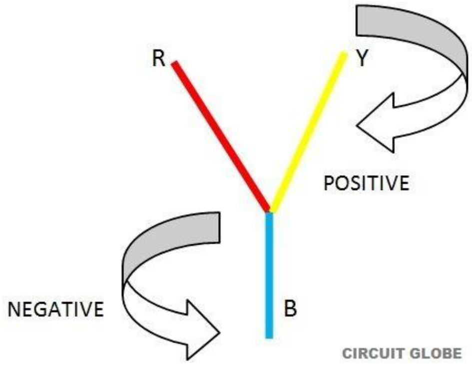


The three phase load may be balanced or unbalanced. If the three loads (impedances) Z_1, Z_2 and Z_3 has the same magnitude and phase angle then the three phase load is said to be a balanced load. Under balance condition, all the phases and the line voltages are equal in magnitude.

PHASE SEQUENCE

In three phase system the order in which the voltages attain their maximum positive value is called **Phase Sequence.** There are three voltages or EMFs in three phase system with the same magnitude, but the frequency is displaced by an angle of 120 deg electrically.

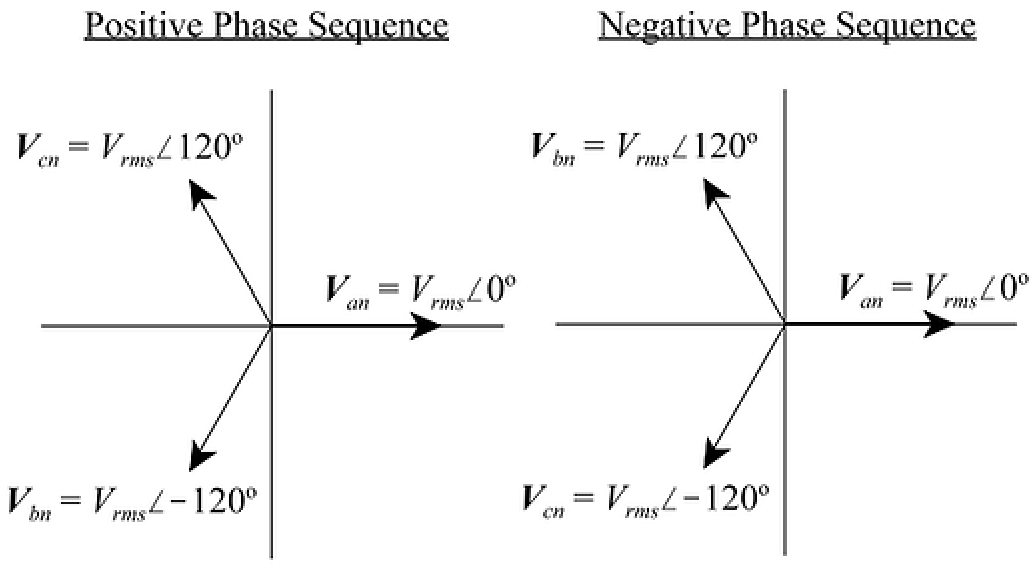
Taking an example, if the phases of any coil are named as R, Y, B then the Positive phase sequence will be RYB, YBR, BRY also called as clockwise sequence and similarly the **Negative** phase sequence will be RBY, BYR, YRB respectively and known as an anti-clockwise sequence.



It is essential because of the following reasons:-

1. The parallel operation of three phase transformer or alternator is only possible when its phase sequence is known.

2. The rotational direction of three phase induction motor depends upon its sequence of phase on three phase supply and thus to reverse its direction the phase sequence of the supply given to the motor has to be changed.



Balanced three phase circuits

Circuit Analysis of 3 Phase System – Balanced Condition

The electrical system is of two types i.e., the single phase system and the three phase system. The single phase system has only one phase wire and one return wire thus it is used for low power transmission. The three-phase system has three live wire and one returns path. The three phase system is used for transmitting a large amount of power. The **3 Phase system** is divided mainly into two types. One is Balanced three phase system and another one is unbalanced three phase system.

The balance system in one in which the load are equally distributed in all the three phases of the system. The magnitude of voltage remains same in all the three phases and it is separated by an angle of 120º. In unbalance system the magnitude of voltage in all the three phases becomes different.

Analysis of Balanced 3 Phase Circuit

It is always better to solve the balanced three phase circuits on per phase basis. When the three phase supply voltage is given without reference to the line or phase value, then it is the line voltage which is taken into consideration.

The following steps are given below to solve the balanced three phase circuits.

Step 1 – First of all draw the circuit diagram.
Step 2 – Determine $X_{LP} = X_L$/phase = $2\pi f_L$.
Step 3 – Determine $X_{CP} = X_C$/phase = $1/2\pi f_C$.
Step 4 – Determine X_P = X/ phase = $X_L – X_C$
Step 5 – Determine Z_P = Z/phase = $\sqrt{R^2{}_P + X^2{}_P}$

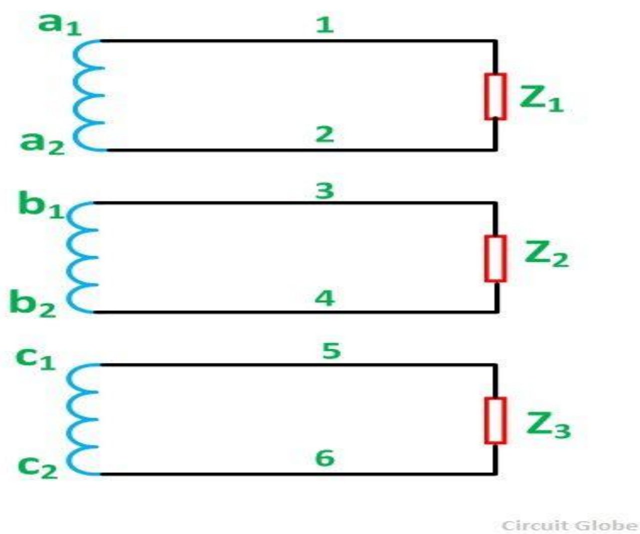
Step 6 – Determine $\cos\phi = R_P/Z_P$; the power factor is lagging when $X_{LP} > X_{CP}$and it is leading when $X_{CP} > X_{LP}$.
Step 7 – Determine V phase.
For star connection $V_P = V_L/\sqrt{3}$ and for delta connection $V_P = V_L$
Step 8 – Determine $I_P = V_P/Z_P$.
Step 9 – Now, determine the line current I_L.
For star connection $I_L = I_P$ and for delta connection $I_L = \sqrt{3}\ I_P$
Step 10 – Determine the Active, Reactive and Apparent power.

Analysis of Unbalanced 3 Phase Circuit

The analysis of the 3 Phase unbalanced system is slightly difficult, and the load is connected either as Star or Delta. The topic is discussed in detail in the article named as Star to Delta and Delta to Star Conversion.

Interconnection of 3 Phase System

In a three-phase AC generator, there are three windings. Each winding has two terminals (start and finish). If a separate load is connected across each phase winding as shown in the figure below, then each phase supplies as independent load through a pair of wires. Thus, six wires will be required to connect the load to a generator. This will make the whole system complicated and costly.

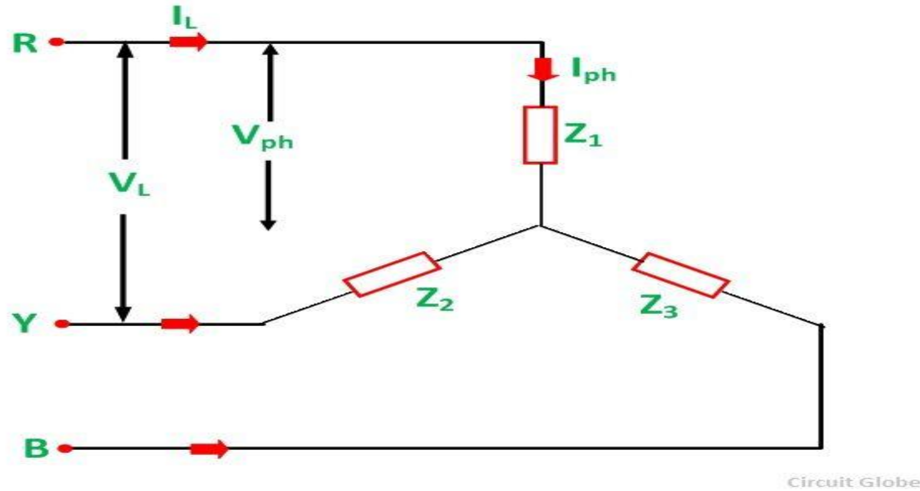


Therefore, in order to reduce the number of line conductors, the three phase windings of an AC generator are interconnected.The interconnection of the windings of a three phase system can be done in following two ways

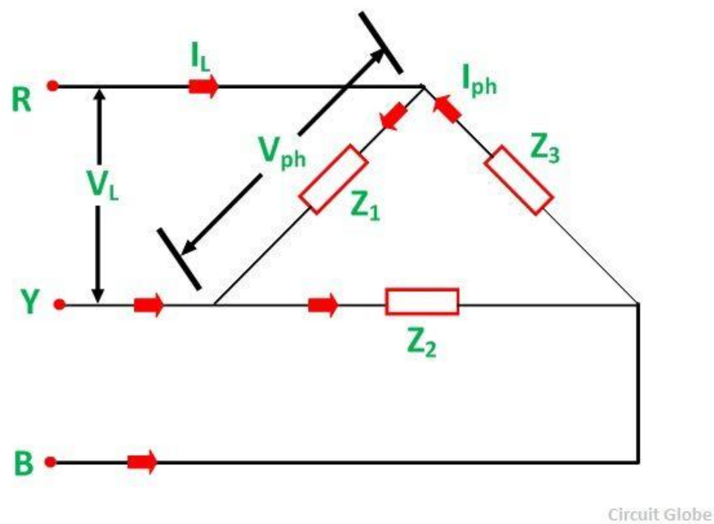
Star or Wye (Y) connection **Also See: <u>Star Connection in 3 Phase System</u>**
Mesh or Delta (Δ) connection. **Also See: Delta Connection in 3 Phase System**

Connection of 3 Phase Loads in 3 Phase System

As the three phase supply is connected in star and delta connections. Similarly, the three-phase loads are also connected either as Star connection or as Delta Connection. The three phase load connected in the star is shown in the figure below.



The delta connection of three phase loads is shown in the figure below.



The three phase loads may be balanced or unbalanced as discussed above. If the three loads Z_1, Z_2 and Z_3 have the same magnitude and phase angle, then the 3 phase load is said to be a balanced load. Under such connections, all the phase or line currents and all the phase or line voltages are equal in magnitude.

STAR AND DELTA CONNECTED LOADS

When the load impedance in the three phases are not equal in magnitude or phase or both, the load is said to be unbalanced. If three unequal loads are connected to form a delta and connected across a 3-phase supply the currents in the three loads will not be equal in magnitude and/or phase. The three-phase currents and the line currents will also be unbalanced.

Example: For the unbalanced delta-connected load of Fig 52, find the phase currents, line currents and total power consumed by the load, when phase sequence is:
(i) RYB
(ii) RBY
(AMIE Advanced Electrical M/c Winter, 1998)
Solution.
(i) **Phase sequence RYB :**
The potential differences across three phases are:
E_{RY} = 200 0°
E_{YB} = 200-120°
E_{BR} = 200 120°
Impedance, Z_{RY} = 12 + j16 = 20 53.13°
Impedance, Z_{YB} = 16 + j12 = 20 36.8°
Impedance, Z_{BR} = 8 – j6 = 10 – 36.8°

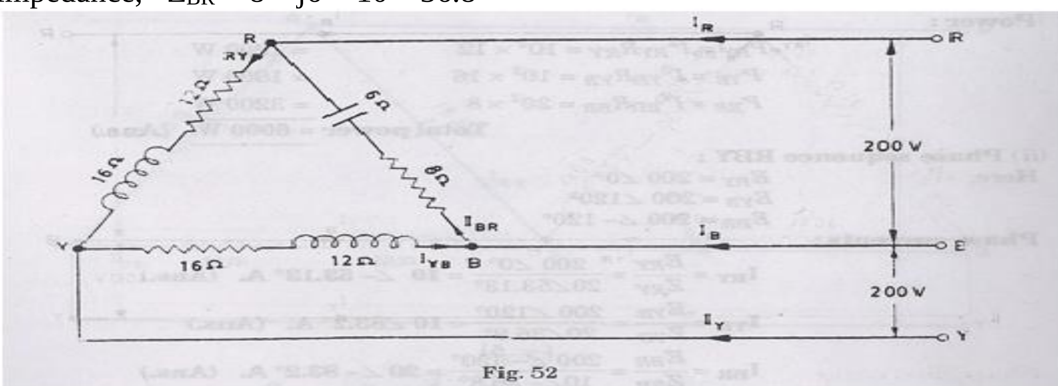


Fig. 52

Phase current, $I_{RY} = \frac{E_{RY}}{Z_{RY}} = \frac{200\angle 0^\circ}{20\angle 53.13^\circ} = \mathbf{10\angle -53.13^\circ\ A.}$ **(Ans.)**

Similary, $I_{YB} = \frac{E_{YB}}{Z_{YB}} = \frac{200\angle -120^\circ}{20\angle 36.8^\circ} = \mathbf{10\angle -156.8^\circ\ A.}$ **(Ans.)**

$I_{BR} = \frac{E_{BR}}{Z_{BR}} = \frac{200\angle -120^\circ}{10\angle -36.8^\circ} = \mathbf{20\angle 156.8^\circ\ A.}$ **(Ans.)**

Line currents:

Line current, $\mathbf{I_R} = I_{RY} - I_{BR} = 10\angle -53.13^\circ - 12\angle 156.8^\circ$

$= 10(0.60 - j0.8) - 20(-0.72 + j0.394) = 6.0 - j8 + 18.4 - j7.88$

$= 24.4 - j15.88 =$ **29.11 ∠- 33° A. (Ans.)**

Similarly, $\mathbf{I_Y} = I_{YB} - I_{RY} = 10\angle -156.8^\circ - 10\angle -53.13^\circ$

$= 10(-0.919 - j0.394) - 10(0.6 - j0.8) = -9.19 - j3.94 - 6 + j8$

$= 15.19 + j1.06 =$ **15.72 ∠*165*° A. (Ans.)**

$\mathbf{I_B} = I_{BR} - I_{YB} = 20\angle 156.8^\circ - 10\angle -156.8$

$= 20(0.919 - j0.394) - 10(-0.919 - j0.394)$

$= -18.38 + j7.88 + 9.19 + j3.94 = -9.19 + j11.82 = 14.97\angle 127.9^\circ$

[Check $\Sigma I = (24.4 - j15.88) + (-15.19 + j4.06) + (-9.19 + j11.82) = 0$]

Power:

$P_{RY} = I_{RY}^2 R_{RY} = 10^2 \times 12 \qquad = 1200\ W$

$P_{YB} = I_{YB}^2 R_{YB} = 10^2 \times 16 \qquad = 1600\ W$

$P_{BR} = I_{BR}^2 R_{BR} = 20^2 \times 8 \qquad = 3200\ W$

Total power $= \mathbf{6000\ W}$ ***(Ans.)***

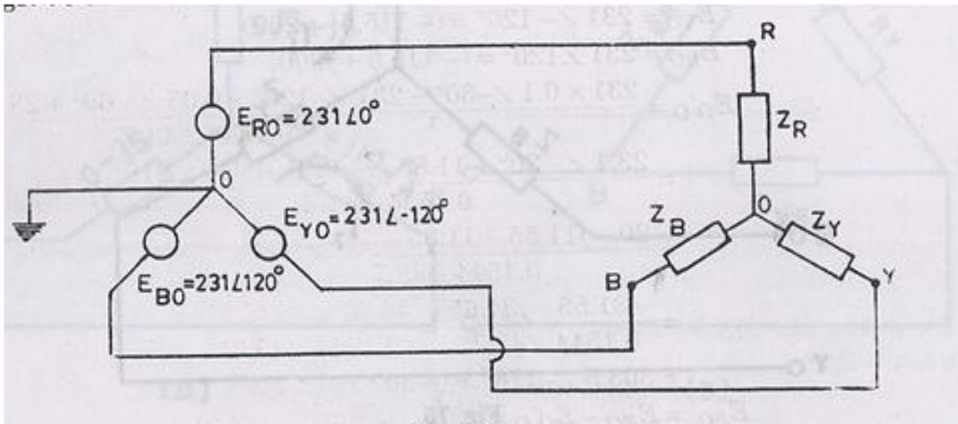


Fig. 76

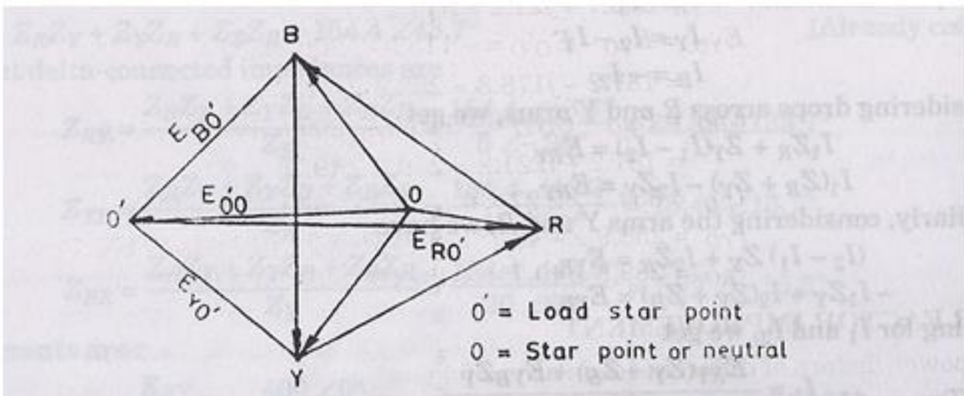


Fig. 77

According to Milliman's theorem, the voltage of the load star point 0′ with respect to the star point or neutral 0 of the generator or supply (normally zero potential) is given by

$$E_{o'o} = \frac{E_{RO}Y_R + E_{YO}Y_Y + E_{BO}Y_B}{Y_R + Y_Y + Y_B}$$

where E_{RO}, E_{YO} and E_{BO} are the phase voltages of the generator or 3-phase supply.

Voltage across each phase of the load is

$E_{RO'} = E_{RO} - E_{O'O}$

$E_{YO'} = E_{YO} - E_{O'O}$

$E_{BO'} = E_{BO} - E_{O'O}$

Now, $I_{RO'} = (E_{RO} - E_{O'O})$

$I_{YO'} = (E_{YO} - E_{O'O})\, Y_Y$

$I_{BO'} = (E_{BO} - E_{O'O})\, Y_B$

UNBALANCED DELTA CONNECTED LOAD

Same as above

Symmetrical Components

1. Symmetrical Component Transformation

2. Real and Reactive Power

3. Orthogonal Transformation
Symmetrical Components
A system of three unbalanced phasors can be resolved in the following three symmetrical components:
1. **Positive Sequence**: A balanced three-phase system with the same phase sequence as the original sequence.
2. **Negative sequence**: A balanced three-phase system with the opposite phase sequence as the original sequence.
3. **Zero Sequence**: Three phasors that are equal in magnitude and phase.

Fig. 7.1 depicts a set of three unbalanced phasors that are resolved into the three sequence components mentioned above. In this the original set of three phasors are denoted by V_a , V_b and V_c , while their positive, negative and zero sequence components are denoted by the subscripts 1, 2 and 0 respectively. This implies that the positive, negative and zero sequence components of phase-a are denoted by V_{a1} , $V_{a2}$and V_{a0} respectively. Note that just like the voltage phasors given in Fig. 7.1 we can also resolve three unbalanced current phasors into three symmetrical components.

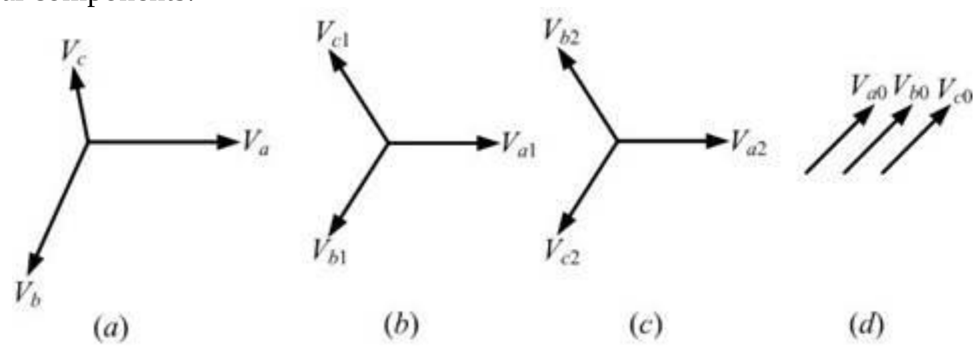


Fig. 7.1 Representation of (a) an unbalanced network, its (b) positive sequence, (c) negative sequence and (d) zero sequence.

POWER MEASUREMENT IN THREE PHASE CIRCUIT
Power measurement in an AC circuit is measured with the help of a Wattmeter. A Wattmeter is an instrument which consists of two coils called **Current coil** and **Potential coil.** The current coil having low resistance is connected in series with the load so that it carries the load current. The potential coil having the resistance is connected across the load and carries the current proportional to the potential difference.

For measuring the power in a 3 phase or Poly Phase system, more than one wattmeter is required, or more than one readings are made by one wattmeter. If more than one wattmeter is connected for the measurement, the process becomes convenient and easy to work with instead of taking various readings with one wattmeter.The number of wattmeters required to measure power in a given polyphase system is determined by Blondel's Theorem.

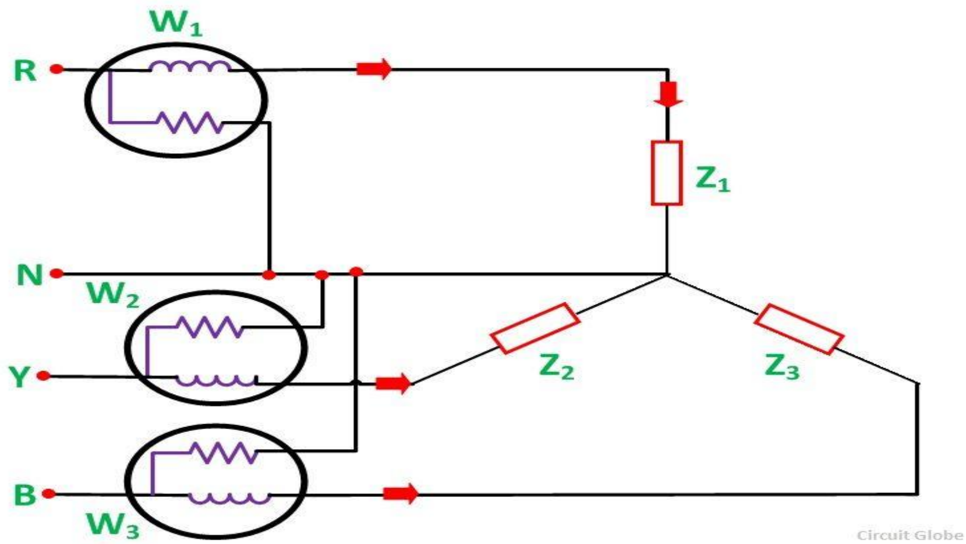
According to Blondel's theorem – When power is supplied by the K wire AC system, the number of wattmeters required to measure power is one less than the number of wire i.e. (K-I), regardless the load is balanced or unbalanced.

Hence, Three wattmeters are required to measure power in three phase, four wire system, whereas, only two wattmeters are required to measure the power in 3 phase, 3 wire system. Here in this article, a Three wattmeter method of power measurement is discussed.

Three-Wattmeter Method of Three Phase Power Measurement

Three Wattmeter method is employed to measure power in a 3 phase, 4 wire system.However, this method can also be employed in a 3 phase, 3 wire delta connected load, where power consumed by each load is required to be determined separately.

The connections for star connected loads for measuring power by 3 wattmeter method is shown below.



The pressure coil of all the Three wattmeters namely W_1, W_2 and W_3 are connected to a common terminal known as the neutral point. The product of the phase current and line voltage represents as phase power and is recorded by individual wattmeter.The total power in a Three wattmeter method of power measurement is given by the algebraic sum of the readings of Three wattmeters. i.e.

$$\text{Total power } P = W_1 + W_2 + W_3$$

Where,

$W_1 = V_1I_1$ $W_2 = V_2I_2$ $W_3 = V_3I_3$

Except for 3 phase, 4 wire unbalanced load, 3 phase power can be measured by using only Two Wattmeter Method.

Active and reactive power

Active Power

The power which is actually consumed or utilized in an AC Circuit is called True power or Active Power or real power. It is measured in kilo watt (kW) or MW. It is the actual outcomes of the electrical system which runs the electric circuits or load.

Reactive Power
The power which flows back and froth that mean it moves in both the direction in the circuit or react upon itself, is called Reactive Power.The reactive power is measured in kilo volt ampere reactive (kVAR) or MVAR.

Apparent Power
The product of root mean square (RMS) value of voltage and current is known as Apparent Power. This power is measured in kVA or MVA.

It has been seen that the power is consumed only in resistance. A pure inductor and a pure capacitor do not consume any power, since in a half cycle whatever power is received from the source by these components, the same power is returned to the source. This power which returns and flows in both the direction in the circuit is called Reactive power. This reactive power does not perform any useful work in the circuit.

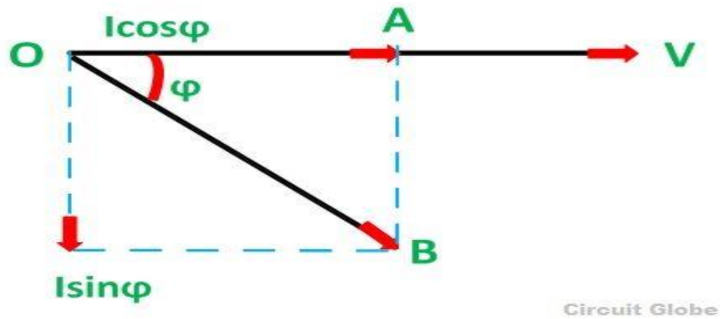
In the pure resistive circuit, the current is in phase with the applied voltage, whereas in pure inductive and capacitive circuit the current is 90 degrees out of phase. i.e If the inductive load is connected in the circuit the current lags voltage by 90 degrees and if the capacitive load is connected the current leads the voltage by 90 degrees.

Hence, from the above all discussion, it is concluded that the current in phase with the voltage produces true or active power, whereas, the current 90 degrees out of phase with the voltage contributes to reactive power in the circuit.

Therefore,

- True power = voltage x current in phase with the voltage
- Reactive power = voltage x current out of phase with the voltage

The phasor diagram for an inductive circuit is shown below



Taking voltage V as reference, the current I lags behind the voltage V by an angle ϕ. The current I is divided into two components

- I Cos ϕ in phase with the voltage V
- I Sin ϕ which is 90 degrees out of phase with the voltage V

Therefore, the following expression shown below gives the active, reactive and apparent power respectively

- Active power $P = V \times I \cos\phi = V I \cos\phi$
- Reactive power P_r or $Q = V \times I \sin\phi = V I \sin\phi$
- Apparent power P_a or $S = V \times I = VI$

Active component of the current
The current component which is in phase with the circuit voltage and contributes to the active or true power of the circuit is called active component or wattfull component or in-phase component of the current.

Reactive component of the current
The current component which is in quadrature or 90 degrees out of phase to the circuit voltage and contributes to the reactive power of the circuit is called reactive component of the current.

Group B

Elements of power distribution—d.c. 2-wire, 3-wire distribution. a.c. 3-wire and 4-wire distributions. Radial and ring main distributions. Current loadings and voltage profile in distributions. Comparison of copper efficiencies in different systems of distribution.

Power transformers, theory of operation, phasor diagram, equivalent circuit. Efficiency and regulation.

Principles of energy conversion; Basic concepts of rotating machines, torque and emf; d.c. machines, characteristics of series, shunt and compound motors and generators.

Basic principles of operation of synchronous and induction machines. Starting of induction motors. Regulation of synchronous generator by synchronous impedance method.

Single-phase induction and commutator machines.

Recommended Books

- S Choudhuri, R Chakrabarti and P K Chattopadhyay. Electrical Science. The Institution of Engineers (India) Textbook Series, Narosa Publishing House, New Delhi.
- A H Cotton. Transmission and Distribution. ELBS edition. (For Group B, first para of the syllabus only.)
- N Parkar Smith. Problems in Electrical Engineering. CBS Publishers and Distributors, New Delhi.

IEI EXAMINATIONS

Group B

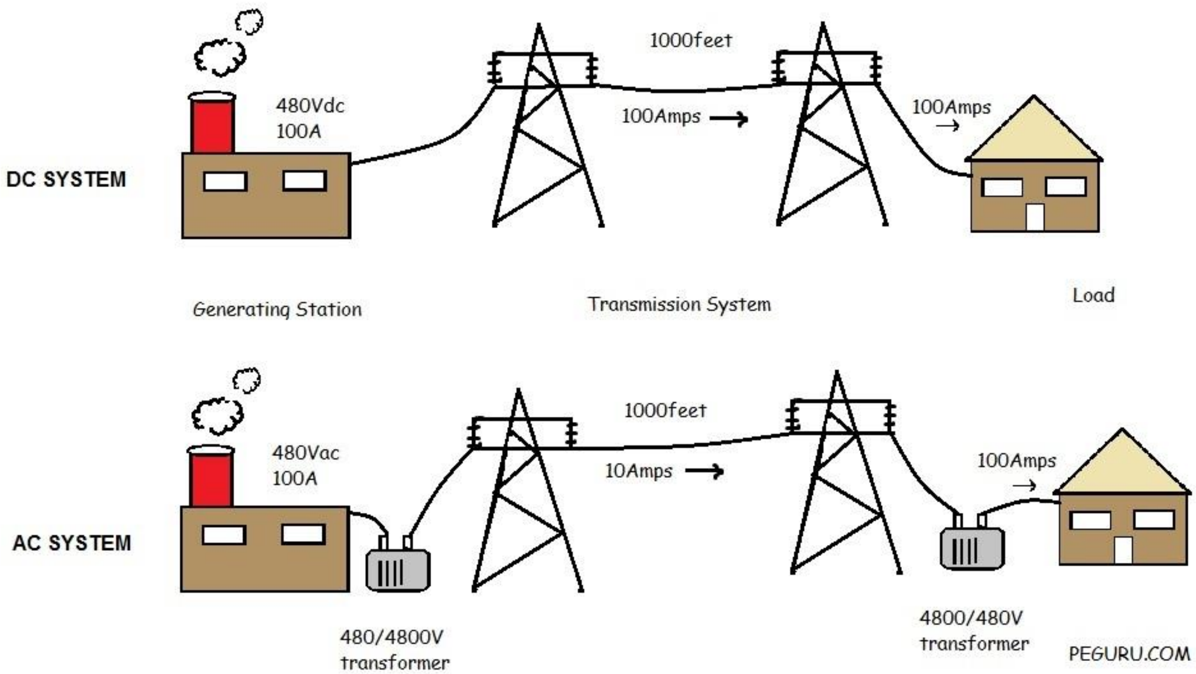
ELEMENTS OF POWER DISTRIBUTION-DC

Power systems use either DC (Direct Current) or AC (Alternating Current).

DC Systems

Consider the following scenario

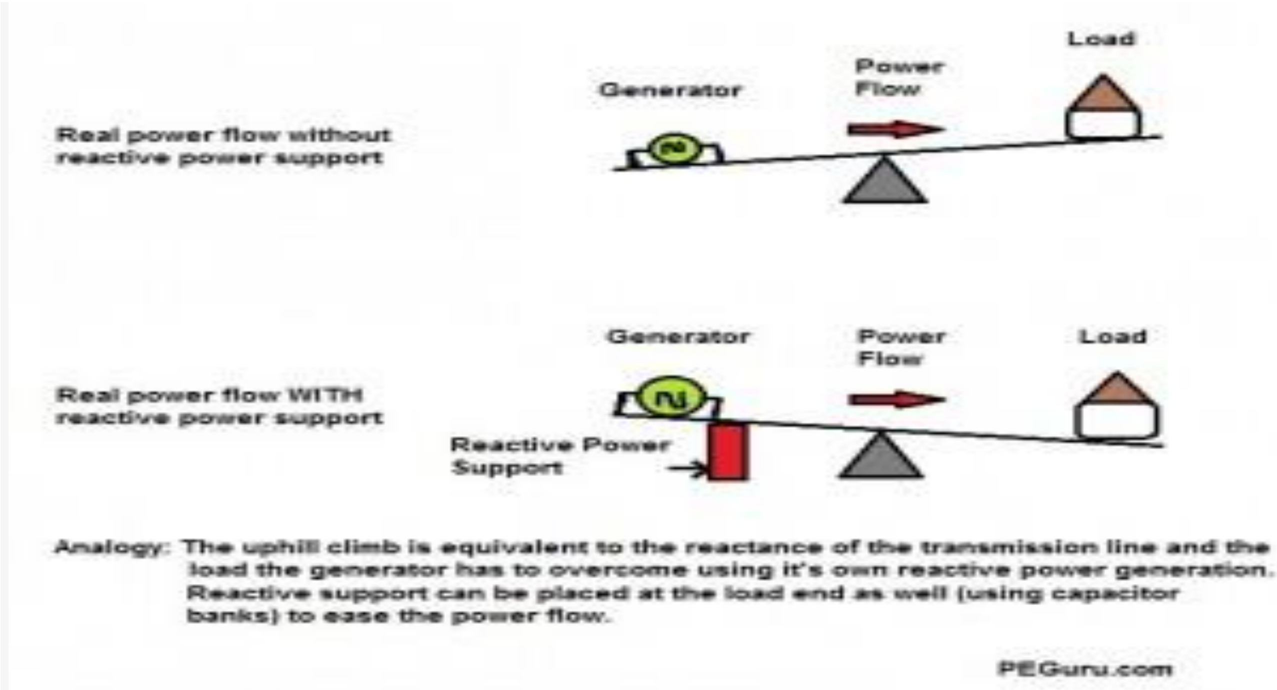
- A power plant is feeding a house located over 1000feet away.
- The house demands 100Amps current at 480V.
- The plant generates 100Amp at 480V
- Assume a DC system and a AC system with the AC system employing a transformer rated 480/4800V near the generating station and a 4800/480V transformer near the house. See figure below.



Let's see how a DC system stacks up against an AC system.

DC SYSTEM	AC SYSTEM
1. To carry 100Amps over the line, a **larger cable** (in diameter) will be required for the DC system.	1. After transformation, the current on the power line will be 10Amps. A smaller cable will be required.
2. Larger cable means lower **conductor resistance**. Typically, 0.15 ohms per 1000feet can be used for a 100Amp conductor (per AWG). In which case,Voltage Drop (VD) across the line = 0.15*100 = 15V.	2. **Smaller cable** (in diameter) means higher resistance. Typically, a 1.5 ohms per 1000feet can be used for a 10Amp conductor. In which case, Voltage Drop (VD) = 1.5*10 = 15V. Same as a DC system.
3. The DC generator must generate 480V plus 15V to deliver power to the house. At the house, the voltage, therefore, will go from 495V at no-load to 480V at full-load. A 15V variation.	3. Allow taps on transformer to raise the voltage by 15V to obtain 4815V. At the house, this is equivalent to 481.5V. A 1.5V variation from no-load to full-load. Engineers call this variation of voltage as the Voltage Regulation (VR). An important factor in the power system. The less the VR the better the system.
4. Losses in transmission system = VD*Current (in watts) = 15*100 = 1500 watts	4. Losses in transmission system (in watts) = 15*10 = 150 watts. Ten times less than DC transmission.
5. Transformers cannot operate with DC supply wired to it. The only way to step down voltage for distribution is through a motor-generator set or a rotary converter – an inefficient process.	5. Transformers operate at 99% efficiency at full load. Used throughout the AC system.

DC system cannot be applied to all areas of power system. **At high voltages and long distance transmission, DC systems are favorable.** High Voltage Direct Current (HVDC) system can be implemented as a highway for bulk power transmission.



Reactive Power Support

AC systems are mostly designed as three phase systems. You can deliver more power with a three phase system than a single or two phase system.

AC currents oscillate 60 times a second (in USA). **If more than one 4-pole generator is connected to the power grid then all these generators must "swing" at 1800 rpm to produce AC power at 60Hz. Failure to do so will cause the generators to trip and shutdown leading to a system blackout.**

Advantage of an AC System

1. Very **flexible system**. It can deliver power to loads over vast distances using transformers.
2. AC generators are **easier to build** than DC generators. DC generators need brushes and commutators to generate DC current.

Disadvantage of an AC System

1. **Very hazardous**. Susceptible to **voltage surges**.
2. **Complex system**.
3. **System stability is crucial**. The system goes down if interconnected generators do not swing at the same frequency (i.e. not synchronized)

Summary

DC systems are great for moving bulk power at really high voltages. They are just not feasible for power distribution, however. AC systems provide easy means to deliver power to remote users from remote generating stations. **A mix of both technologies is viable for the future power system.**

DISTRIBUTION SUBSTATION

It typically operates at **2.4 – 34.5 kV voltage levels**, and delivers electric energy directly to **industrial and residential consumers.**

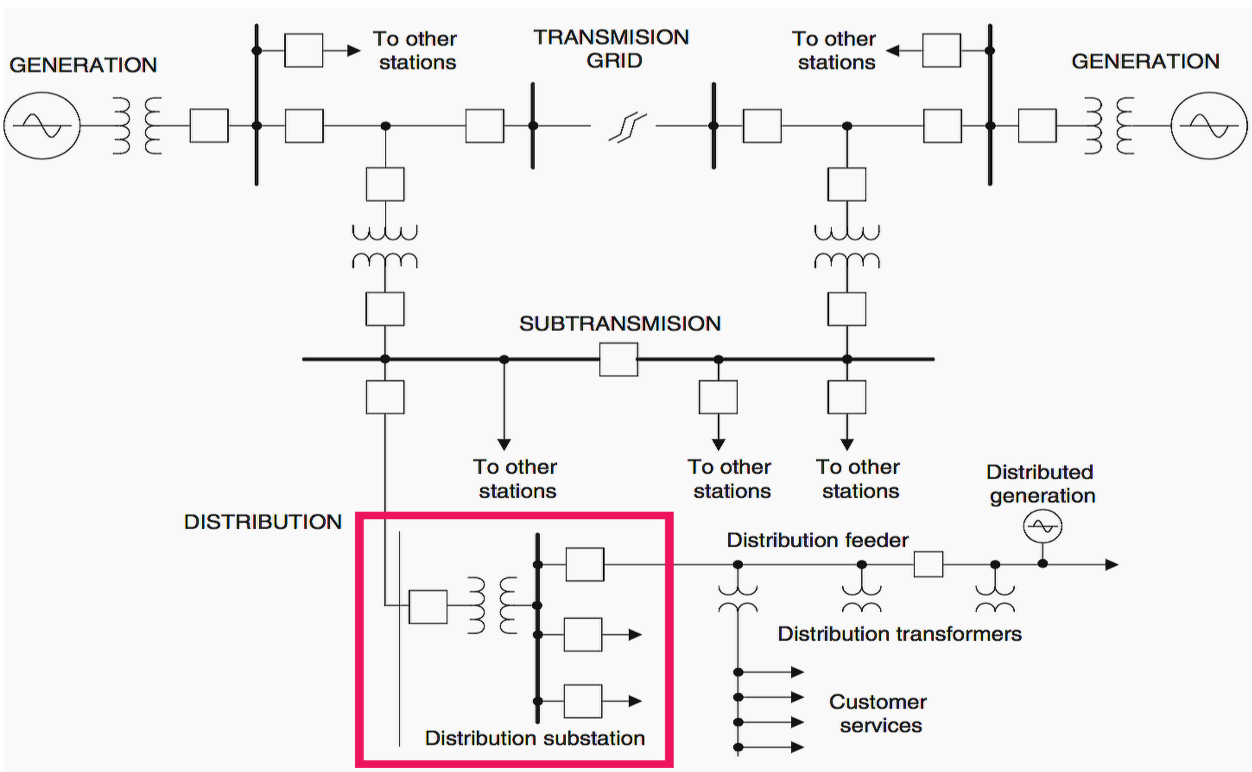
Distribution feeders transport power from the distribution substations to the end consumers premises. **Distribution substation--→Transport Power---→End Consumers.**

At the consumers' premises, distribution transformers **transform the distribution voltage** to the service level voltage directly used in households and industrial plants, usually from 110 to 600 V.

End consumer's premises-→ distribution transformers--→ service level voltage--→House Hold and Industrial Purposes.

Distribution substation components

1. Supply Line.	2. Transformers.
3. Busbars.	4. Switchgear.
5. Outcoming feeders.	6. Switching apparatus (Switches, Fuses and Circuit Breakers)
7. Surge voltage protection.	8. Grounding.

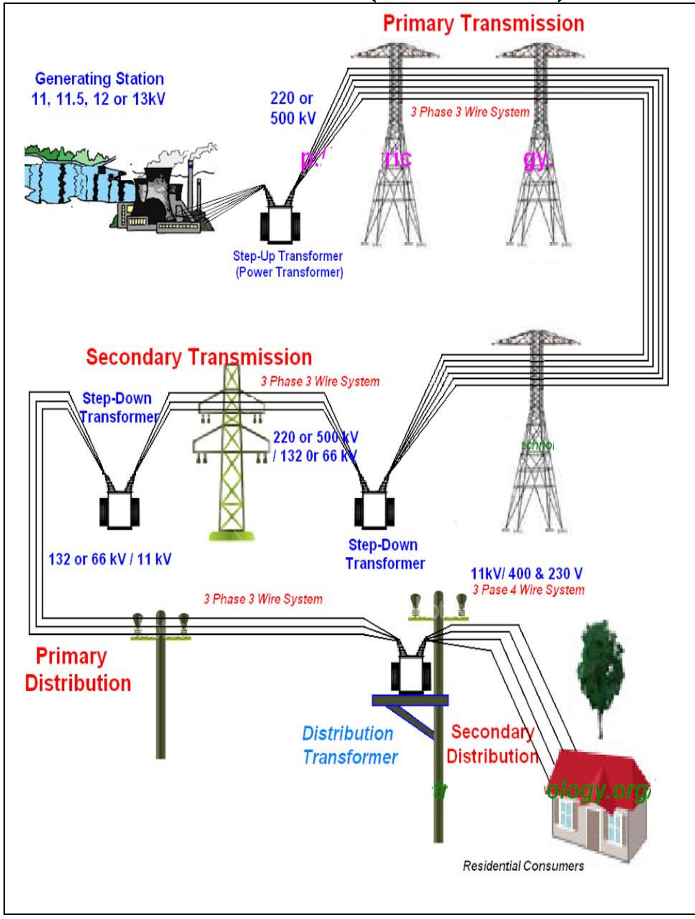


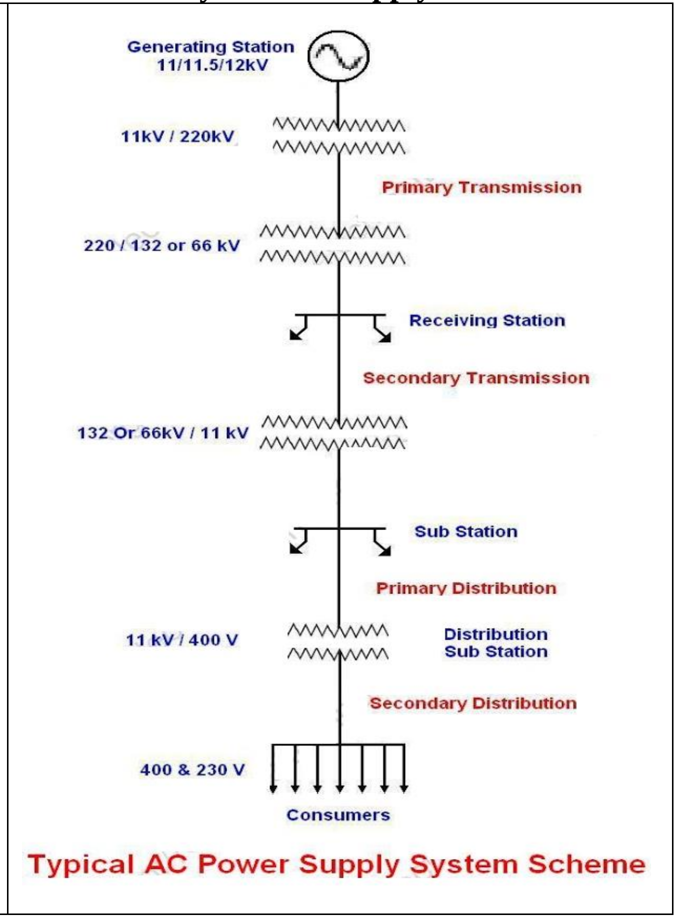
Single line diagram of major components of power system from generation to consumption

Supply Line / primary feeder

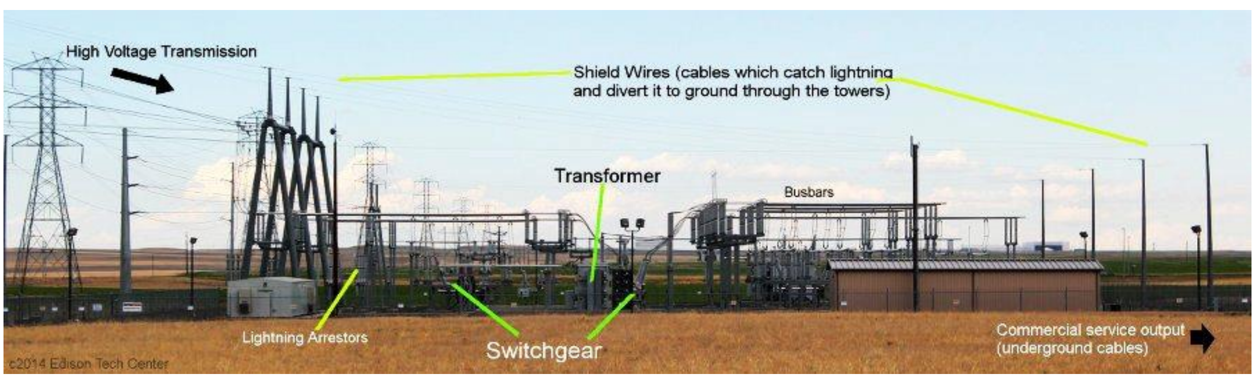
Distribution substation is connected to a sub-transmission system via at least one supply line, which is often called a primary feeder. However, it is typical for a distribution substation to be supplied by two or more supply lines to increase reliability of the power supply in case one supply line is disconnected.

Distribution substation—(Connected to) --→ sub-transmission system via Supply Line.





Supply lines are connected to the substation via high voltage disconnecting switches in order to isolate lines from substation to perform maintenance or repair work.



Distribution substation connection diagram

Transformers
Transformers "step down" supply line voltage to distribution level voltage.
Distribution substation uses three-phase / single-phase transformers.

Transformers Classification factors:
a. Power rating:-Unit: kilovolt-amperes (kVA) / megavolts- amperes (MVA)
It indicates **the amount of power that can be transferred through the transformer**.
Distribution substation transformers are typically in the range of 3 kVA to 25 MVA.
b. Insulation
Which includes **liquid / dry types of transformer insulation**.
Liquid insulation can be mineral oil, nonflammable or low-flammable liquids.
Dry type includes the ventilated, cast coil, enclosed non-ventilated, and sealed gas- filled types.
c. Voltage rating
Transformer voltage rating is indicated by the manufacturer.
For example, 115/34.5 kV means the high-voltage winding of the transformer is rated at 115 kV, and the low voltage winding is rated at 34.5 kV between different phases.
d. Cooling
Transformer rating includes **self-cooled rating** at the specified temperature rise or forced-cooled rating of the transformer if so equipped.
e. Winding connections
Which indicates how the three phases of transformer windings are connected together at each side.
Transformer windings connections
Delta –High Voltage Side
(where the end of each phase winding is connected to the beginning of the next phase forming a triangle); and
Star-Low Voltage Side
(where the ends of each phase winding are connected together, forming a neutral point and the beginning of windings are connected outside).
f. Voltage regulation
It indicates that the **transformer is capable of changing the low voltage side voltage** in order to maintain **nominal voltage at customer service points.**
3. Bus bars/ buses
Busbars are **used to carry large current** and to distribute current to multiple circuits within switchgear or equipment.

Outdoor switchgear busbar (upper conductors) with voltage transformers

The busbars were also **covered with insulation** for safety and to permit closer spacing of bars of opposite polarity in order to achieve lower reactance and voltage drop.

Busbars expanded and increased, loads demanded higher current ratings (225-600A) and housings were ventilated to provide better cooling at higher capacities.

Each stack may contain all **three phases, neutral, and grounding conductors** to minimize circuit reactance. Busbars' conductors and current-carrying parts can be either copper, aluminum, or copper alloy rated for the purpose.

4. Switchgear

It covers primary switching and interrupting devices together with its control and regulating equipment. Power switchgear includes breakers; disconnect switches, main bus conductors, interconnecting wiring, support structures with insulators, enclosures, and secondary devices for monitoring and control.

> Power switchgear is used throughout the entire power system, **from generation to industrial plants to connect incoming power supply and distribute power to consumers**.

Switchgear can be of outdoor or indoor types, or a combination of both. Outdoor switchgear is typically used for voltages above 26 kV, whereas indoor switchgear is commonly for voltages below 26 kV.

5. out coming Feeders

A number of out coming feeders are connected to the substation bus to carry power from the substation to points of service. Feeders can be run overhead along streets, or beneath streets, and carry power to distribution transformers at or near consumer premises. The feeders' breaker and isolator are part of the substation low voltage switchgear and are **typically the metal-clad type.**

6. Switching Apparatus

Switching apparatus is needed **to connect or disconnect elements of the power system** to or from other elements of the system. Switching apparatus includes switches, fuses, circuit breakers, and service protectors.

a. Switches

Switches are used for **isolation, load interruption, and transferring service** between different sources of supply.

Isolating switches are used to provide visible disconnect to enable safe access to the isolated equipment. These switches usually have no interrupting current rating, meaning that the circuit must be opened by other means (such as breakers). Interlocking is generally provided to prevent operation when the switch is carrying current.

> Load interrupting or a load-break switch combines the functions of a disconnecting switch and a load interrupter for interrupting at rated voltage and currents not exceeding the continuous-current rating of the switch.

Load-break switches are of the air- or fluid-immersed type. The interrupter switch is usually manually operated and has a "quick-make, quick-break" mechanism which functions independently of the speed-of-handle operation. **These types of switches are typically used on voltages above 600 V.**

Automatic transfer switches are of double-throw construction and are primarily used for emergency and standby power generation systems rated at 600 V and lower. These switches are used to provide protection against normal service failures.

b. Fuses

Fuses are used as an over current protective device with a circuit-opening fusible link that is heated and severed as over current passes through it. Fuses are available in a wide range of voltage, current, and interrupting ratings, current-limiting types, and for indoor and outdoor applications. Fuses perform the same function as circuit breakers, and there is no general rule for using one versus the other.

The decision to use a fuse or circuit breaker is usually based **on the particular application**, and factors such as the current interrupting requirement, coordination with adjacent protection devices, space requirements, capital and maintenance costs, automatic switching, etc.

c. Circuit breakers

They are devices **designed to open and close a circuit either automatically or manually.** When applied within its rating, an **automatic circuit breaker** must be capable of opening a circuit automatically on a predetermined overload of current without damaging itself or adjacent elements. Circuit breakers are required to operate infrequently, although some classes of circuit breakers are suitable for more frequent operation.

Outdoor medium voltage oil-immersed circuit breaker

Traditionally, oil circuit breakers were used in the power industry, which use oil as a media to extinguish the arc and rely upon vaporization of some of the oil to blast a jet of oil through the arc.

a. Gas (usually sulfur hexafluoride) circuit breakers sometimes stretch the arc using a magnetic field, and then rely upon the dielectric strength of the sulfur hexafluoride to quench the stretched arc.

b. Vacuum circuit breakers have minimal arcing (as there is nothing to ionize other than the contact material), so the arc quenches when it is stretched by a very small amount (<2–3 mm). Vacuum circuit breakers are frequently used in modern medium-voltage switchgear up to 35 kV.

c. Air blast circuit breakers may use compressed air to blow out the arc, or alternatively, the contacts are rapidly swung into a small sealed chamber, where the escaping displaced air blows out the arc.

7. Surge Voltage Protection

Transient overvoltage's are due to natural and inherent characteristics of power systems. Overvoltage's may be caused by lightning or by a sudden change of system conditions (such as switching operations, faults, load rejection, etc.), or both. Generally, the overvoltage types can be classified as lightning generated and as switching generated.

The magnitude of overvoltages can be above maximum permissible levels, and therefore needs to be reduced and protected against to avoid damage to equipment and undesirable system performance.

The appropriate application of surge-protective devices will lessen the magnitude and duration of voltage surges seen by the protected equipment. The problem is complicated by the fact that insulation failure results from impressed overvoltages, and because of the aggregate duration of repeated instances of overvoltages.

High voltage side 144kV Surge arresters with grounded bottom terminals (photo credit: arresterworks.com) Surge arresters have been used in power systems **to protect insulation from overvoltages.** Historically, the evolution of surge arrester material technology has produced various arrester designs, starting with the valve-type arrester, which has been used almost exclusively on power system protection for decades. The active element (i.e., valve element) in these arresters is a nonlinear resistor that exhibits relatively high resistance (megaohms) at system operating voltages, and a much lower resistance (ohms) at fast rate-of-rise surge voltages. Arresters have a dual fundamental-frequency (RMS) voltage rating (i.e., duty- cycle voltage rating), and a corresponding maximum continuous operating voltage rating. Duty-cycle voltage is defined as the designated maximum permissible voltage between the terminals at which an arrester is designed to perform.

8. Grounding

It is divided into two categories: **power system grounding and equipment grounding.** Power system grounding means that at some location in the system there are intentional electric connections between the electric system phase conductors and ground (earth).

Power system grounding

System grounding is needed to control overvoltages and to provide a path for ground-current flow in order to facilitate sensitive ground-fault protection based on detection of ground-current flow.

Power system grounding can be as follows
1. Solidly grounded. 2. Ungrounded. 3. Resistance grounded.

Each grounding arrangement has advantages and disadvantages, with choices driven by local and global standards and practices, and engineering judgment.

Solidly grounded systems are arranged such that circuit protective devices will detect a faulted circuit and isolate it from the system regardless of the type of fault. All transmission and most sub-transmission systems are solidly grounded for system stability purposes. Low voltage service levels of 120–480 V four-wire systems must also be solidly grounded for safety of life.

Where service continuity is required, such as for a continuously operating process, the **resistance grounded** power system can be used. With this type of grounding, the intention is that any contact between one phase conductor and a ground will not cause the phase overcurrent protective device to operate. Resistance grounding is typically used from 480 V to 15 kV for three-wire systems**. Resistance grounding is achieved by connecting** the neutral of the wye-connected winding of the power transformer to the ground through the resistor, or by employing special grounding transformers.

The operating advantage of an **ungrounded system** is the ability to continue operations during a single phase-to-ground fault, which, if sustained, will not result in an automatic trip of the circuit by protection!. Ungrounded systems are usually employed at the distribution level and are originated from delta-connected power transformers.

Equipment grounding
It refers to the system of electric conductors (grounding conductor & ground buses) by which all non-current-carrying metallic structures within an industrial plant are interconnected & grounded.
Purposes of equipment grounding:
a. To maintain low potential difference between metallic structures or parts, minimizing the possibility of electric shocks to personnel in the area
b. To contribute to adequate protective device performance of the electric system, and safety of personnel and equipment
c. To avoid fires from volatile materials and the ignition of gases in combustible atmospheres by providing an effective electric conductor system for the flow of ground-fault currents and lightning and static discharges to eliminate arcing and other thermal distress in electrical equipment

DC 2, 3-WIRE DISTRIBUTIONS

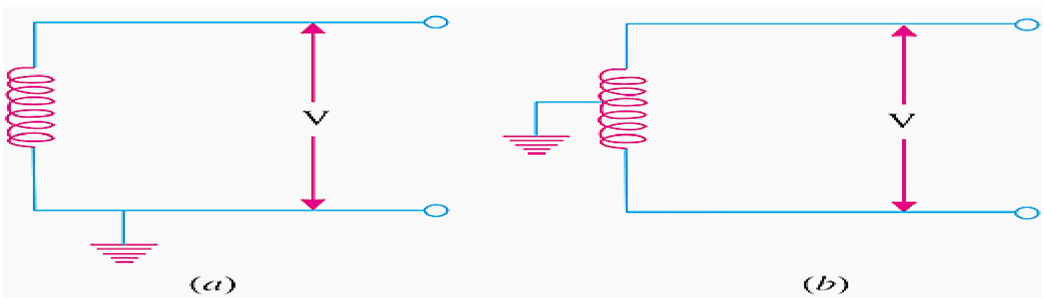
Types of AC Power Distribution Systems

Electrical power is **generated, transmitted and distributed** in its **AC form**. A distribution system begins from a substation where the power is delivered by a transmission network. In some cases, the distribution system may start from a generating station itself, such as when consumers are located near the generating station.

Types of AC distribution system classified based on phases and wires involved in it

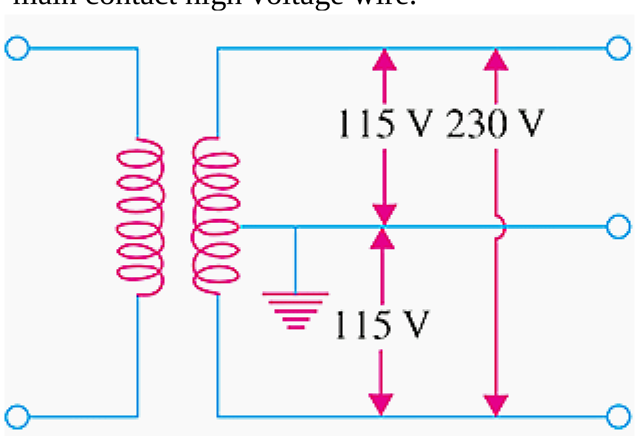
SINGLE PHASE, 2-WIRE SYSTEM

It is shown in Figure one of the two wires is earthed whereas in Figure 1 (b) mid-point of the phase winding is earthed.



Single phase, 3-wire system

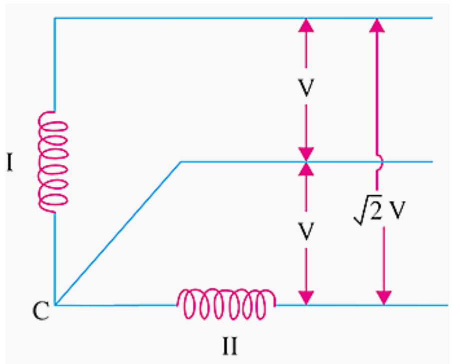
The 1-phase, 3-wire system is identical in principle with the **3-wire DC system**. As shown in Figure 2, the third wire or neutral is connected to the centre of the transformer secondary and earthed for protecting personnel from electric shock should the transformer insulation break down or the secondary main contact high voltage wire.



Two phase, 3-wire system

This system is still used at some places. The third wire is taken from the junction of the two-phase windings I and II, whose voltages are in quadrature with each other as shown in Figure 3.

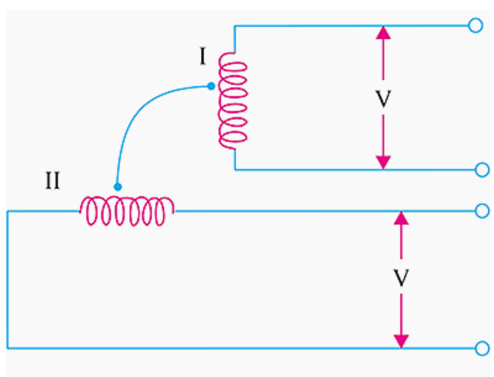
If the voltage between the third or neutral wire and either of the two wires is V, then the voltage between the outer wires is V as shown. As compared to 2-phase, 4-wire system, the 3-wire system suffers from the defect that it produces voltage unbalance because of the unsymmetrical voltage drop in the neutral.



Two phase, 4-wire system

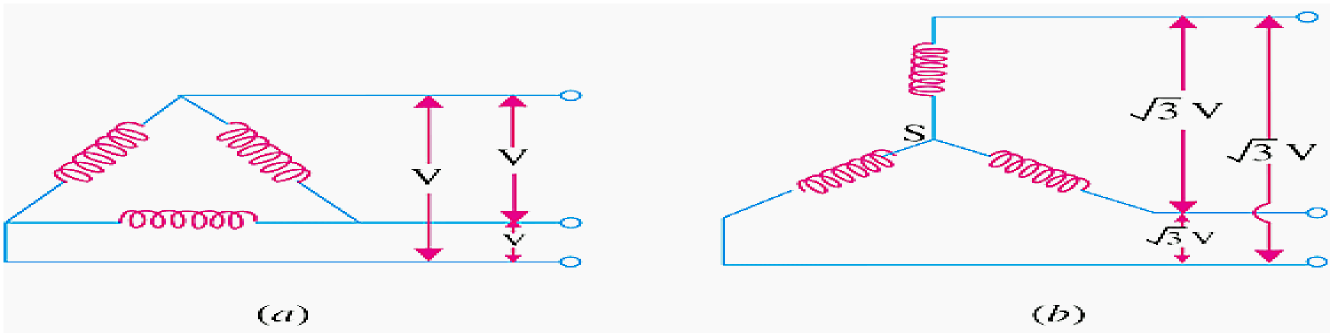
As shown in Figure 4, the four wires are taken from the ends of the two-phase windings and the mid-points of the windings are connected together.

As before, the voltage of the two windings are in quadrature with each other and the junction point may or may not be earthed. If voltage between the two wires of a phase winding be V , then the voltage between one wire of phase I and one wire of phase II is 0.707 V.

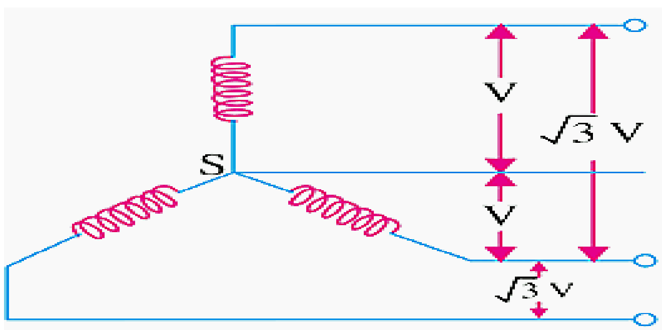


Three phase, 3-wire system

They are used extensively. The 3-wire system may be delta-connected or star-connected whose star point is usually earthed. The voltage between lines is V in delta-connection and √3 V in case of star connection where V is the voltage of each phase as shown in Figure 5 (a) and (b) respectively.



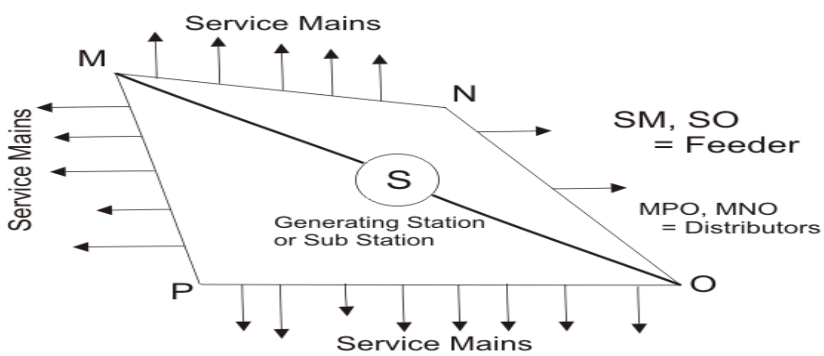
Three phase, 4-wire system
The 4th or neutral wire is taken from the star point of the star-connection as shown in Figure 6 and is of half the cross-section of the outers or line conductors. If V is the voltage of each winding, then line voltage is **3 V**. Usually, phase voltage i.e. voltage between any outer and the neutral for a symmetrical system is **230V** so that the voltage between any two lines or outers is **3×230=400V.**



Single-phase residential lighting loads or single-phase motors which run on 230 V are connected between the neutral and any one of the line wires. These loads are connected symmetrically so that line wires are loaded equally. Hence, the resultant current in the neutral wire is **zero or at least minimum. The three phase induction motors requiring higher voltages of 400 V or so are put across the lines directly.**

RADIAL AND RING MAIN DISTRIBUTIONS
Electrical Power Distribution System
Its function is Distribution of electric power to different consumers is done with much low **voltage** level. Distribution of electric power is done by distribution networks.
Parts Distribution networks

1. Distribution substation.	Electric power is stepped down in substations, for primary distribution purpose.
2. Primary distribution feeder.	Now the stepped down electric power is fed to the distribution transformer through primary distribution feeders.
3. Distribution Transformer.	
4. Distributors.	The secondary of the transformer is connected to distributors.
5. Service mains.	Different consumers are fed electric power by means of the service mains. These service mains are tapped from different points of distributors.



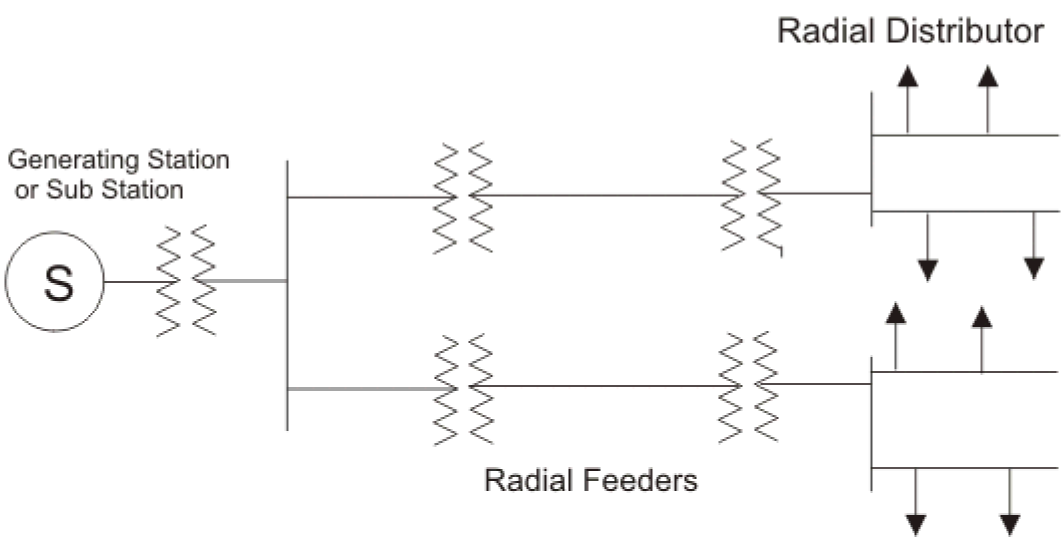
The distributors' types: distributors and sub distributors. Distributors are directly connected to the secondary of distribution transformers whereas sub distributors are tapped from distributors. Service mains of the consumers may be either connected to the distributors or sub distributors depending upon the position and agreement of consumers. **Both feeder and distributor carry the electrical load,** but they have one basic difference.

Feeder feeds power from one point to another without being tapped from any intermediate point. As because there is no tapping point in between, the **current** at sending end is equal to that of receiving end of the conductor.

The distributors are tapped at different points for feeding different consumers; and hence the current varies along their entire length.

Radial Electrical Power Distribution System

Here different feeders radially came out from the substation and connected to the primary of distribution transformer.

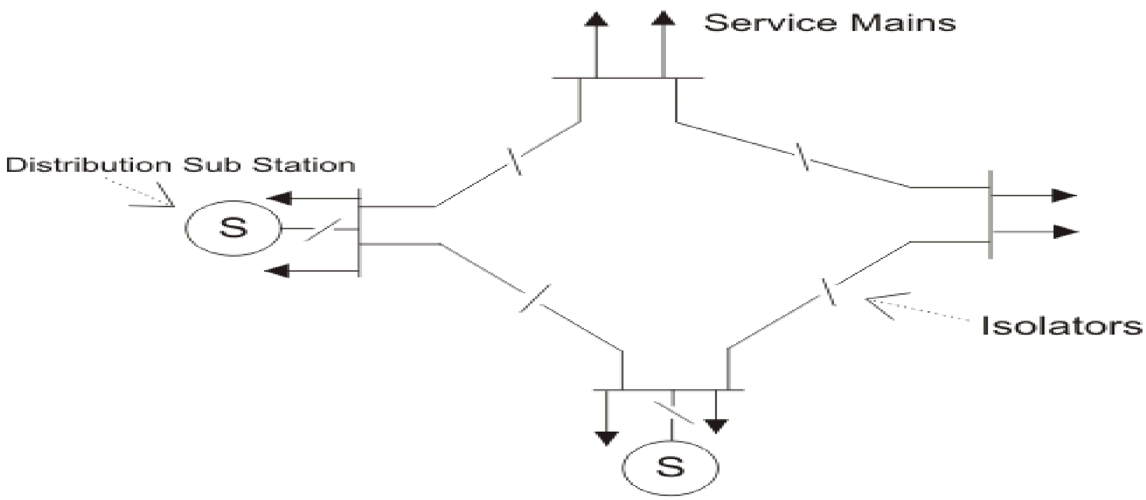


Drawback of radial electrical power distribution system

In case of any feeder failure, the associated consumers would not get any power as there was no alternative path to feed the transformer. In case of **transformer** failure also, the power supply is interrupted.

Drawback of Ring Main Electrical Power Distribution System

It can be overcome by introducing a **ring main electrical power distribution system**. Here one ring network of distributors is fed by more than one feeder. In this case if **one feeder is under fault or maintenance**, **the ring distributor is still energized by other feeders connected to it.** In this way the supply to the consumers is not affected even when any feeder becomes out of service.



In this way, supply to the consumers connected to the healthy zone of the ring, can easily be maintained even when one section of the ring is under shutdown.

The number of feeders connected to the **ring main electrical power distribution system** depends upon the following factors.

1. Maximum Demand of the System: If it is more, then more numbers of feeders feed the ring.
2. Total Length of the Ring Main Distributors: It length is more, to compensate the voltage drop in the line, more feeders to be connected to the ring system.
3. Required Voltage Regulation: The number of feeders connected to the ring also depends upon the permissible allowable, voltage drop of the line.

The sub distributors and service mains are taken off may be via distribution transformer at different suitable points on the ring depending upon the location of the consumers. Sometimes, instead of connecting service main directly to the ring, sub distributors are also used to feed a group of service mains where direct access of ring distributor is not possible.

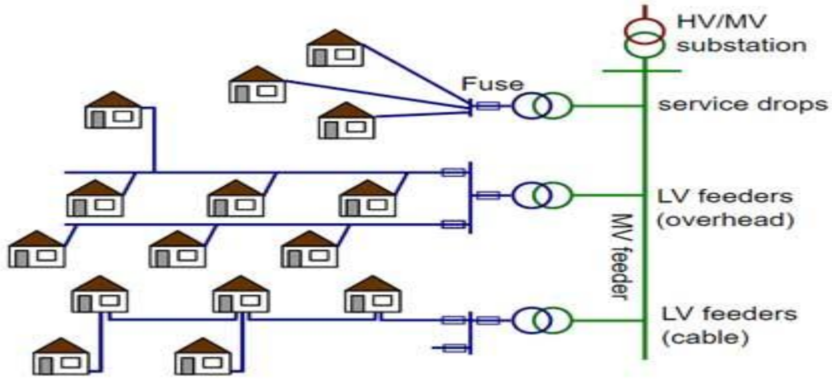
Radial, Parallel, Ring Main and Interconnected Distribution Systems

An **electric power distribution** system can be classified according to its **feeder connection schemes / topologies** as follows -

1. Radial distribution system. 2. Parallel feeder's distribution.
3. Ring main distribution system. 4. Interconnected distribution

Radial Distribution System

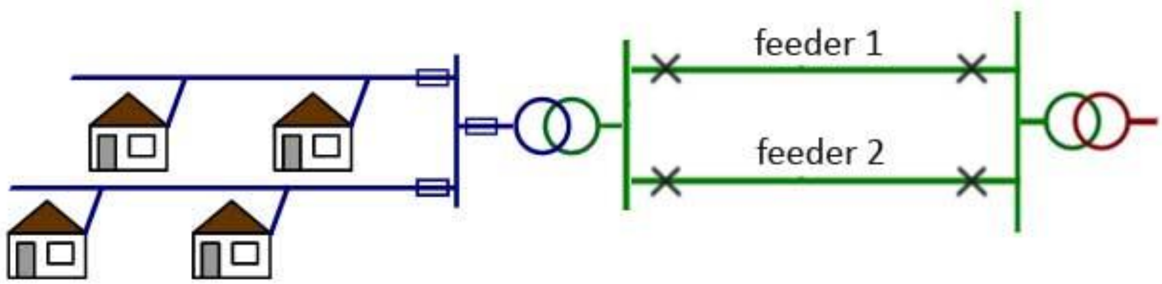
It is used only when **substation / generating station** is located at the center of the consumers. In this system, different feeders radiate from a substation or a generating station and feed the distributors at one end. Main **characteristic of a radial distribution system** is that the **power flow is in only one direction.** It is the simplest system, lowest initial cost it is not highly reliable.



A major **drawback of a radial distribution system** is, a fault in the feeder will result in supply failure to associated consumers as there won't be any alternative feeder to feed distributors.

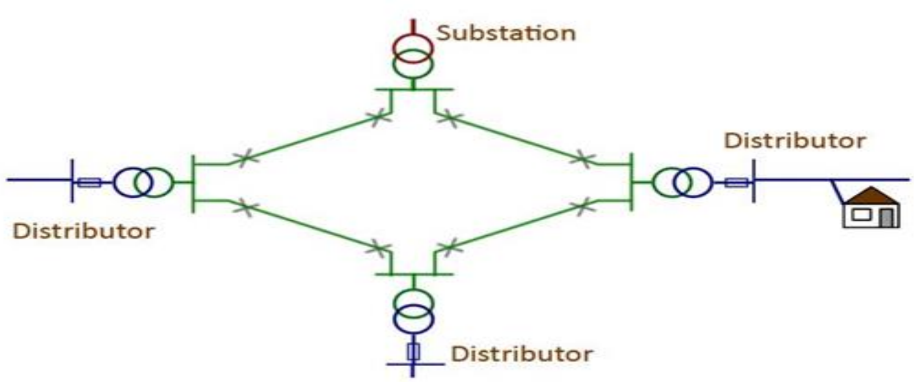
Parallel Feeders Distribution System

Disadvantage of a radial system can be minimized by introducing parallel feeders. The initial cost of this system is much more as the number of feeders is doubled. Such system may be used where reliability of the supply is important or for load sharing where the load is higher.



Ring Main Distribution System

Parallel feeders reliability can be achieved by using **ring distribution system**. Here, each distribution **transformer** is fed with two feeders but in different paths. The feeders in this system form a loop which starts from the substation bus-bars, runs through the load area feeding distribution transformers and returns to the substation bus-bars.



Ring main distribution system

Advantages of Ring Main Distribution System

- There are **fewer voltage fluctuations** at consumer's terminal.
- The system is very **reliable as each distribution transformer** is fed with two feeders. That means, in the event of a fault in any section of the feeder, the continuity of the supply is ensured from the alternative path.

Interconnected Distribution System

When a ring main feeder is energized by two or more substations or generating stations, it is called as an interconnected distribution system. This system ensures reliability in an event of transmission failure. Also, any area fed from one generating stations during peak load hours can be fed from the other generating station or substation for meeting power requirements from increased load.

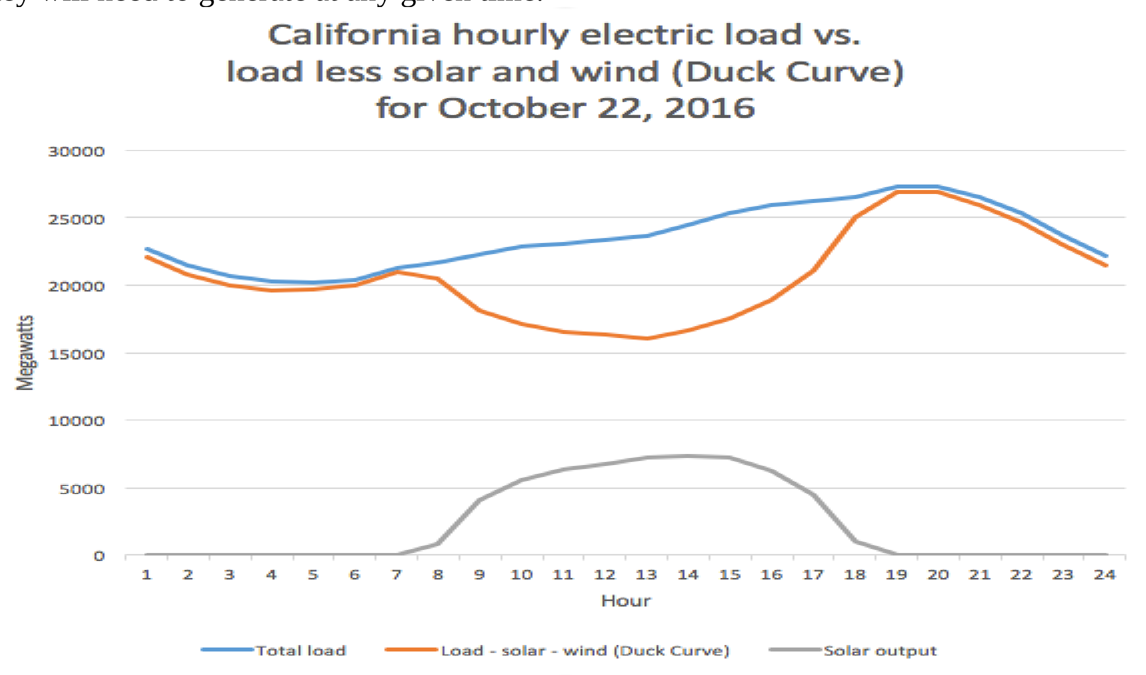
CURRENT LOADING AND VOLTAGE PROFILE IN DISTRIBUTIONS

Load profile

It is a graph of the variation in the **electrical load versus time.** A load profile will vary according to customer type (typical examples include residential, commercial and industrial), temperature and holiday seasons. **Power producers** use this information to plan how much electricity they will need to make available at any given time.

Power generation

Here a **load curve / profile** is a chart illustrating the variation in demand/electrical load over a specific time. **Power Generation companies use load curve / profile** to plan how much power they will need to generate at any given time.



Electricity distribution
Here the load profile of electricity usage is important to the efficiency and reliability of power transmission. The power transformer or battery-to-grid are critical aspects of power distribution and sizing and modeling of batteries or transformers depends on the load profile.

Calculating and recording load profiles
Load profiles determined by **direct metering** but on smaller devices such as distribution network transformers this is not routinely done. Instead a load profile can be inferred from customer billing or other data. An example of a practical calculation used by utilities is using a transformer's maximum demand reading and taking into account the known number of each customer type supplied by these transformers. This process is called **load research**.

Actual demand can be collected at strategic locations to perform more detailed **load analysis;** this is beneficial to both distribution and end-user customers looking for peak consumption. Smart grid meters, utility meter load profilers, data logging sub-meters and portable data loggers are designed to accomplish this task by recording readings at a set interval.

COMPARISON OF COPPER EFFICIENCIES IN DIFFERENT SYSTEMS OF DISTRIBUTION

Transformer - Losses and Efficiency

Losses in Transformer

In **electrical machine**, 'loss' = input power - output power.
A transformer is a static device = mechanical losses (like wind age or friction losses) are **absent** in it. **A transformer consists of electrical losses (iron losses and copper losses).**

1. Core Losses Or Iron Losses
Eddy current loss and hysteresis loss depend upon the magnetic properties of the material used for the construction of core. Hence these losses are also known as **core losses** or **iron losses**.
Hysteresis loss in transformer: It is due to reversal of magnetization in the transformer core. This loss depends upon the volume and grade of the iron, frequency of magnetic reversals and value of flux density. It can be given by, Steinmetz formula:

$$W_h = \eta B_{max}^{1.6} f V \text{ (watts)}$$

where, η = Steinmetz hysteresis constant and V = volume of the core in m^3

Eddy current loss in transformer: In transformer, AC current is supplied to the primary winding which sets up alternating magnetizing flux. When this flux links with secondary winding, it produces induced emf in it. But some part of this flux also gets linked with other conducting parts like steel core or iron body or the transformer, which will result in induced emf in those parts, causing small circulating current in them. This current is called as eddy current. Due to these eddy currents, some energy will be dissipated in the form of heat.

2. Copper Loss In Transformer
It is due to ohmic resistance of the transformer windings. Copper loss for the primary winding is $I_1^2R_1$ and for secondary winding is $I_2^2R_2$. Where, I_1 and I_2 are current in primary and secondary winding respectively, R_1 and R_2 are the resistances of primary and secondary winding

respectively. It is clear that Cu loss is proportional to square of the current, and current depends on the load. Hence copper loss in transformer varies with the load.

Efficiency of Transformer= **output power / input power.**
Transformers are electrical devices have full load efficiency between 95% to 98.5%. As a transformer being highly efficient, output and input are having nearly same value.
Efficiency of Transformer

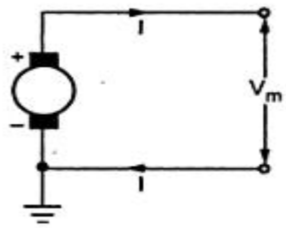
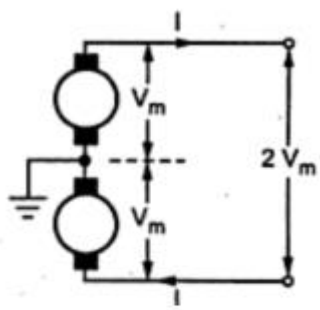
$$\text{ordinary efficiency} = \frac{\text{output (in watts)}}{\text{input (in watts)}}$$

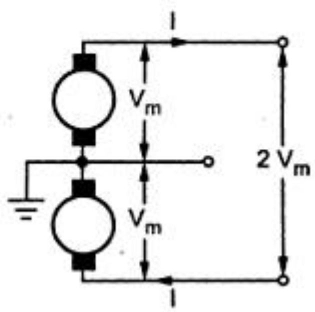
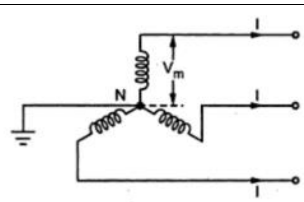
A better method to find efficiency of a transformer is using,
Efficiency = (input - losses) / input = 1 - (losses / input).
Condition For Maximum Efficiency
Let, Copper loss = I12R1 Iron loss = Wi
Hence, **efficiency of a transformer** will be maximum when copper loss and iron losses are equal. That is Copper loss = Iron loss.

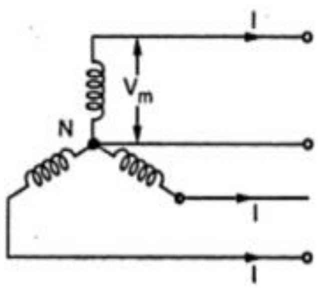
All day efficiency of a transformer is always less than ordinary efficiency of it.

CHARACTERISTICS	COPPER	ALUMINUM
Tensile strength (lb/in2)	50,000	32,000
Tensile strength for same conductivity (lb.)	50,000	50,000
Weight for same conductivity (lb.)	100	54
Cross section for same conductivity	100	156
Specific resistance (ohms-cir/mil ft) (20°C ref)	10.6	18.52
Coefficient of expansion (per deg. C x 10^-6)	16.6	23

Types of systems for the volume of copper required.

Two Wire D.C. System With One Line Earthed		The maximum voltage between the conductors is Vm, as one material is earthed. P = Power transmitted Let R = resistance of each conductor $I = \frac{P}{V_m}$ $\therefore\ R = \frac{\rho l}{A}$ Total copper losses in both the lines are, $W = 2I^2R = 2\left(\frac{P}{V_m}\right)^2 \times \frac{\rho l}{A}$ $\therefore\ A = 2\left(\frac{P}{V_m}\right)^2 \times \frac{\rho l}{W}$ = area of cross-section Volume of copper required is = 2 × area of cross-section × length = 2 A l $= 2 \times 2\left(\frac{P}{V_m}\right)^2\left(\frac{\rho l}{W}\right) l$ $= \frac{4P^2\rho l^2}{W V_m^2}$
Two Wire D.C. System With Midpoint Earthed		power transmitted is same as P, the current in each conductor is, $I = \frac{P}{2V_m}$ The total copper loss in both the lines is, $W = 2I^2R = \frac{2P^2}{4V_m^2} \cdot \frac{\rho l}{A}$ where A = area of cross-section of each line. $\therefore\ A = \frac{P^2}{2V_m^2}\,\frac{\rho l}{W}$ The total volume of copper required is,

		$= 2 \times A \times l + (0.5\ A) \times l$ $= 2.5\ A\ l$ $= 2.5\ \frac{P^2}{2V_m^2} \cdot \frac{\rho l^2}{W} = \frac{2.5}{2} \times \frac{4}{4} \cdot \frac{P^2 \rho l^2}{V_m^2\ W}$ $= \frac{2.5}{8} K = 0.3125K \quad \text{where} \quad K = \frac{4P^2 \rho l^2}{V_m^2\ W}$ Thus the volume of copper required in this system is one fourth the volume of copper required for two wire d.c. system with one line earthed.
Three Wire D.C. System		When the load is balanced, current through the third neutral wire is zero. $I = \frac{P}{2V_m}$ Let A = Cross-section of outer conductors The total copper loss is, $W = 2I^2R = \frac{2P^2}{4V_m^2} \cdot \frac{\rho l}{A}$ $= \frac{P^2}{2V_m^2} \cdot \frac{\rho l}{A}$ $\therefore \quad A = \frac{P^2}{2V_m^2} \cdot \frac{\rho l}{W}$ Let area of cross-section of the middle neutral wire is half of the area of cross-section of the outer conductor. Hence the total volume of copper= Volume of copper for outer wires + volume of copper for neutral wire $= 2 \times A \times l + (0.5\ A) \times l$ $= 2.5\ A\ l$ $= 2.5\ \frac{P^2}{2V_m^2} \cdot \frac{\rho l^2}{W} = \frac{2.5}{2} \times \frac{4}{4} \cdot \frac{P^2 \rho l^2}{V_m^2\ W}$ $= \frac{2.5}{8} K = 0.3125K \quad \text{where} \quad K = \frac{4P^2 \rho l^2}{V_m^2\ W}$
Three Phase Three Wire A.C. System		This is most commonly used system for the transmission. The three phase three wire star connected system with neutral earthed is shown in the Fig. 4. The three phase three wire star connected system with neutral earthed is shown in the Fig. The maximum voltage between each line conductor and the neutral is Vm as shown in the Fig. 4. The R.M.S. value of the voltage per phase given by,

		$V_{ph} = \frac{V_m}{\sqrt{2}}$ Then total power transmitted is P watts hence per phase power transmission is, $P_{ph} = \frac{P}{3}$ Let cosΦ be the load power factor
Three Phase Four Wire A.C. System This system is popularly used for secondary distribution. The neutral is also made available for the connection of the load. The system is shown in the Fig. 4.		The maximum voltage between any conductor and the neutral is Vm hence r.m.s. voltage per phase is, $V_{ph} = \frac{V_m}{\sqrt{2}}$ The power transmitted per phase is, $P_{ph} = \frac{P}{3}$ Hence all the calculations up to the copper losses and expression of A remain same as derived for three phase three wire system. $\therefore \quad A = \frac{2}{3} \frac{P^2}{V_m^2 \cos^2\phi} \cdot \frac{\rho l}{W}$ The total volume of copper requires= Volume of copper for 3 lines + copper required for neutral $= 3\,A\,l + 0.5\,A\,l = 3.5\,A\,l$ $= 3.5 \times \frac{2}{3} \frac{P^2}{V_m^2 \cos^2\phi} \frac{\rho l}{W} \times l$ $= \frac{7}{3} \times \frac{4}{4} \frac{P^2}{V_m^2 \cos^2\phi} \frac{\rho l^2}{W}$ $= \frac{7}{12\cos^2\phi} K = \frac{0.583}{\cos^2\phi} K \quad$ where $K = \frac{4 P^2 \rho l^2}{V_m^2 W}$

POWER TRANSFORMER
It is used **in transmission network of higher voltages** for **step-up and step down application** (400 kV, 200 kV, 110 kV, 66 kV, 33kV) and are generally rated > 200MVA.

Distribution transformers are used for **lower voltage** distribution networks as a means to end user connectivity. (11kV, 6.6 kV, 3.3 kV, 440V, 230V) and are generally rated < 200 MVA.

Distribution transformer is used for the distribution of electrical energy at **low voltage** as less than 33KV in industrial purpose and 440v-220v in domestic purpose.

Transformer Size / Insulation Level:
Power transformer is used for the **transmission purpose at heavy load, high voltage** greater than 33 KV & 100% efficiency. It also having a **big in size** as compare to distribution transformer, it used in generating station and Transmission substation high insulation level.

Iron Losses and Copper Losses
Power Transformers are used in Transmission network so they do **not directly connect to the consumers**, so load fluctuations are very less. These are loaded fully during 24 hr's a day, so Cu losses & Fe losses takes place throughout day the specific weight i.e. (iron weight)/(cu weight) is very less.

Power Transformers are used in Distribution Network so directly connected to the consumer so load fluctuations are very high. these are not loaded fully at all time so iron losses takes place 24hr a day and cu losses takes place based on load cycle. the specific weight is more i.e. (iron weight)/(cu weight).average loads are about only 75% of full load and these are designed in such a way that max efficiency occurs at 75% of full load. As these are time dependent the all day efficiency is defined in order to calculate the efficiency.
Power transformers are used for transmission as a step up devices so that the I2r loss can be minimized for a given power flow. These transformers are designed to utilize the core to maximum and will operate very much near to the knee point of B-H curve (slightly above the knee point value).This brings down the mass of the core enormously.
Naturally these transformers have the matched iron losses and copper losses at peak load (i.e. the maximum efficiency point where both the losses match).

Distribution transformers cannot be designed like this. Hence the all-day-efficiency comes into picture while designing it. It depends on the typical load cycle for which it has to supply. Definitely Core design will be done to take care of peak load and as well as all-day-efficiency. It is a bargain between these two points.

Power transformer generally **operates at full load.** Hence, it is designed such that copper losses are minimal. However, a distribution transformer is always online and operated at loads less than full load for most of time. Hence, it is designed such that core losses are minimal. In Power Transformer the flux density is higher than the distribution transformer.

Maximum Efficiency
The main difference between power and distribution transformer is distribution transformer is designed for maximum efficiency at 60% to 70% load as normally doesn't operate at full load all the time. Its load depends on distribution demand. Whereas power transformer is designed for maximum efficiency at 100% load as it always runs at 100% load being near to generating station.

Distribution Transformer is used at the distribution level where voltages tend to be lower .The secondary voltage is almost always the voltage delivered to the end consumer. Because of voltage drop limitations, it is usually not possible to deliver that secondary voltage over great distances. As a result, most distribution systems tend to involve many 'clusters' of loads fed from distribution transformers, and this in turn means that the thermal rating of distribution transformers doesn't have to be very high to support the loads that they have to serve.

Transformer

It is a static machine used for transforming power from one circuit to another without changing frequency. This is a very basic **definition of transformer**. Since, there is no rotating or moving part, so a transformer is a static device. Transformer operates on an ac supply. A transformer works on the principle of mutual induction.

In the year 1950, 400KV **electrical power transformer** was introduced in high voltage electrical power system. In the early 1970s, unit rating as large as 1100 MVA was produced. V

Use of Power Transformer

Generation of electrical power in low voltage level is very much cost effective. Theoretically, this low voltage level power can be transmitted to the receiving end. This low voltage power if transmitted results in greater line current which indeed causes more line losses. But if the voltage level of a power is increased, the **current** of the power is reduced which causes reduction in ohmic or I^2R losses in the system, reduction in cross sectional area of the conductor i.e. reduction in capital cost of the system and it also improves the **voltage regulation** of the system. Because of these, low level power must be stepped up for efficient **electrical power transmissio**n. This is done by **step up transformer** at the sending side of the power system network. As this high voltage power may not be distributed to the consumers directly, this must be stepped down to the desired level at the receiving end with the help of **step down transformer.** Electrical power transformer thus plays a vital role in power transmission.

Two winding transformers are generally used where ratio of high voltage and low voltage is greater than 2. It is cost effective to use **auto transformer** where the ratio between high voltage and low voltage is less than 2. Again a single unit three phase transformer is more cost effective than a **bank of three single phase transformers** unit in a **three phase system.** But a single three phase transformer unit is a bit difficult to transport and have to be removed from service entirely if one of the phase winding breaks down.

Types of Transformer

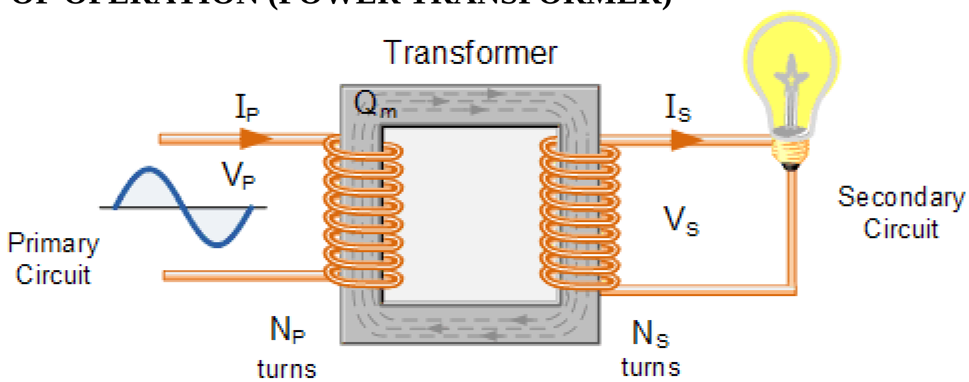
Based on their purpose, use, construction etc.

1. Step Up Transformer and Step Down Transformer - Used for stepping up and down the voltage level of power in transmission and distribution power system network.
2. Three Phase Transformer and Single Phase Transformer - Used in three phase power system as it is cost effective.
3. Electrical Power Transformer, Distribution Transformer and Instrument Transformer - **Power transformers** are used in **transmission network** for **stepping up / down the voltage level.** It operates mainly during high or peak loads and has maximum efficiency at or near full load. **Distribution transformer** steps down the voltage for distribution purpose to domestic or commercial users. It has good voltage regulation and operates 24 hrs a day with maximum efficiency at 50% of full load. **Instrument transformers** include C.T and P.T which are used to

reduce high voltages and current to lesser values which can be measured by conventional instruments.

1. Two Winding Transformer and Auto Transformer - Used where ratio between high voltage and low voltage is greater than 2
2. Outdoor Transformer and Indoor Transformer - Transformers are designed for installing at outdoor are outdoor transformers and transformers designed for installing at indoor are indoor transformers.
3. Oil Cooled and Dry Type Transformer - Here the cooling medium is transformer oil whereas the **dry type transformer** is air cooled.
4. Core type, Shell type and Berry type transformer - It has two vertical legs or limbs with two horizontal sections named yoke. Core is rectangular in shape with a common magnetic circuit. Cylindrical coils (HV and LV) are placed on both the limbs. Shell type transformer: It has a central limb and two outer limbs. Both HV, LV coils are placed on the central limb. Double magnetic circuit is present. Berry type transformer: The core looks like spokes of wheels. Tightly fitted metal sheet tanks are used for housing this type of transformer with transformer oil filled inside.

THEORY OF OPERATION (POWER TRANSFORMER)



One of the main reasons that we use alternating AC voltages and currents in our homes and workplace's is that **AC supplies can be easily generated** at a **convenient voltage**, transformed (hence the name transformer) into much higher voltages and then distributed around the country using a **national grid of pylons** and cables over very long distances.

The reason for transforming the voltage to a much higher level is that higher distribution voltages implies lower currents for the same power and therefore **lower I^2R losses** along the networked grid of cables.

The **Voltage Transformer** is a electrical component is very simple static (or stationary) electro-magnetic passive electrical device that works on the **principle of Faraday's law of induction** by converting electrical energy from one value to another.

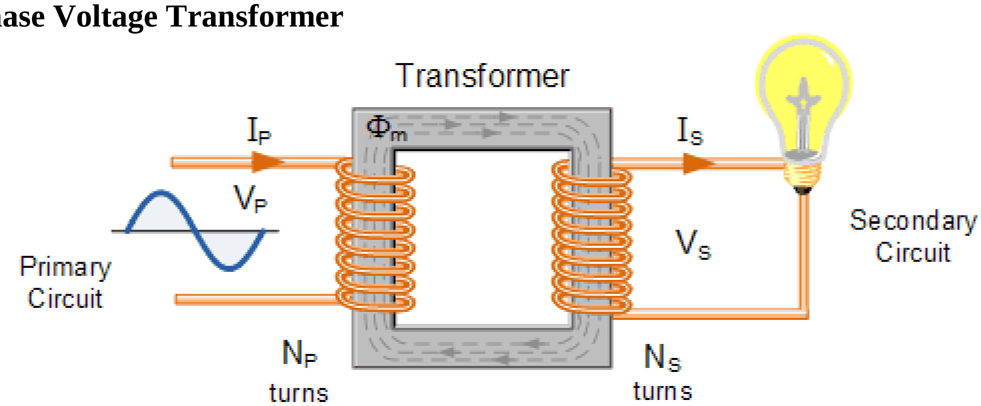
Mutual induction is the process by which **a coil of wire magnetically induces a voltage into another coil** located in close proximity to it. Then we can say that **transformers work in the "magnetic domain"**, and transformers get their name from the fact that they "transform" one voltage or current level into another.

Transformers are capable of either **increasing / decreasing the voltage** and current levels of their supply, **without modifying its frequency**, or the amount of electrical power being transferred from one winding to another via the magnetic circuit.

A **single phase voltage transformer** consists of 2 electrical coils (Primary, Secondary Windings).The "primary" side of the transformer takes power, and the "secondary" as the side delivers power. Here the primary is usually the side with the higher voltage.

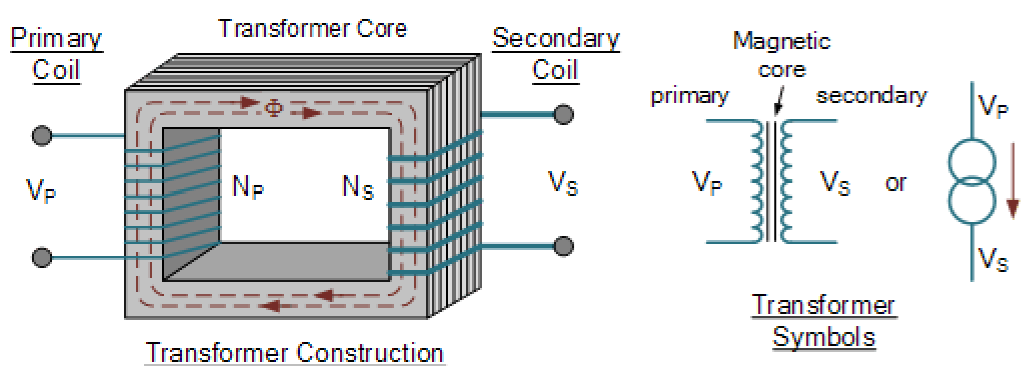
These **two coils are not in electrical contact** with each other but are instead wrapped together around a common closed magnetic iron circuit called the "core". This **soft iron core** is not solid but made up of individual laminations connected together to help **reduce the core's losses**.

Single Phase Voltage Transformer



Here transformer there is **no direct electrical connection** between the **two coil windings,** thereby giving it the name also of an **Isolation Transformer**. The **primary winding** of a transformer is connected to the **input voltage supply** and **converts / transforms** the electrical power into a magnetic field. While the job of the secondary winding is to convert this alternating magnetic field into electrical power producing the required output voltage.

Transformer Construction (single-phase)



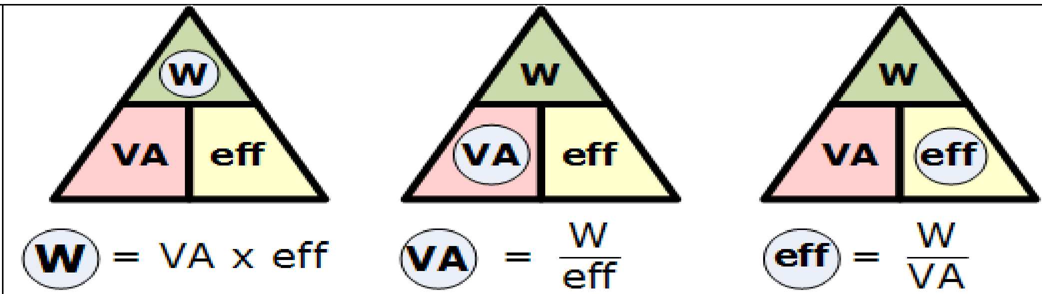
V_P - is the Primary Voltage
V_S - is the Secondary Voltage
NP - is the Number of Primary Windings
NS - is the Number of Secondary Windings
Φ (phi) - is the Flux Linkage

A single-phase transformer can operate to either increase or decrease the voltage applied to the primary winding. When a transformer is used to "increase" the voltage on its secondary winding with respect to the primary, it is called a **Step-up transformer**. When it is used to "decrease" the voltage on the secondary winding with respect to the primary it is called a **Step-down transformer**.

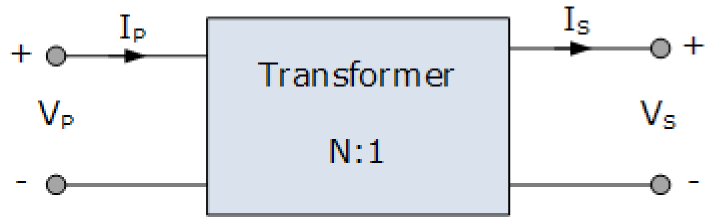
If a **transformer produces** the **same voltage on its secondary** as is applied to its **primary winding**. In other words, its output is identical with respect to voltage, current and power transferred. This type of transformer is called an "**Impedance Transformer**".

The difference in voltage between the primary and the secondary windings is achieved by changing the number of coil turns in the primary winding (N_P) compared to the number of coil turns on the secondary winding (N_S). In other words, **transformers DO NOT operate on steady state DC voltages**, only alternating or pulsating voltages.

Transformers turn ratio	**TTR= number of turns (primary coil N_P / secondary coil N_S).** **Transformers turn ratio=Transformers Voltage ratio**= input / output=**3:1** $$\frac{N_P}{N_S} = \frac{V_P}{V_S} = n = \text{Turns Ratio}$$
Transformer EMF Equation(E_{rms})	$$E_{rms} = 4.44 f N \Phi_{max}$$ f - is the flux frequency in Hertz, $= \omega/2\pi$ N - is the number of coil windings. Φ - is the amount of flux in Weber's
Power rating=current* voltage	**Volt-amperes=Kilo volt-amperes=Mega volt-amperes**.
Power in a Transformer	$$\text{Power}_{\text{Primary}} = \text{Power}_{\text{Secondary}}$$ $$P_{(PRIM)} = P_{(SEC)} = V_P I_P \cos\theta_P = V_S I_S \cos\theta_S$$ Where: Φ_P is the primary phase angle and Φ_S is the secondary phase angle.
Transformer Efficiency	$$\text{efficiency}, \eta = \frac{\text{Output Power}}{\text{Input Power}} \times 100\%$$ $$= \frac{\text{Input Power - Losses}}{\text{Input Power}} \times 100\%$$ $$= 1 - \frac{\text{Losses}}{\text{Input Power}} \times 100\%$$ $$\text{Efficiency}, \eta = \frac{\text{Secondary Watts (Output)}}{\text{Primary VA (Input)}}$$

Transformer Efficiency Triangle	

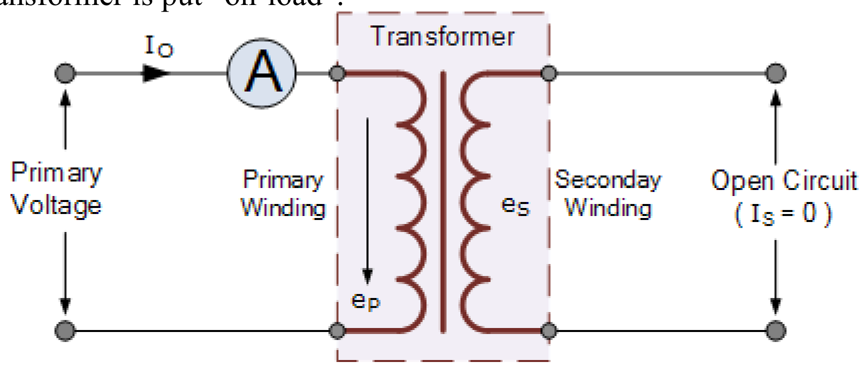
Transformer Representation



PHASOR DIAGRAM

Transformer Loading

Ideal transformer has no core losses or copper losses in the transformers windings.
It means the transformer is put “on-load”.

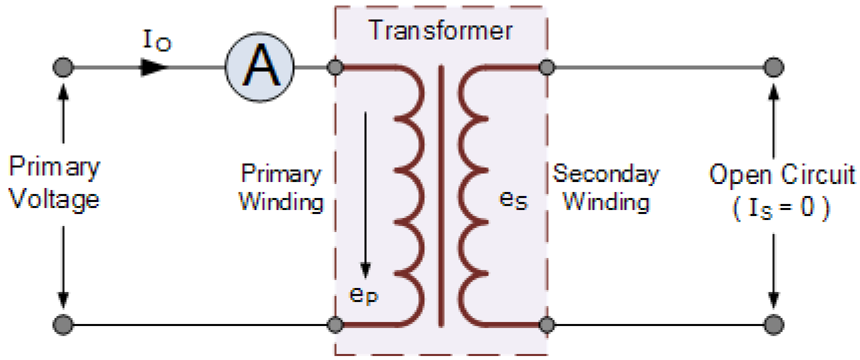


Transformer “No-load”

It means no electrical load connected to its secondary winding and therefore no secondary current flowing.

A transformer is said to be on “no-load” when its **secondary side winding is open circuited**. When an AC sinusoidal supply is connected to the primary winding of a transformer, a small current, I_{OPEN} will flow through the primary coil winding due to the presence of the primary supply voltage.

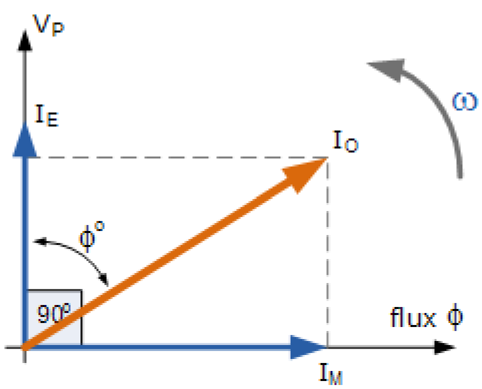
With the secondary circuit open, nothing connected, a back EMF along with the primary winding resistance acts to limit the flow of this primary current. Obviously, this no-load primary current (Io) must be sufficient to maintain enough magnetic field to produce the required back emf. Consider the circuit below.



The **ammeter will indicate** a small current flowing through the primary winding even though the secondary circuit is open circuited.

No-load primary current components(I_O):

- An **In-phase current= I_E** which supplies the core losses (eddy current and hysteresis).
- A **small current =I_M** at 90° to the voltage which sets up the **magnetic flux**.



$$I_E = I_O \cos\phi$$

$$I_M = I_O \sin\phi$$

$$I_O = \sqrt{I_M^2 + I_E^2}$$

Magnetising component=I_M
No-load current=I_O
In-phase current= I_E
power factor=sine theta

$$\sin\phi = \frac{I_M}{I_O}$$

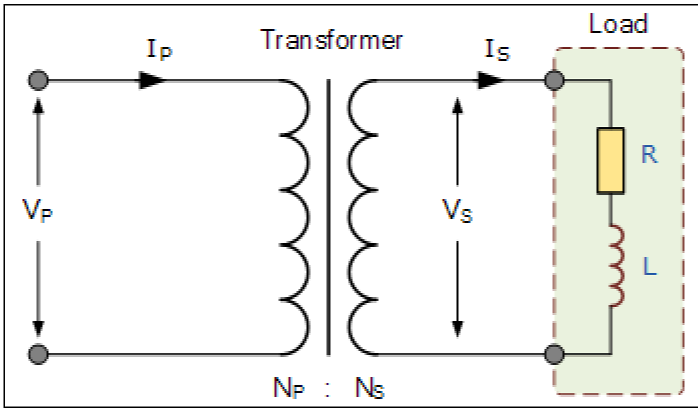
Note that this no-load primary current, Io is very small compared to the transformers normal full-load current. Also due to the iron losses present in the core as well as a small amount of copper losses in the primary winding, Io does not lag behind the supply voltage, Vp by exactly 90°, (cosφ = 0), there will be some small phase angle difference.

Transformer "On-load"

When an electrical load is connected to the secondary winding of a transformer, a current flows in the secondary winding and out to the load. This secondary current is due to the induced secondary voltage, set up by the magnetic flux created in the core from the primary current. The **secondary current, I_S** creates a **self-induced secondary magnetic field, Φ_S** in the transformer core which flows in the exact opposite direction to the main primary field, Φ_P. These two magnetic fields oppose each other resulting in a combined magnetic field of less magnetic strength than the single field produced by the primary winding alone when the secondary circuit was open circuited.

This combined magnetic field reduces the back EMF of the primary winding causing the primary current, I_P to increase slightly. The primary current continues to increase until the cores magnetic field is back at its original strength, and for a transformer to operate correctly, a balanced condition must always exist between the primary and secondary magnetic fields. This results in the power to be balanced and the same on both the primary and secondary sides.

Transformer "On-load"



$$V_P = \frac{V_S N_P}{N_S} = \frac{V_S I_S}{I_P}, \qquad V_S = \frac{V_P N_S}{N_P} = \frac{V_P I_P}{I_S}$$

$$N_P = \frac{V_P N_S}{V_S} = \frac{N_S I_S}{I_P}, \qquad N_S = \frac{V_S N_P}{V_P} = \frac{N_P I_P}{I_S}$$

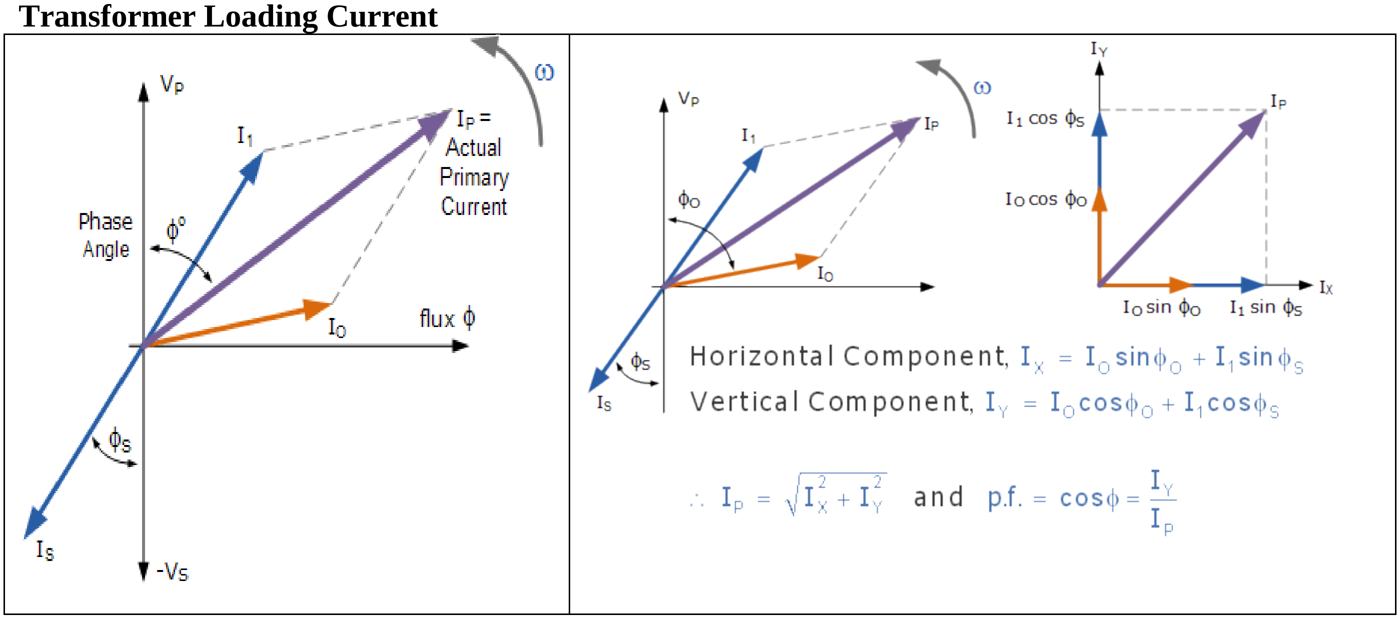
$$I_P = \frac{V_S I_S}{V_P} = \frac{N_S I_S}{N_P}, \qquad I_S = \frac{V_P I_P}{V_S} = \frac{N_P I_P}{N_S}$$

Power Primary = Power Secondary

$N_P/N_S = V_P/V_S = I_S/I_P$ =Turns Ratio=Voltage Ratio = Current Ratio

The total current drawn from the supply by the primary winding is the vector sum of the no-load current, Io and the additional supply current, I_1 as a result of the secondary transformer loading and which lags behind the supply voltage by an angle of Φ.

Transformer Loading Current

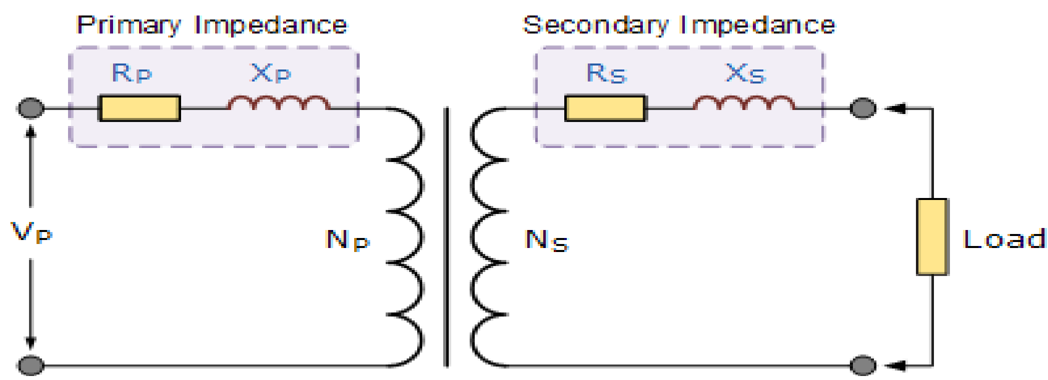


If we are given currents, I_S and Io, we can calculate the primary current, I_P by the following methods.

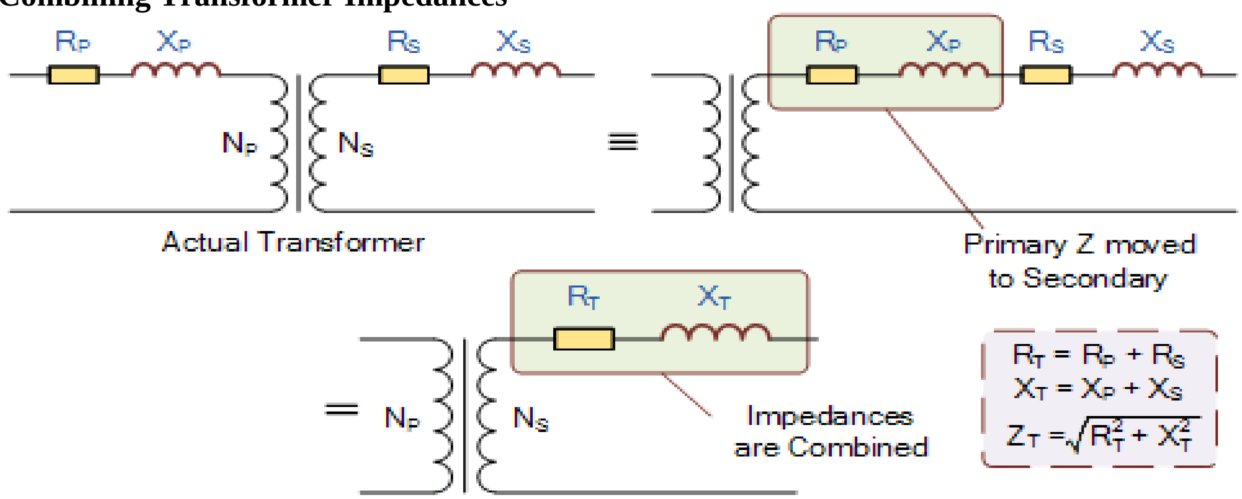
$$I_x = I_o \sin\phi_o + I_1 \sin\phi_s$$
$$I_y = I_o \cos\phi_o + I_1 \cos\phi_s$$
$$I_p = \sqrt{I_x^2 + I_y^2}$$
$$p.f. = \cos\phi = \frac{I_y}{I_p}$$

Phase angle of the primary current, φ_P
Secondary current phase angle, φ_S.

Actual real life, transformer windings have impedances of both X_L and R. These impedances need to be taken into account when drawing the phasor diagrams as these internal impedances cause voltage drops to occur within the transformers windings. The internal impedances are due to the resistance of the windings and an inductance drop called the leakage reactance resulting from the leakage flux. These internal impedances are given as:



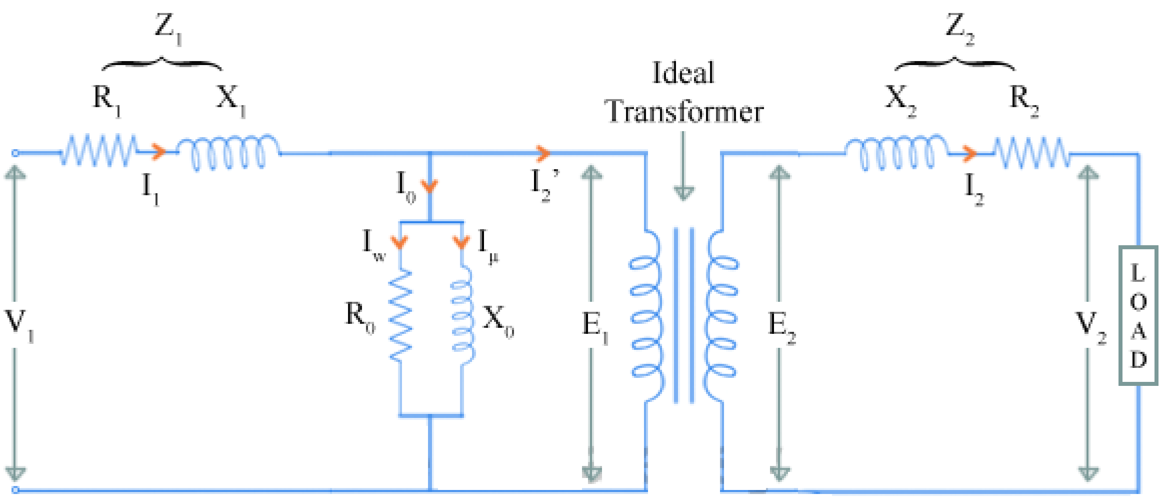
Combining Transformer Impedances



Equivalent Circuit of Transformer
Practical transformer
a. **leakage flux** is present at both primary and secondary sides. This leakage gives rise to **leakage**

reactance's at both sides, which are denoted as X_1 and X_2 respectively.
b. Both the primary and secondary winding possesses resistance, denoted as R_1 and R_2respectively. These resistances cause voltage drop as, I_1R_1 and I_2R_2 and also **copper loss $I_1^2R_1$ and $I_2^2R_2$.**
c. Permeability of the core cannot be infinite, hence some magnetizing current is needed. Mutual flux also causes **core loss** in iron parts of the transformer.
We need to consider all the above things to derive **equivalent circuit of a transformer.**

Equivalent Circuit of Transformer
Resistances and reactance's of transformer, which is described above, can be imagined separately from the windings (as shown in the figure below). Hence, the function of windings, thereafter, will only be the transforming the voltage.



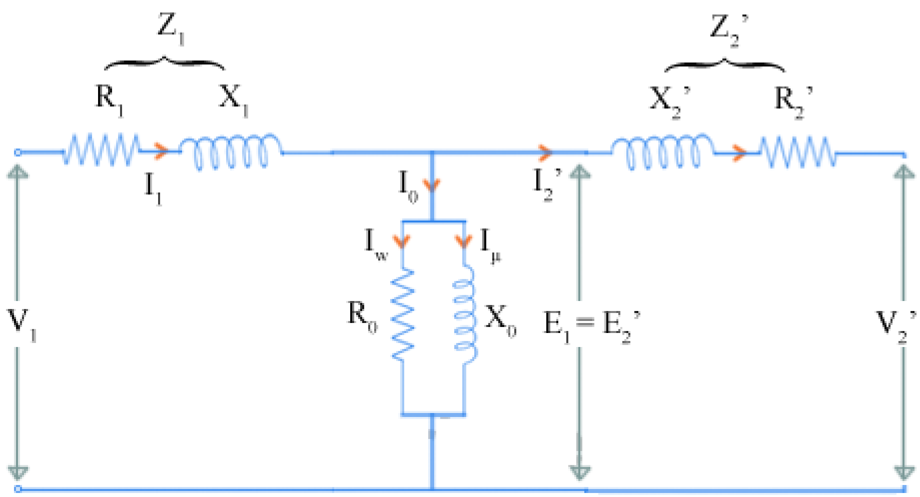
The no load current I_0 is divided into, pure inductance X_0 (taking magnetizing components I_μ) and non induction resistance R_0 (taking working component I_w) which are connected into parallel across the primary. The value of E_1 can be obtained by subtracting I_1Z_1 from V_1. The value of $R_0$and X_0 can be calculated as, $R_0 = E_1 / I_w$ and $X_0 = E_1 / I_\mu$.

But, using this equivalent circuit does not simplifies the calculations. To make calculations simpler, it is preferable to transfer current, voltage and impedance either to primary side or to the secondary side. In that case, we would have to work with only one winding which is more convenient.

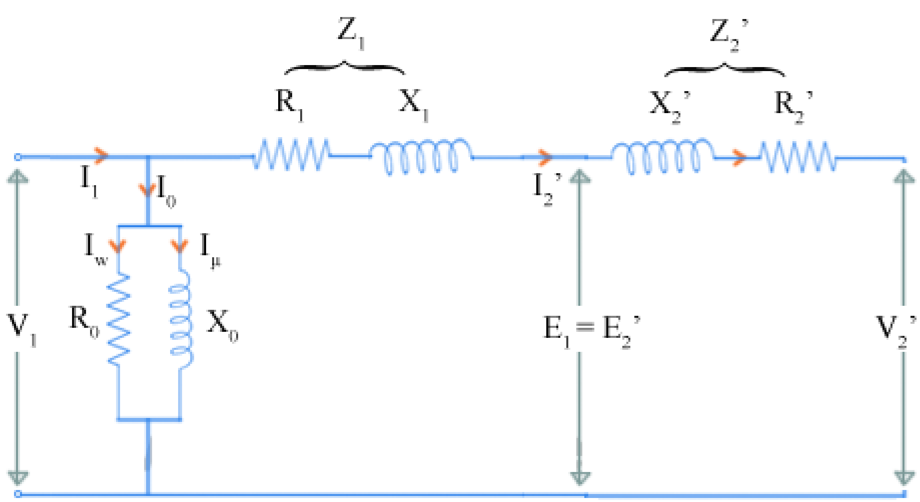
From the voltage transformation ratio, it is clear that,
$E_1 / E_2 = N_1 / N_2 = K$

Now, lets refer the parameters of secondary side to primary.
Z_2 can be referred to primary as Z_2'
where, $Z_2' = (N_1/N_2)^2Z_2 = K^2Z_2$. ....where $K= N_1/N_2$.
that is, $R_2'+jX_2' = K^2(R_2+jX_2)$
equating real and imaginary parts, $R_2' = K^2R_2$ and $X_2' = K^2X_2$. And $V_2' = KV_2$

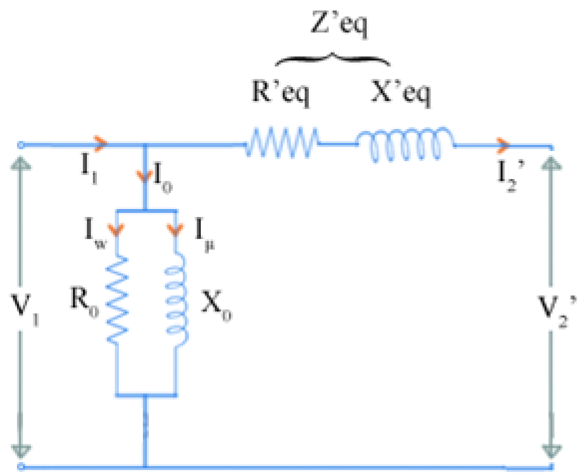
The following figure shows the **equivalent circuit of transformer with secondary parameters referred to the primary**.



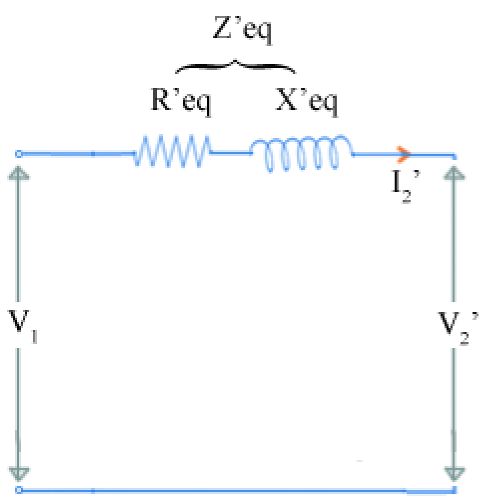
Now, as the values of winding resistance and leakage reactance are so small that, V_1 and E_1 can be assumed to be equal. Therefore, the exciting current drawn by the parallel combination of R_0 and X_0 would not affect significantly, if we move it to the input terminals as shown in the figure below.



Now, let $R_1 + R_2' = R'eq$ and $X_1 + X_2' = X'eq$
Then the **equivalent circuit of transformer** becomes as shown in the figure below



Approximate Equivalent Circuit Of Transformer
If only voltage regulation is to be calculated, then even the whole excitation branch (parallel combination of R0 and X0) can be neglected. Then the equivalent circuit becomes as shown in the figure below



EFFICIENCY AND VOLTAGE REGULATION
Transformer Efficiency = output power/ input power.
The efficiency of transformer is very high because, it's static device there is no rotentional part as well as no friction loss. Transformer efficiency is above 90%.

Voltage Regulations- It is percentage of voltage difference between no load and full load voltage of a transformer with respect to its full load voltage.

$$Voltage\ regulation(\%) = \frac{E_2 - V_2}{V_2} \times 100\%$$

Where, E2= No load voltage V2=Full load voltage

Voltage Regulation of Transformer for Lagging Power Factor	Voltage Regulation of Transformer for Leading Power Factor

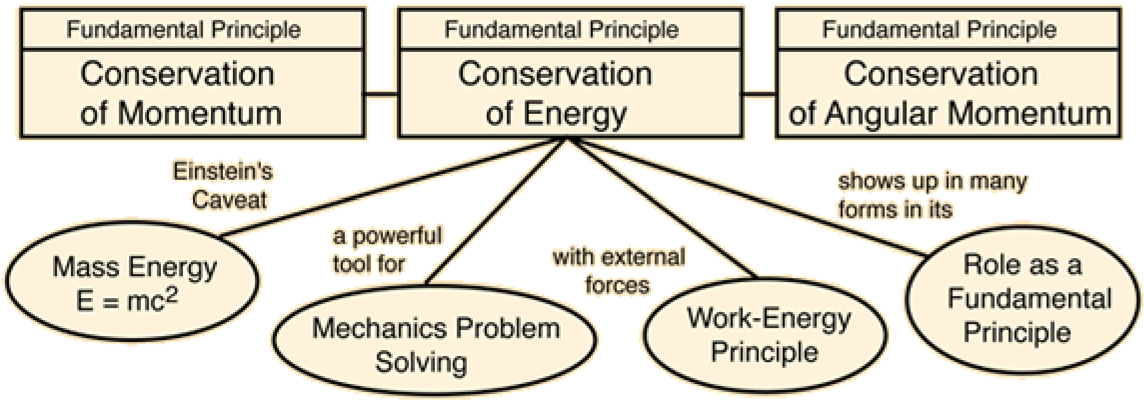
Let's derive the expression of voltage regulation with lagging current, Say lagging **power factor** of the load is $\cos\theta_2$, that means angle between secondary current and voltage is θ_2.	Let's derive the expression of voltage regulation with leading current, say leading power factor of the load is $\cos\theta_2$, that means angle between secondary current and voltage is θ_2.
$Voltage\ regulation\ (\%) = \frac{E_2 - V_2}{V_2} \times 100(\%)$ $= \frac{I_2R_2\cos\theta_2 + I_2X_2\sin\theta_2}{V_2} \times 100(\%)$	$Voltage\ regulation\ (\%) = \frac{E_2 - V_2}{V_2} \times 100(\%)$ $= \frac{I_2R_2\cos\theta_2 - I_2X_2\sin\theta_2}{V_2} \times 100(\%)$

PRINCIPLES OF ENERGY CONSERVATION
It that **energy is neither be created or destroyed**, i.e. in an isolated system,
It is only transferred from one form to other.
Total energy before transformation =Total energy after transformation.

Examples of Energy Transformation
1. In an electric bulb, electrical energy is converted into light and heat energy.
2. In a microphone, sound energy is converted into electrical energy, while in a loudspeaker electrical energy is converted into sound energy.
3. In a hydroelectric plant water falls from a height on to a turbine causing it to turn. The turbine turns a coil in a magnetic field, thereby generating a electric current. Therefore, potential energy of the water is converted into kinetic energy of the turbine, which is converted into electrical energy.
4. In the sun, nuclear energy is converted into light and heat energy. The same occurs in all nuclear reactions in stars.
5. When a substance is heated, heat energy is converted into kinetic energy of the molecules. Part of the energy is used to do work during expansion.
6. When a current passes through a resistance, heat is generated. Thus, electrical energy is converted into heat energy, e.g. toasters, irons, geysers, etc.
7. In an electric motor, electrical energy is changed into mechanical energy.
8. In a generator or dynamo, mechanical energy is converted into electrical energy.

Einstein's mass energy relation E = mc2 Where	E = Energy produced, M = Mass converted to energy, called mass defect c = Velocity of light.

Conservation of Energy
Energy is defined as the capacity for doing work. It may exist in a variety of forms and may be transformed from one type of energy to another. **Energy transformations** constrained by **Conservation of Energy principle**. i.e. "Energy can neither be created nor destroyed". Another approach is to say that the total energy of an isolated system remains constant.



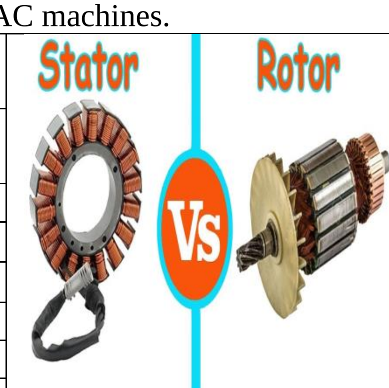
BASIC CONCEPTS OF ROTATING MACHINES

The transformer is a static device having primary and secondary windings.

In rotating machines, there are two parts: a. stator. b. rotor

Basis for Comparison	**Stator**	**Rotor**
Definition	It is a stationary part of the machine	It is the rotating part of the motor.
Parts	Outer frame, stator core and stator winding.	Rotor winding and Rotor core
Supply	Three-phase Supply	DC supply
Winding Arrangement	Complex	Easy
Insulation	Heavy	Less
Friction Loss	High	Low
Cooling	Easy	Difficult

Types of rotating electrical machines: a. DC machines. b. AC machines.

<table>
<tr><td rowspan="8">Electrical Machines Classification</td><td rowspan="2">DC Machines</td><td colspan="2">DC Generator</td><td rowspan="8">
</td></tr>
<tr><td colspan="2">DC Motor</td></tr>
<tr><td rowspan="6">AC Machines</td><td rowspan="2">Synchronous</td><td>1 Phase</td></tr>
<tr><td>3 Phase</td></tr>
<tr><td rowspan="2">Induction</td><td>1 Phase</td></tr>
<tr><td>3 Phase</td></tr>
<tr><td rowspan="2">Asynchronous</td><td>1 Phase</td></tr>
<tr><td>3 Phase</td></tr>
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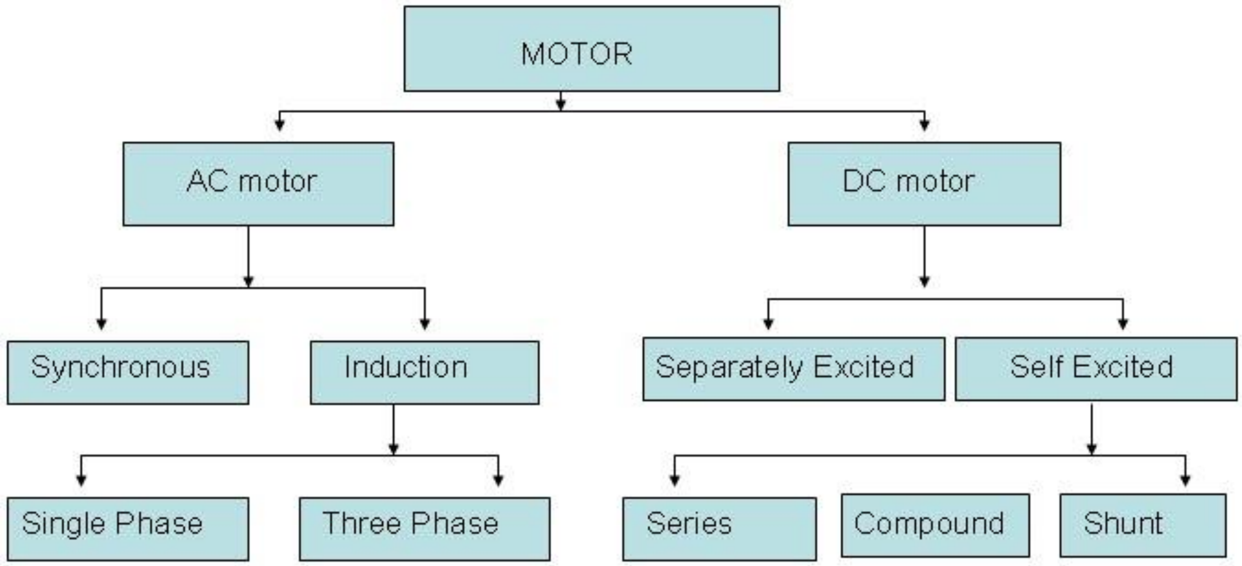
AC machine

AC machine is using the ac power supply for working of motor.

Types of electrical AC machine: 1. Induction motor. 2. Induction generator



Induction motor

Induction motors are also classified in the other types: (1) Single phase and (2) Three phase. Single phase induction motors have to winding on stator and on the rotor. The single phase ac supply is given to the stator of the single phase induction motor. The rotor is not feed by any source. Now by using the capacitor we can split the ac supply of the stator in to two different phases. So, there is rotating field is produced in around the stator. This flux is linked with the rotor and according to the principle of the electromagnetic induction the electricity is produced in the rotor that is induced power. This induced voltage will flow current in the rotor winding. So, the rotor magnetic field is produced. This magnetic field is in phase opposition of the stator flux. So, two different fluxes will cause opposite torque and by this means rotor start to rotate.

Induction generator

It is rotated by **some external mechanical torque**. The excitation is get from the stator. So, the rotor magnetic field is created and it is also rotating. So, this will induce the voltage.

DC machine

It uses the dc power supply for working of motor.
Types of electrical DC machine's: 1. DC motor. 2. DC generator.

DC Motor: It converts the electrical power input to the mechanical output.
It has two windings. Stator of the motor is having the field winding and rotor of the motor is having the armature winding.

Types of the dc motor
1. Self excited DC motor
In this type of Dc motor the field is energies by the supply of the armature winding. No other separate supply is need for the field excitation.

2. Separately excited DC motor
Here the field is energies by the supply of the armature winding. No other separate supply is need for the field excitation.
Series motor
Here the field winding is in series of the armature. So, this type of the motor is creating motor torque compare to the other motors. Starting torque of this type of motor is very high. This type of motor is used in the crane and in the elevator. This type of motor is never run on the no load condition. If it is running on no load condition then very high torque is produced in the motor and maybe there are chances to blast.
Shunt motor
Here the field winding is connected with the parallel of the armature. So, the load current is divided in the armature current and the field current. The torque of this type of motor is low as compare to the series motor.
Compound motor
Here the field winding is in shunt and as well as in the series of the armature winding. Now a day these types of motors are used in the industries.

DC Generator: It converts the mechanical power input to the electrical output.
In Dc generator the DC supply is given to the field winding and commutator. The commutator will do the reversal of the current so it will produce the AC current as same as the ac supply. The rotor is rotated by using some prime movers. So the rotating field is produce is link with the rotor and dc output is taken from the rotor by using commutator. In the case of the motor the commutator is convert dc supply to AC supply and by this means rotor of the DC motor is produce the rotating field. In the generator the generated ac current is rectified by the commutator.

TORQUE AND EMF ROTATING MACHINES
Torque: a force that tends to cause rotation.

Electromotive force (**EMF**)
It is a measurement of the energy that causes current to flow through a circuit. It can also be **defined** as the potential difference in charge between two points in a circuit. **Electromotive force** is also known as voltage, and it is measured in volts.

EMF Equation Of A DC Generator with parameters

P = number of field poles Ø = flux produced per pole in Wb (Weber) Z = total no. of armature conductors A = no. of parallel paths in armature N = rotational speed of armature in rpm.	**EMF=Eg = PΦNZ / 60A** The conductors are connected in series per parallel path, and the emf across the generator terminals is equal to the generated emf across any parallel path.

For simplex lap winding, number of parallel paths is equal to the number of poles (i.e. A=P),
Therefore, for simplex lap wound dc generator, **Eg = PΦNZ / 60P**
For simplex wave winding, number of parallel paths is equal to 2 (i.e P=2),
Therefore, for simplex wave wound dc generator, **Eg = PΦNZ / 120**

Torque Equation of A DC Motor
When armature conductors of a DC motor carry current in the presence of stator field flux, a mechanical torque is developed between the armature and the stator.

Torque T = Force (F) * Radius of the armature at which this force acts (r).

Work done by this force in once revolution = Force × distance = F × 2πr
(Where, 2πr = circumference of the armature)

Net power developed in the armature = word done / time
= (force × circumference × no. of revolutions) / time
= (F × 2πr × N) / 60 (Joules per second)

Net power developed in the armature = P = T × ω (Joules per second)

Armature Torque (Ta)	Shaft Torque (Tsh)
$T_a = (PZ / 2\pi A) \times \Phi . I_a$ (N-m)	Shaft torque of a DC motor = Tsh = output in watts / (2πN/60) ....(where, N is speed in RPM)
The term (PZ / 2πA) is practically constant for a DC machine. Thus, armature torque is directly proportional to the product of the flux and the armature current i.e. $T_a \propto \Phi . I_a$	Due to iron and friction **losses in a dc machine,** the total developed armature torque is not available at the shaft of the machine. Some torque is lost, and therefore, shaft torque is always less than the armature torque.

DC MACHINE
Each DC machine can **act as a generator / motor. DC machines Classified into 2types based of their field excitation method**. **1. Separately excited. 2. Self-excited.**

Separately excited DC machine
Here the **field winding is electrically separated** from the **armature circuit.**
They require additional power source / circuitry. self-excited DC generators are unsatisfactory. In this type, the stator field flux may also be provided with the help of permanent magnets (such as in **permanent magnet DC motors)**. PMDC (permanent magnet DC) motors are popularly used in small toys, e.g. a toy car.

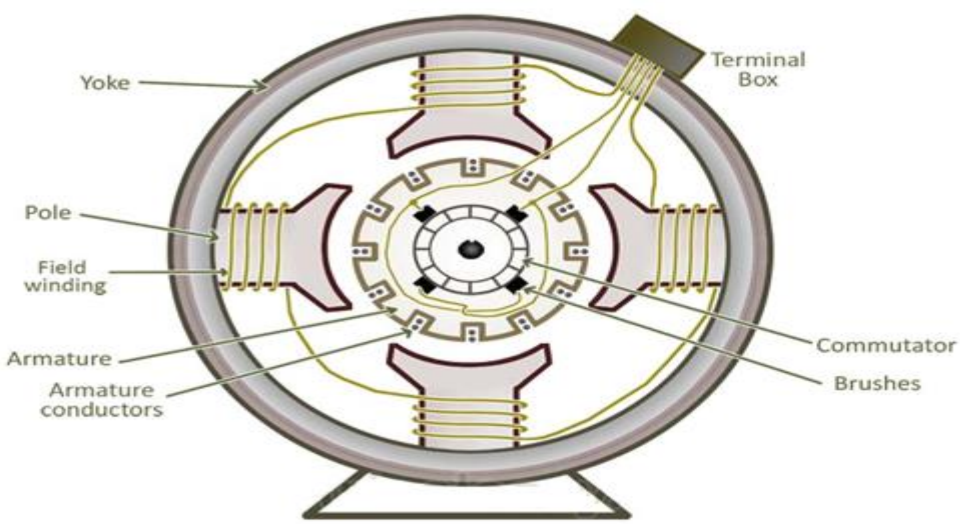
Self-excited DC machines
1. Here **field winding and armature winding** are **interconnected** in various ways to achieve a wide range of performance characteristics (Example, field winding in series or parallel with the armature winding).
2. In a **self-excited type of DC generator**, the field winding is energized by the current produced by themselves. A small amount of flux is always present in the poles due to the residual magnetism. So, initially, current induces in the armature conductors of a dc generator only due to the residual magnetism. The field flux gradually increases as the induced current starts flowing through the field winding.

Types of Self-excited machines
1. Series wound dc machines – Here the field **winding is connected in series with the armature winding.** Therefore, the field winding carries whole of the load current (armature current). That is why series winding is designed with few turns of thick wire and the resistance is kept very low (about 0.5 Ohm).
2. Shunt wound dc machines – Here the **field winding is connected in parallel with the armature winding.** Hence, the full voltage is applied across the field winding. Shunt winding is made with a large number of turns and the resistance is kept very high (about 100 Ohm). It takes only small current which is less than 5% of the rated armature current.
3. Compound wound dc machines – Here there are two sets of field winding. **One is connected in series** and the **other** is connected in **parallel with the armature winding.**

Types of Compound wound machines
1. Short shunt – field winding is connected in parallel with only the armature winding
2. Long shunt – field winding is connected in parallel with the combination of series field winding and armature winding.

DC Generator
It **converts mechanical energy** into **direct current electricity**. This energy conversion is based on the principle of production of dynamically induced emf.

Construction Of A DC Machine
A DC generator can be used as a DC motor without any constructional changes and vice versa is also possible. Thus, DC **generator / motor/machine.** These basic constructional details are also valid for the **construction of a DC motor**.



4-pole DC machine.

A DC machine consists of two basic parts; stator and rotor.
Basic constructional parts of a DC machine

1. Yoke: The outer frame of a dc machine is called as yoke. It is made up of cast iron or steel. It not only provides mechanical strength to the whole assembly but also carries the magnetic flux produced by the field winding.
2. Poles and pole shoes: Poles are joined to the yoke with the help of bolts or welding. They carry field winding and pole shoes are fastened to them. Pole shoes serve two purposes; (i) they support field coils and (ii) spread out the flux in air gap uniformly.
3. Field winding: They are usually made of copper. Field coils are former wound and placed on each pole and are connected in series. They are wound in such a way that, when energized, they form alternate North and South poles.

Armature core (rotor)

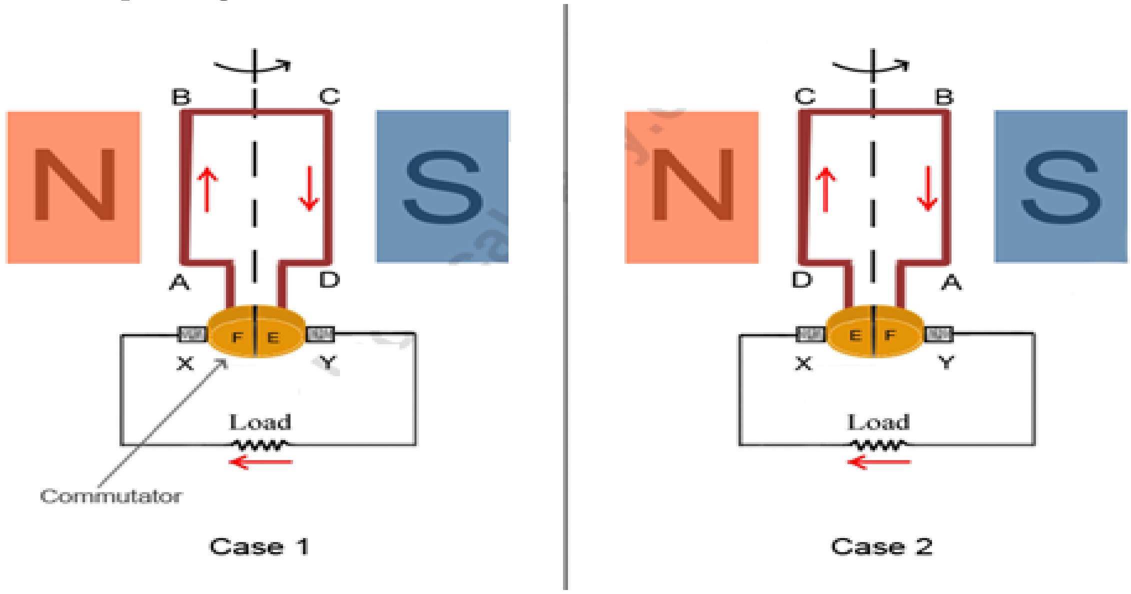
4. Armature core: Armature core is the rotor of a dc machine. It is cylindrical in shape with slots to carry armature winding. The armature is built up of thin laminated circular steel disks for reducing eddy current losses. It may be provided with air ducts for the axial air flow for cooling purposes. Armature is keyed to the shaft.
5. Armature winding: It is usually a former wound copper coil which rests in armature slots. The armature conductors are insulated from each other and also from the armature core. Armature winding can be wound by one of the two methods; lap winding or wave winding. Double layer lap or wave windings are generally used. A double layer winding means that each armature slot will carry two different coils.
6. Commutator and brushes: Physical connection to the armature winding is made through a commutator-brush arrangement. The function of a commutator, in a dc generator, is to collect the current generated in armature conductors. Whereas, in case of a dc motor, commutator helps in providing current to the armature conductors. A commutator consists of a set of copper segments which are insulated from each other. The number of segments is equal to the number of armature coils. Each segment is connected to an armature coil and the commutator is keyed to the shaft. Brushes are usually made from carbon or graphite. They rest on commutator segments and slide on the segments when the commutator rotates keeping the physical contact to collect or supply the current.

COMMUTATOR

Working Principle of A DC Generator:

According to Faraday's laws of electromagnetic induction, whenever a conductor is placed in a varying magnetic field (OR a conductor is moved in a magnetic field), an emf (electromotive force) gets induced in the conductor. The magnitude of induced emf can be calculated from the emf equation of dc generator. If the conductor is provided with a closed path, the induced current will circulate within the path. In a DC generator, field coils produce an electromagnetic field and the armature conductors are rotated into the field. Thus, an electromagnetically induced emf is generated in the armature conductors. The direction of induced current is given by Fleming's right hand rule.

Need of a Split ring commutator



According to Fleming's right hand rule, the direction of induced current changes whenever the direction of motion of the conductor changes. Let's consider an armature rotating clockwise and a conductor at the left is moving upward. When the armature completes a half rotation, the direction of motion of that particular conductor will be reversed to downward. Hence, the direction of current in every armature conductor will be alternating. If you look at the above figure, you will know how the direction of the induced current is alternating in an armature conductor. But with a split ring commutator, connections of the armature conductors also get reversed when the current reversal occurs. And therefore, we get unidirectional current at the terminals.

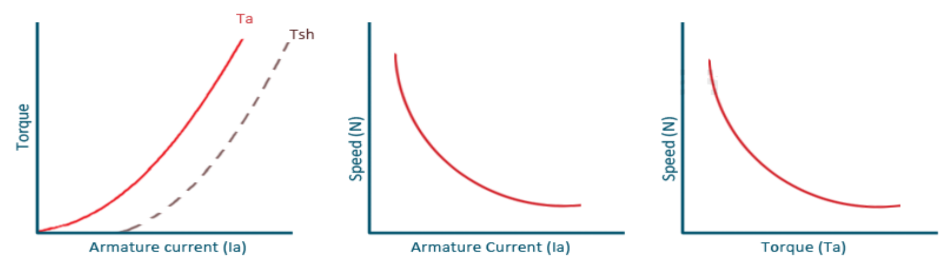
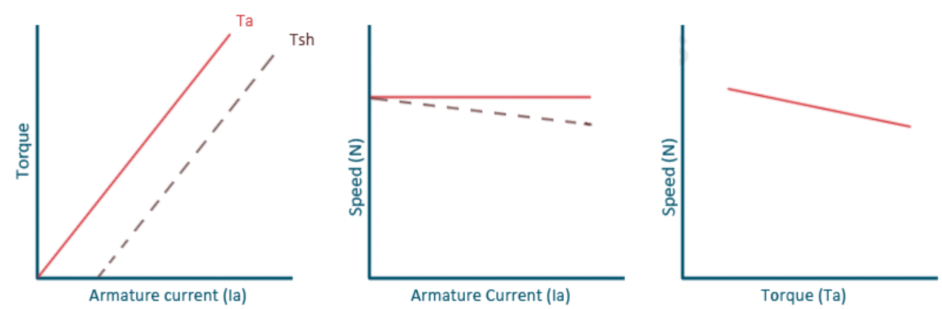
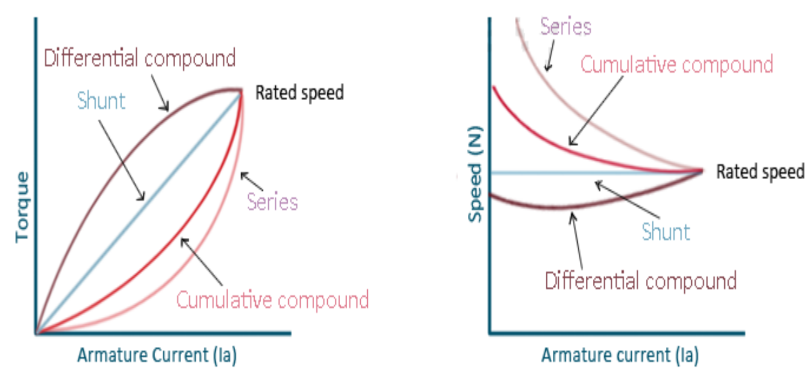
CHARACTERISTICS OF SERIES, SHUNT AND COMPOUND MOTORS AND GENERATORS

Characteristics of DC Motors

Generally, three characteristic curves are considered important for **DC motors** which are,
1. Torque vs. armature current.
2. Speed vs. armature current.
3. Speed vs. torque.

These characteristics are determined by keeping the following two relations in mind.
$\mathbf{T_a \propto \phi . I_a}$ and $\mathbf{N \propto E_b / \phi}$

These above equations can be studied at - emf and torque equation of dc machine. For a DC motor, magnitude of the back emf is given by the same emf equation of a dc generator i.e. $E_b = P\phi NZ / 60A$. For a machine, P, Z and A are constant, therefore, $N \propto E_b/\phi$

 Characteristics of DC series motor	Torque is directly proportional to the product of armature current and field flux, $T_a \propto \phi.I_a$.
 Characteristics of DC shunt motor	$N \propto E_b/\phi$
 Characteristics of DC compound motor	

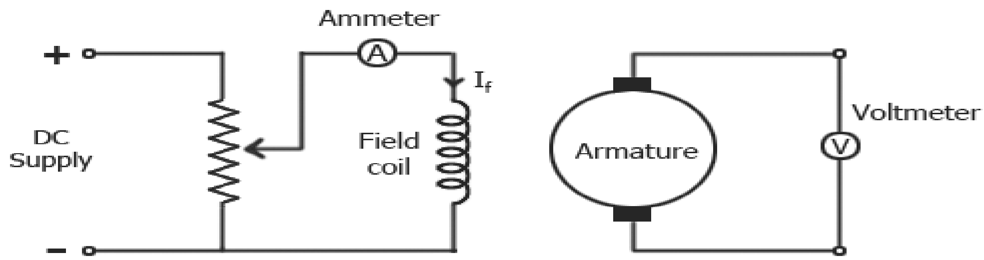
3 Characteristics of DC Generators

1. Open Circuit Characteristic (O.C.C.).
2. Internal or Total Characteristic.
3. External Characteristic.

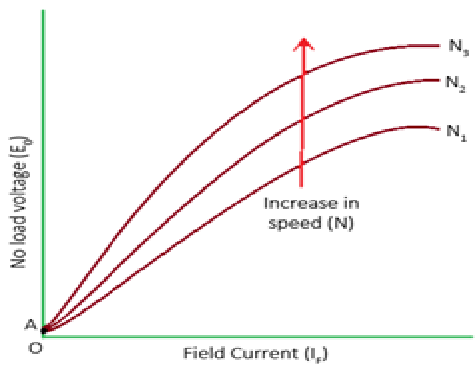
Open Circuit Characteristic (O.C.C.) (E_0/I_f)

It is also known as **magnetic characteristic** or **no-load saturation characteristic**.

It shows the relation between generated **emf at no load (E_0) and the field current (I_f)** at a given fixed speed. The O.C.C. curve is just the magnetization curve and it is practically similar for all type of generators. The data for O.C.C. curve is obtained by **operating the generator at no load and keeping a constant speed.** Field current is gradually increased and the corresponding terminal voltage is recorded. The connection arrangement to obtain O.C.C. curve is as shown in the figure below. For shunt or series excited generators, the field winding is disconnected from the machine and connected across an external supply.



EMF equation of dc generator= Eg = kϕ. Hence, the generated emf should be directly proportional to field flux (and hence, also directly proportional to the field current). However, even when the field current is zero, some amount of emf is generated (represented by OA in the figure below). This initially induced emf is due to the fact that there exists some residual magnetism in the field poles. Due to the residual magnetism, a small initial emf is induced in the armature. This initially induced emf aids the existing residual flux, and hence, increasing the overall field flux. This consequently increases the induced emf. Thus, O.C.C. follows a straight line. However, as the flux density increases, the poles get saturated and the ϕ becomes practically constant. Thus, even we increase the I_f further, ϕ remains constant and hence, Eg also remains constant.



Open Circuit Characteristic (O.C.C.)

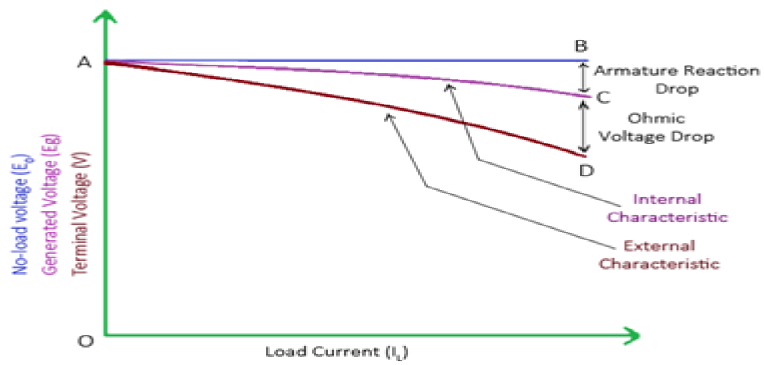
Internal Or Total Characteristic (E/I_a)

It shows the relation between the on-load generated emf (Eg) and the armature current (I_a). The on-load generated emf Eg is always less than E_0 due to the armature reaction. Eg can be determined by subtracting the drop due to demagnetizing effect of armature reaction from no-load voltage E_0. Therefore, internal characteristic curve lies below the O.C.C. curve.

3. External Characteristic (V/I_L)

It shows the relation between terminal voltage (V) and the load current (I_L). Terminal voltage V is less than the generated emf Eg due to voltage drop in the armature circuit. Therefore, external characteristic curve lies below the internal characteristic curve. External characteristics are very important to determine the suitability of a generator for a given purpose. Therefore, this type of characteristic is sometimes also called as **performance characteristic** or **load characteristic**. Internal and external characteristic curves are shown below for each **type of generator.**

Characteristics of Separately Excited DC Generator

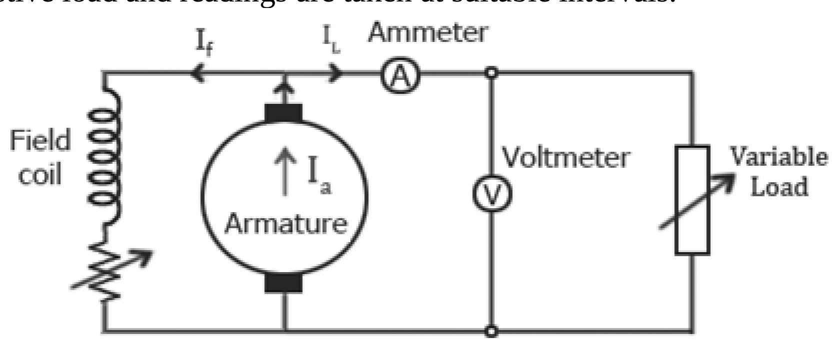


Characteristics of separately excited DC generator

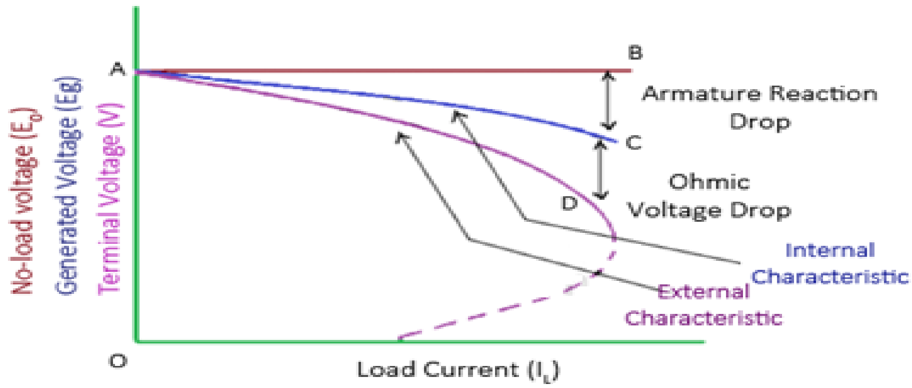
If there is no armature reaction and armature voltage drop, the voltage will remain constant for any load current. Thus, the straight line AB in above figure represents the no-load voltage vs. load current I_L. Due to the demagnetizing effect of **armature reaction,** the on-load generated emf is less than the no-load voltage. The curve AC represents the on-load generated emf Eg vs. load current I_Li.e. internal characteristic (as $I_a = I_L$ for a separately excited dc generator). Also, the terminal voltage is lesser due to ohmic drop occurring in the armature and brushes. The curve AD represents the terminal voltage vs. load current i.e. external characteristic.

Characteristics Of DC Shunt Generator

To determine the internal and external load characteristics of a DC shunt generator the machine is allowed to build up its voltage before applying any external load. To build up voltage of a shunt generator, the generator is driven at the rated speed by a prime mover. Initial voltage is induced due to residual magnetism in the field poles. The generator builds up its voltage as explained by the O.C.C. curve. When the generator has built up the voltage, it is gradually loaded with resistive load and readings are taken at suitable intervals.



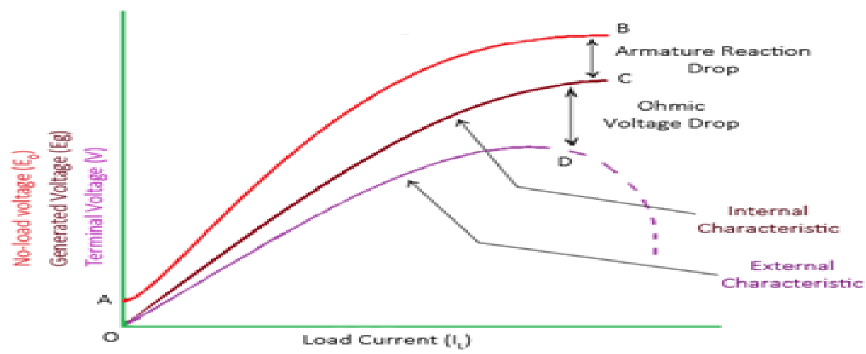
Unlike, separately excited DC generator, here, $I_L \neq I_a$. For a shunt generator, $I_a=I_L+I_f$. Hence, the internal characteristic can be easily transmitted to Eg vs. I_L by subtracting the correct value of $I_f$from I_a.



Characteristics of DC shunt generator

During a normal running condition, when load resistance is decreased, the load current increases. But, as we go on decreasing the load resistance, terminal voltage also falls. So, load resistance can be decreased up to a certain limit, after which the terminal voltage drastically decreases due to excessive armature reaction at very high armature current and increased I^2R losses. Hence, beyond this limit any further decrease in load resistance results in decreasing load current.

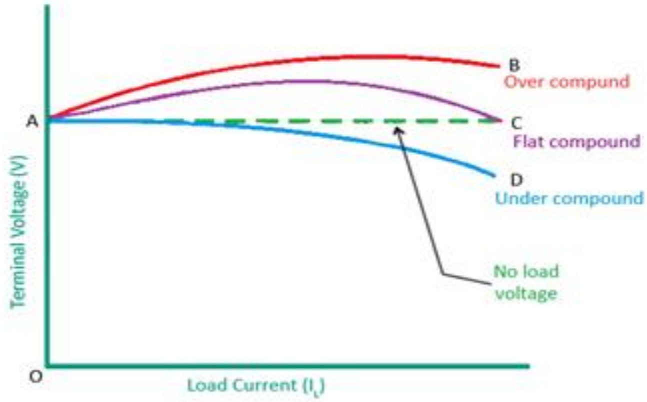
Characteristics of DC Series Generator



Characteristics of DC series generator

The curve AB in above figure identical to open circuit characteristic (O.C.C.) curve. This is because in DC series generators field winding is connected in series with armature and load. Hence, here load current is similar to field current (i.e. I_L=I_f). The curve OC and OD represent internal and external characteristic respectively. In a DC series generator, terminal voltage increases with the load current. This is because, as the load current increases, field current also increases. However, beyond a certain limit, terminal voltage starts decreasing with increase in load. This is due to excessive demagnetizing effects of the armature reaction.

Characteristics Of DC Compound Generator



External characteristic of DC compound generator

If series winding amp-turns are adjusted so that, increase in load current causes increase in terminal voltage then the generator is called to be over compounded. The external characteristic for over compounded generator is shown by the curve AB in above figure.
If series winding amp-turns are adjusted so that, the terminal voltage remains constant even the load current is increased, then the generator is called to be flat compounded. The external characteristic for a flat compounded generator is shown by the curve AC.
If the series winding has lesser number of turns than that would be required to be flat compounded, then the generator is called to be under compounded.

BASIC PRINCIPLES OF OPERATION SYNCHRONOUS AND INDUCTION MACHINES

Synchronous Machine

It constitutes of **both synchronous motors as well as synchronous generators.** An AC system has some advantages over DC system. Therefore, the AC system is exclusively used for generation, transmission and distribution of electric power. The machine which converts mechanical power into AC electrical power is called as **Synchronous Generator / Alternator**. However, if the same machine can be operated as a motor is known as **Synchronous Motor.**
A synchronous machine is an AC machine whose satisfactory operation depends upon the maintenance of the following relationship.

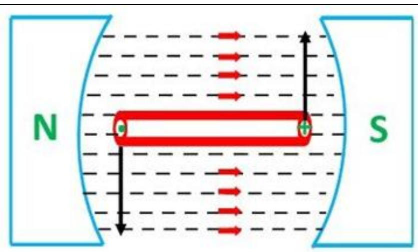
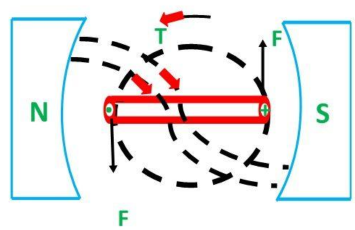
$N_s = \frac{120f}{P}$ $f = \frac{PN_s}{120}$	Where, N_s = synchronous speed in r.p.m f = supply frequency P = the number of poles of the machine.

When connected to an electric power system, a synchronous machine always maintains the above relationship shown in the equation (1). If the synchronous machine working as a motor fails to maintain the average speed (N_s) the machine will not develop sufficient torque to maintain its rotation and will stop. Then the motor is said to be **Pulled Out of Step.**

In case, when the synchronous machine is operating as a generator, it has to run at a fixed speed called Synchronous speed to generate the power at a particular frequency. As all the appliances or machines are designed to operate at this frequency. In some countries, the value of the frequency is 50 hertz.

Basic Principles of Synchronous Machine

A synchronous machine is an electromechanical transducer which **converts mechanical energy into electrical energy or vice versa.** The law which makes these conversions possible are known as the **Law of Electromagnetic Induction** and **Law of interaction.**

Law of Electro-Magnetic Induction or Faraday's First Law	**Law of Interaction**
It relates to the production of emf, i.e.; emf is induced in a conductor cuts across the magnetic field.	It relates to the **production of force / torque,** i.e., whenever a current carrying conductor is placed in the magnetic field, by the interaction of the magnetic field produced by the current carrying conductor and the main field, force is exerted on the conductor producing torque.
	

In a small synchronous machine: the fielding winding is placed on the stator, and the armature winding is placed on the rotor.
In large synchronous machine: the field winding is placed on the rotor, and the armature winding is placed on the stator.

Difference between Induction Motor and Synchronous Motor

They are explained with various factors, like the type of excitation used for the machine. The Speed of the motor, starting and operation, the efficiency of both the motors, its cost, usage, applications and frequency.

Property	**SYNCHRONOUS MOTOR**	**INDUCTION MOTOR**
Type of Excitation	A synchronous motor is a doubly excited machine.	An induction motor is a single excited machine.
Supply System	Its armature winding is energized from an AC source and its field winding from a DC source.	Its stator winding is energized from an AC source.
Speed	It always runs at synchronous speed. The speed is independent of load.	If the load increased the speed of the induction motor decreases. It is always less than the synchronous speed.
Starting	It is not self starting. It has to be run up to synchronous speed by any means before it can be synchronized to AC	Induction motor has self starting torque.

	supply.	
Operation	A synchronous motor can be operated with lagging and leading power by changing its excitation.	An induction motor operates only at a lagging power factor. At high loads the power factor becomes very poor.
Usage	It can be used for power factor correction in addition to supplying torque to drive mechanical loads.	An induction motor is used for driving mechanical loads only.
Efficiency	It is more efficient than an induction motor of the same output and voltage rating.	Its efficiency is lesser than that of the synchronous motor of the same output and the voltage rating.
Cost	A synchronous motor is costlier than an induction motor of the same output and voltage rating	An induction motor is cheaper than the synchronous motor of the same output and voltage rating.

Induction Motor /Asynchronous Motor so called because it never runs at synchronous speed. i.e., $N_s = 120f/P$. The induction motor is most widely used motor in all domestic and commercial motor. The Synchronous motor always follows a synchronous speed. The speed of the rotor is maintained or synchronized with the supply current

Difference between Three Phase Induction Motor and Synchronous Motor

- A three phase Synchronous motor is a doubly excited machine, whereas an induction motor is a single excited machine.
- The armature winding of the Synchronous motor is energized from an AC source and its field winding from a DC source. The stator winding of Induction Motor is energized from an AC source.
- Synchronous Motor always runs at synchronous speed, and the speed of the motor is independent of load, but an induction motor always runs less than the synchronous speed. If the load increased the speed of the induction motor decreases.
- The **induction motor** has **self-starting torque** whereas the synchronous motor is not self starting. It has to be run up to synchronous speed by any means before it can be synchronized to AC supply.
- A **synchronous motor** can be operated with **lagging and leading power** by changing its excitation. An **induction motor** operates only at a **lagging power factor**. At high loads, the power factor of the induction motor becomes very poor.
- The Synchronous Motor can be used for **power factor correction** in addition to the supplying torque to drive mechanical loads whereas an **induction motor** is used **for driving mechanical loads** only.
- The synchronous motor is **more efficient** than an induction motor of the same output and voltage rating.
- A synchronous motor is **costlier** than an induction motor of the same output and voltage rating.

STARTING OF INDUCTION MOTOR

Different starting methods are employed for starting induction motors because they draw more starting current during starting. To prevent damage to the windings due to the high starting current flow, we employ different types of starters.

Introduction

Most large induction motors are started directly on line, but when very large motors are started that way, they cause a disturbance of voltage on the supply lines due to large starting current surges. To limit the starting current surge, large induction motors are started at reduced voltage and then have full supply voltage reconnected when they run up to near rotated speed.

Two methods of reduced voltage starting are star delta starting and autotransformer stating. Contactors perform the switching action in the starter to connect and disconnect the power supply to the motor. If the current is above the rated current for the motor, the contactor will be tripped automatically to disconnect the motor from the supply.

A three phase supply is given to the stator of the three phase induction motor, and this in turn produces a magnetic field which revolves in space around the stator. As if the magnetic poles are being rotated, the speed of the rotating magnetic field is given by

$N = 120\ f\ /P$

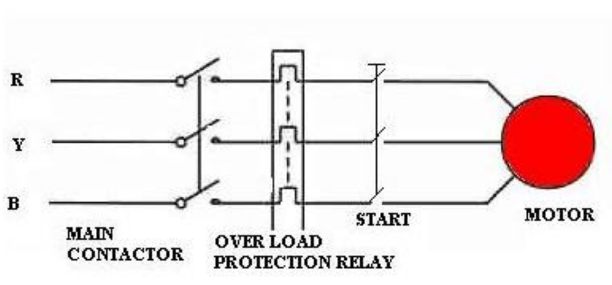
Starting Principle

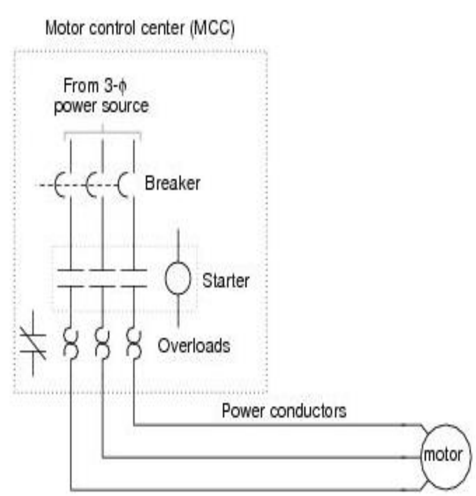
The high starting current will produce severe a voltage drop and will affect the operation of other equipment. It is not desirable to start large motors direct on line (giving full voltage to the stator). Normally with motors beyond 5 HP, starters are provided. For reduction in the starting current, a lower voltage is applied to the stator, especially for the squirrel cage induction motors. Full voltage is only applied when the motor picks up speed.

Starting methods of Induction motor include:

1. Direct –On– line (DOL) starters for less than 10 Kw motors.
2. Star–Delta starters for large motors. The stator winding is initially connected in a star configuration and later on changed over to a Delta connection, when the motor reaches rated speed.
3. Auto transformer.

1. Direct On Line Starter

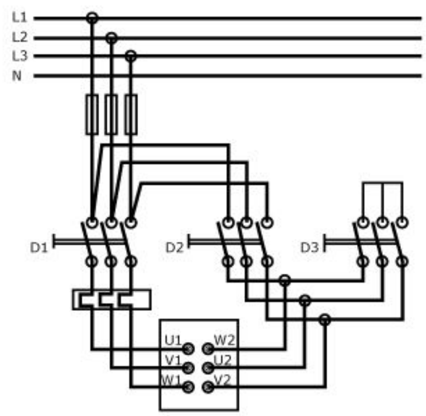




1. It is simple and cheap starter for a 3-phase induction motor.
2. The contacts close against spring action.
3. This method is normally limited to smaller cage induction motors, because starting current can be as high as eight times the full load current of the motor. Use of a double –cage rotor requires lower staring current(approximately four times) and use of quick acting A.V.R enables motors of 75 Kw and above to be started direct on line.

4. An isolator is required to isolate the starter from the supply for maintenance.
5. Protection must be provided for the motor. Some of the safety protections are over-current protection, under-voltage protection, short circuit protection, etc. Control circuit voltage is sometimes stepped down through an autotransformer.

2. Star-Delta Starter



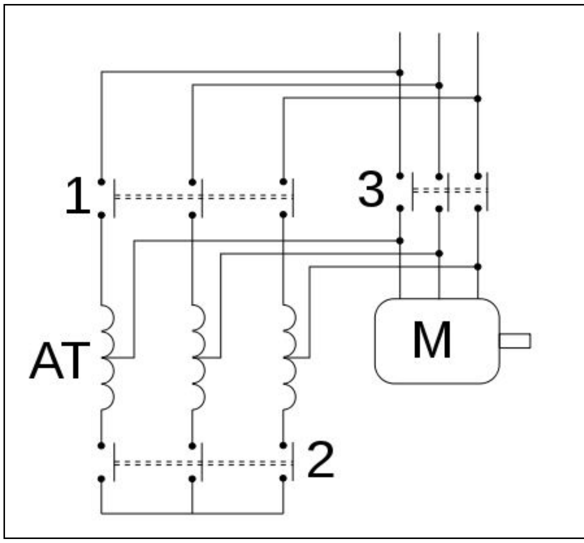
A three phase motor will give three times the power output when the stator windings are connected in delta than if connected in star, but will take 1/3 of the current from the supply when connected in star than when connected in delta. The starting torque developed in star is ½ that when starting in delta.

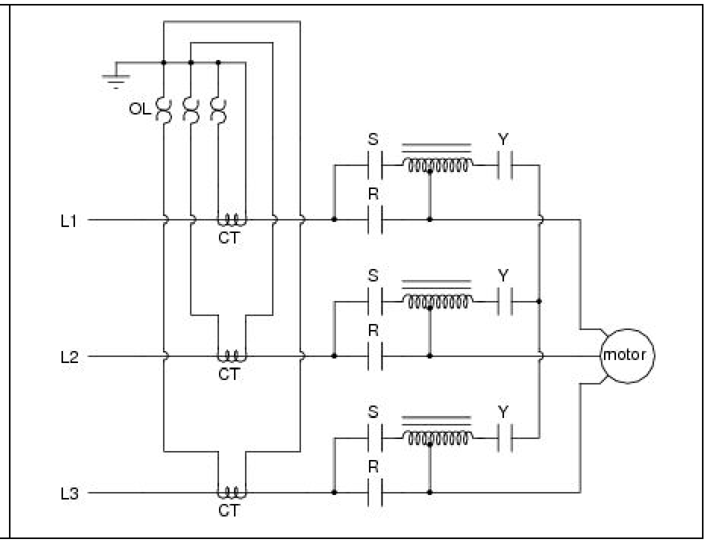
1. A two-position switch (manual or automatic) is provided through a timing relay.
2. Starting in star reduces the starting current.
3. When the motor has accelerated up to speed and the current is reduced to its normal value, the starter is moved to run position with the windings now connected in delta.
4. More complicated than the DOL starter, a motor with a star-delta starter may not produce sufficient torque to start against full load, so output is reduced in the start position. The motors are thus normally started under a light load condition.
5. Switching causes a transient current which may have peak values in excess of those with DOL.

3. Auto Transformer Motor Starting

6. Operated by a two position switch i.e. manually / automatically using a timer to change over from start to run position.
7. In starting position supply is connected to stator windings through an auto-transformer which reduces applied voltage to 50, 60, and 70% of normal value depending on tapping used.

8. Reduced voltage reduces current in motor windings with 50% tapping used motor current is halved and supply current will be half of the motor current. Thus starting current taken from supply will only be 25% of the taken by DOL starter.
9. For an induction motor, torque T is developed by V2, thus on 50% tapping, torque at starting is only $(0.5V)^2$ of the obtained by DOL starting. Hence 25% torque is produced.
10. Starters used in lager industries, it is larger in size and expensive.
11. Switching from start to run positions causing transient current, which can be greater in value than those obtained by DOL starting.





4. Rotor Resistance Starter

1. This starter is used with a wound rotor induction motor. It uses an external resistance/phase in the rotor circuit so that rotor will develop a high value of torque.
2. High torque is produced at low speeds, when the external resistance is at its higher value.
3. At start, supply power is connected to stator through a three pole contactor and, at a same time, an external rotor resistance is added.
4. The high resistance limits staring current and allows the motor to start safely against high load.
5. Resistors are normally of the wire-wound type, connected through brushes and slip rings to each rotor phase. They are tapped with points brought out to fixed contactors.
6. As the motor starts, the external rotor resistance is gradually cut out of circuit ; the handle or starter is turned and moves the three contacts simultaneously from one fixed contact to the next.
7. The three moving contacts are interconnected to form a start point for the resistors.
8. To ensure that the motor cannot be started until all rotor resistance is in circuit, an interlock is fitted which prevents the contactors from being closed until this condition is fulfilled.

Regulation of synchronous generator by synchronous impedance method
Synchronous Impedance Method or Emf Method

It is based on the concept of **replacing the effect of armature reaction** by **an imaginary reactance.** For calculating the regulation, the synchronous method requires the following data; they are the armature resistance per phase and the open circuit characteristic. The open circuit characteristic is the graph of the circuit voltage and the field current. This method also requires short circuit characteristic which is the graph of the short circuit and the field current.

Contents:

- DC resistance test
- Open Circuit Test
- Short Circuit Test
- Calculation of Synchronous Impedance
- Assumptions in the Synchronous Impedance Method

For a synchronous generator following are the equation given below

$$V = E_a - Z_s I_a$$

$$Z_s = R_a + jX_s$$

For calculating the synchronous impedance, Z_s is measured, and then the value of E_a is calculated. From the values of E_a and V, the voltage regulation is calculated.

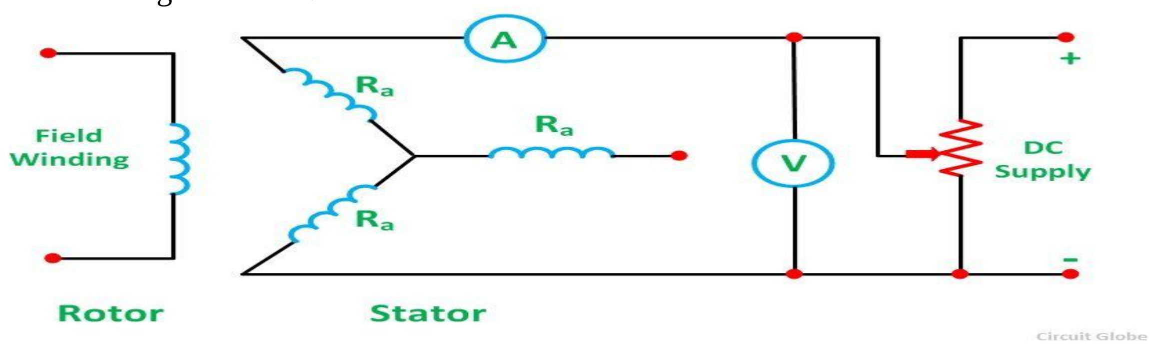
Measurement of Synchronous Impedance

It is done by the following methods. They are known as

1. DC resistance test. 2. Open circuit test 3.Short circuit test

DC resistance test

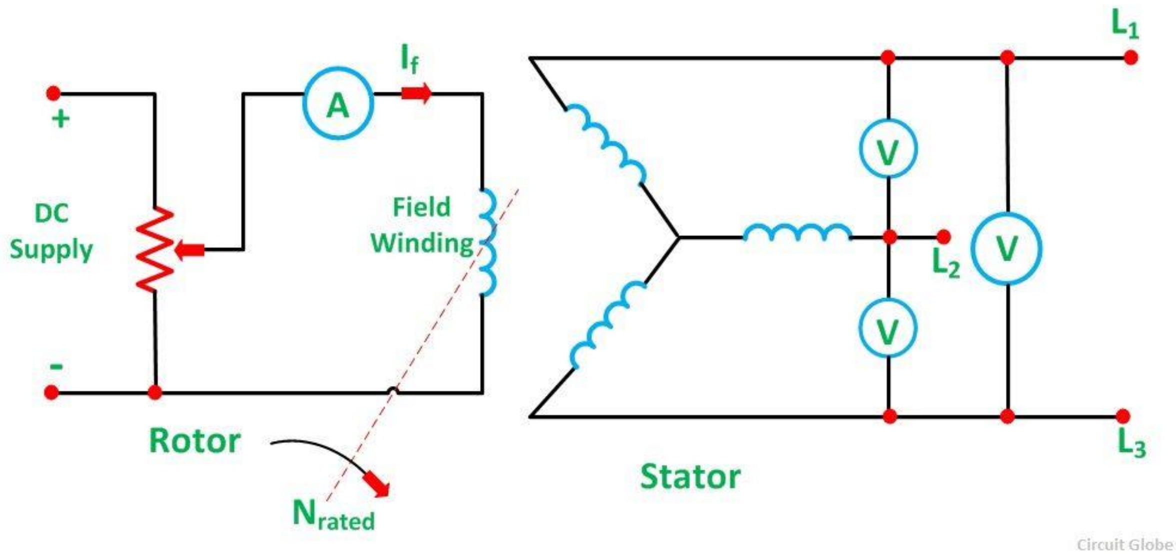
Here it is assumed that the alternator is star connected with the DC field winding open as shown in the circuit diagram below.



It measures the DC resistance between each pair of terminals either by using an ammeter – voltmeter method or by using the Wheatstone's bridge. The average of three sets of resistance value R_t is taken. The value of R_t is divided by 2 to obtain a value of DC resistance per phase. Since the effective AC resistance is larger than the DC resistance due to skin effect. Therefore, the effective AC resistance per phase is obtained by multiplying the DC resistance by a factor 1.20 to 1.75 depending on the size of the machine. A typical value to use in the calculation would be 1.25.

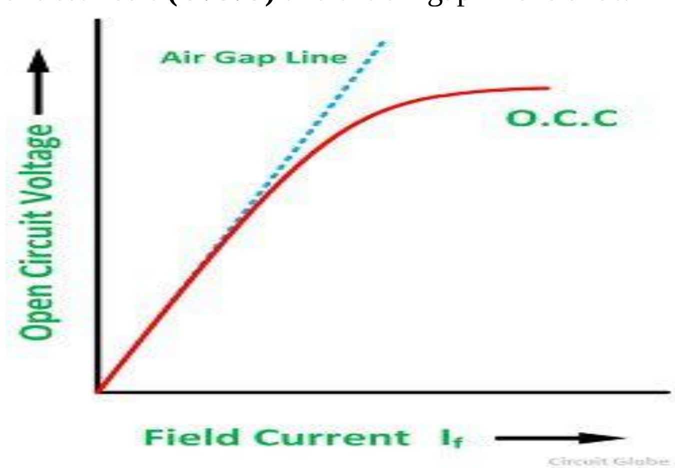
Open Circuit Test

It determines the synchronous impedance, the alternator is running at the rated synchronous speed, and the load terminals are kept open. This means that the loads are disconnected, and the field current is set to zero. The circuit diagram is shown below.



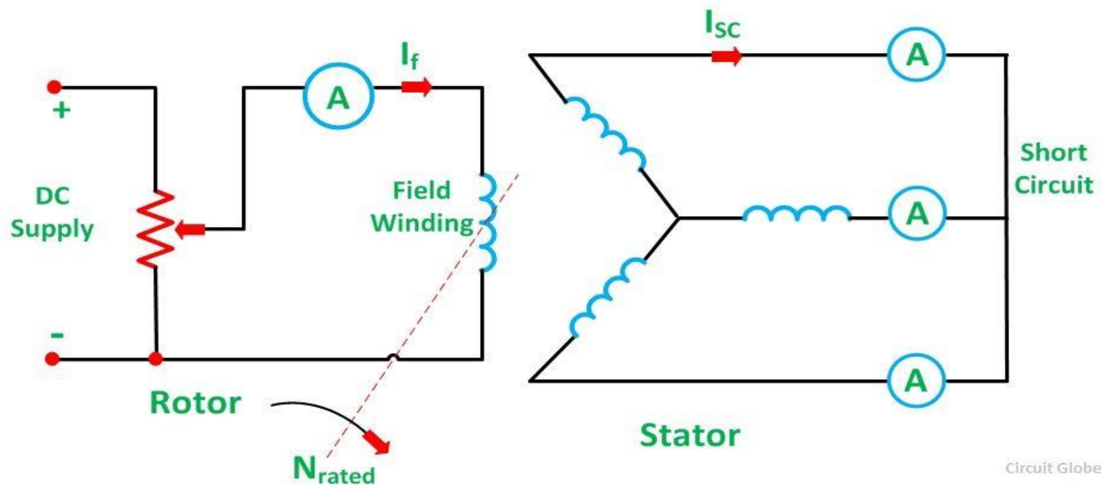
After setting the field current to zero, the field current is gradually increased step by step. The terminal voltage E_t is measured at each step. The excitation current may be increased to get 25% more than the rated voltage. A graph is drawn between the open circuit phase voltage $E_p = E_t/\sqrt{3}$ and the field current I_f. The curve so obtains called Open Circuit Characteristic (O.C.C). The shape is same as normal magnetisation curve. The linear portion of the O.C.C is extended to form an air gap line.

The **Open Circuit Characteristic (O.C.C)** and the air gap line is shown in the figure below.



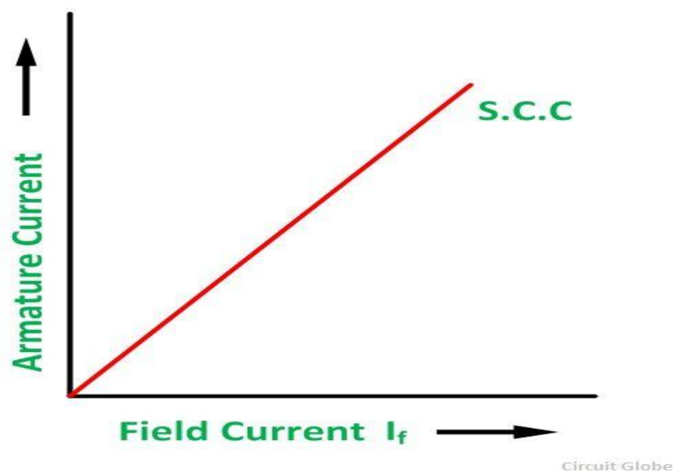
Short Circuit Test

Here the armature terminals are shorted through three ammeters as shown in the figure below.



The field current should first be decreased to zero before starting the alternator. Each ammeter should have a range greater than the rated full load value. The alternator is then run at synchronous speed. Same as in an open circuit test that the field current is increased gradually in steps and the armature current is measured at each step. The field current is increased to get armature currents up to 150% of the rated value.

The value of field current If and the average of three ammeter readings at each step is taken. A graph is plotted between the armature current Ia and the field current If. The characteristic so obtained is called **Short Circuit Characteristic (S.C.C)**.



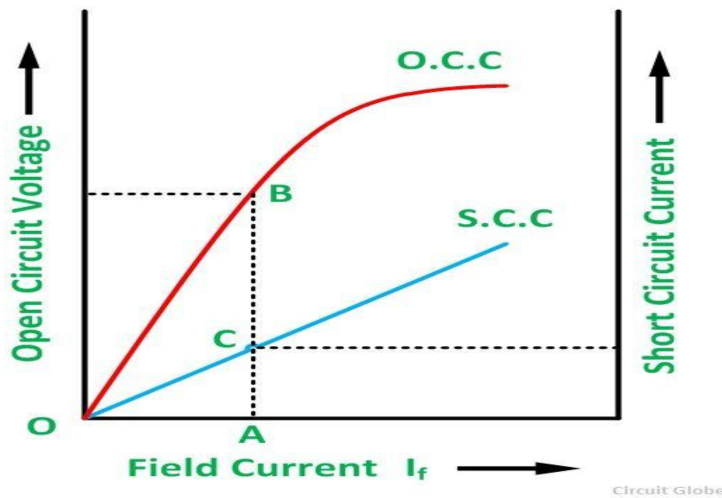
Steps for Calculation of Synchronous Impedance

- The open circuit characteristics and the short circuit characteristic are drawn on the same curve.
- Determine the value of short circuit current I_{sc} and gives the rated alternator voltage per phase.
- The synchronous impedance Z_S will then be equal to the open circuit voltage divided by the short circuit current at that field current which gives the rated EMF per phase.

$$Z_S = \frac{\text{Open circuit voltgae per phase}}{\text{Short circuit armature current}} \quad \text{(for the same value of field current)}$$

The synchronous reactance is determined as

$$X_S = \sqrt{Z_S^2 - R_a^2}$$



From the above figure consider the field current I_f = OA that produces rated alternator voltage per phase. Corresponding to this field current, the open circuit voltage is AB

$$Z_S = \frac{AB \text{ (in volts)}}{AC \text{ (in amperes)}}$$

Assumptions in the Synchronous Impedance Method

The following assumptions made in the synchronous Impedance Method are given below.

- The synchronous Impedance is constant
  The synchronous impedance is determined from the **O.C.C** and **S.C.C**. It is the ratio of the open circuit voltage to the short circuit current. When the O.C.C and S.C.C are linear, the **synchronous impedance** Z_S is **constant**.
- The flux under test conditions is the same as that under load conditions.
  It is assumed that a given value of the field current always produces the same flux. This assumption introduces considerable error. When the armature is short circuited, the current in the armature lag the generated voltage by almost 90 degrees, and hence the armature reaction is almost completely demagnetizing.
- The effect of the armature reaction flux can be replaced by a voltage drop proportional to the armature current and that the armature reaction voltage drop is added to the armature reactance voltage drop.
- The magnetic reluctance to the armature flux is constant regardless of the power factor.
  For a cylindrical rotor machine, this assumption is substantially true because of the uniform air gap. Regulation obtained by using a synchronous impedance method is higher than that obtained by actual loading. Hence, this method is also called the **Pessimistic method.**
  At lower excitations, **Z_S** is **constant**, since the open circuit characteristics coincide with the air gap line. This value of Z_S is called the **linear** or **Unsaturated Synchronous Impedance**. However, with increasing excitation, the effect of saturation is to decrease Z_S and the values

beyond the linear part of the open circuit called as **Saturated Value** of the Synchronous Impedance.

Single phase induction and commutator machine
Single Phase Induction Motor
We use the single-phase power system more widely than **three phase system** for domestic purposes, commercial purposes and some extent in industrial uses. Because, the single-phase system is more economical than a three-phase system and the power requirement in most of the houses, shops, offices are small, which can be easily met by single phase system. The single phase motors are simple in construction, cheap in cost, reliable and easy to repair and maintain. Due to all these advantages, the single phase motor finds its application in vacuum cleaners, fans, washing machines, centrifugal pumps, blowers, washing machines, etc.

The single phase AC motors are further classified as:
1. **Single phase induction motors** or **asynchronous motors**.
2. Single phase synchronous motors.
3. Commutator motors.

Construction of Single Phase Induction Motor
Electrical motor asynchronous motor also have two main parts namely rotor and stator. Stator: As its name indicates stator is a stationary part of **induction motor.** A single phase AC supply is given to the stator of single phase induction motor.
Rotor: The rotor is a rotating part of an induction motor. The rotor connects the mechanical load through the shaft. The rotor in single phase induction motor is of squirrel cage rotor type. The **construction of single phase induction motor** is almost similar to the squirrel cage three-phase induction motor. But in case of a single phase induction motor, the stator has two windings instead of one three-phase winding in **three phase induction motor.**
Stator of Single Phase Induction Motor
The stator of the single phase induction motor has laminated stamping to reduce **eddy current** losses on its periphery. The slots are provided on its stamping to carry stator or main winding. Stampings are made up of silicon steel to reduce the hysteresis losses. When we apply a single phase AC supply to the stator winding, the **magnetic field** gets produced, and the motor rotates at speed slightly less than the synchronous speed N_s. Synchronous speed N_s is given by

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

Where, f = supply voltage frequency, P = No. of poles of the motor.
The construction of the stator of single-phase induction motor is similar to that of three phase induction motor except there are two dissimilarities in the winding part of the single phase induction motor.
1. Firstly, the single-phase induction motors are mostly provided with concentric coils. We can easily adjust the number of turns per coil can with the help of concentric coils. The mmf distribution is almost sinusoidal.
2. Except for shaded pole motor, the asynchronous motor has two stator windings namely the main winding and the auxiliary winding. These two windings are placed in space quadrature to each other.

Rotor of Single Phase Induction Motor

The construction of the rotor of the single-phase induction motor is similar to the squirrel cage three-phase induction motor. The rotor is cylindrical and has slots all over its periphery. The slots are not made parallel to each other but are a little bit skewed as the skewing prevents magnetic locking of stator and rotor teeth and makes the **working of induction motor** more smooth and quieter, i.e. less noise. The squirrel cage rotor consists of aluminium, brass or copper bars. These aluminium or copper bars are called rotor conductors and placed in the slots on the periphery of the rotor. The copper or aluminium rings permanently short the rotor conductors called the end rings. To provide mechanical strength, these rotor conductors are braced to the end ring and hence form a complete closed circuit resembling like a cage and hence got its name as squirrel cage induction motor. As end rings permanently short the bars, the rotor **electrical resistance** is very small and it is not possible to add external **resistance** as the bars get permanently shorted. The absence of slip ring and brushes make the **construction of single phase induction motor** very simple and robust.

Working Principle of Single Phase Induction Motor

We know that for the working of any **electrical motor** whether its AC or DC motor, we require two fluxes as the interaction of these two fluxes produced the required torque. When we apply a single phase AC supply to the stator winding of single phase induction motor, the alternating current starts flowing through the stator or main winding. This alternating current produces an alternating flux called main flux. This main flux also links with the rotor conductors and hence cut the rotor conductors. According to the **Faraday's law of electromagnetic induction,** emf gets induced in the rotor. As the rotor circuit is closed one so, the current starts flowing in the rotor. This current is called the rotor current. This rotor current produces its flux called rotor flux. Since this flux is produced due to induction principle so, the motor working on this principle got its name as an induction motor. Now there are two fluxes one is main flux, and another is called rotor flux. These two fluxes produce the desired torque which is required by the motor to rotate.

Why Single Phase Induction Motor is not Self Starting?

According to double field revolving theory, we can resolve any alternating quantity into two components. Each component has a magnitude equal to the half of the maximum magnitude of the alternating quantity, and both these components rotate in the opposite direction to each other.

For example - a flux, φ can be resolved into two components $\frac{\phi_m}{2}\ and\ -\frac{\phi_m}{2}$ Each of these components rotates in the opposite direction i. e if one $\varphi_m / 2$ is rotating in clockwise direction then the other $\varphi_m / 2$ rotates in anticlockwise direction.

When we apply a single phase AC supply to the stator winding of single phase induction motor, it produces its flux of magnitude, φ_m. According to the double field revolving theory, this alternating flux, φ_m is divided into two components of magnitude $\varphi_m /2$. Each of these components will rotate in the opposite direction, with the synchronous speed, N_s. Let us call these two components of flux as forwarding component of flux, φ_f and the backward component of flux, φ_b. The resultant of these two components of flux at any instant of time gives the value of instantaneous stator flux at that particular instant.

$i.e. \phi_r = \frac{\phi_m}{2} + \frac{\phi_m}{2} \; or \; \phi_r = \phi_f + \phi_b$ Now at starting condition, both the forward and backward components of flux are exactly opposite to each other. Also, both of these components of flux are equal in magnitude. So, they cancel each other and hence the net torque experienced by the rotor at starting condition is zero. So, the single phase induction motors are not self-starting motors.

Methods for Making Single Phase Induction as Self Starting Motor

From the above topic, we can easily conclude that the single-phase induction motors are not self-starting because the produced stator flux is alternating in nature and at the starting, the two components of this flux cancel each other and hence there is no net torque. The solution to this problem is that if we make the stator flux rotating type, rather than alternating type, which rotates in one particular direction only. Then the induction motor will become self-starting. Now for producing this rotating magnetic field, we require two alternating flux, having some phase difference angle between them. When these two fluxes interact with each other, they will produce a resultant flux. This resultant flux is rotating in nature and rotates in space in one particular direction only. Once the motor starts running, we can remove the additional flux. The motor will continue to run under the influence of the main flux only. Depending upon the methods for making asynchronous motor as Self Starting Motor, there are mainly four types of single phase induction motor namely,

1. Split phase induction motor,
2. Capacitor start inductor motor,
3. Capacitor start capacitor run induction motor,
4. Shaded pole induction motor.
5. Permanent split capacitor motor or single value capacitor motor.

Comparison between Single Phase and Three Phase Induction Motors

6. Single phase induction motors are simple in construction, reliable and economical for small power rating as compared to three phase induction motors.
7. The electrical power factor of single phase induction motors is low as compared to three phase induction motors.
8. For the same size, the single-phase induction motors develop about 50% of the output as that of three phase induction motors.
9. The starting torque is also low for asynchronous motors / single phase induction motor.
10. The efficiency of single phase induction motors is less compared to that of three-phase induction motors.

Single phase induction motors are simple, robust, reliable and cheaper for small ratings. They are available up to 1 KW rating.

SINGLE-PHASE COMMUTATOR MOTORS

The commutator motors are so called because the wound rotor of this kind of motor is equipped with a commutator and brushes. This group consists of the following two classes:

1. Those operating on ‘repulsion principle’ (repulsion motors) in which energy is inductively transferred from the single-phase stator field winding to the rotor.
2. Those operating on the principle of the series motor in which the energy is conductively carried both to the rotor armature and-its series-connected single-phase stator field.