TVET CERTIFICATE III IN WELDING

BASIC OF ELECTRICITY

WELDBE 301

Apply Basic of Electricity

Competence

Credits: 12

Learning hours:120

Sector: Manufacturing.

Sub-sector: Welding.

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Purpose statement

This core module describes the skills, knowledge and attitude required to interpret basic concepts in electricity, analyze characteristics of AC signal, study the behavior of different AC circuit and analyze 3-phase circuit. The learner will be able to apply DC circuits laws and theorems, apply magnetism and electromagnetism, identify and interpret waveform signals. He/she will also be able to identify power in AC circuits and apply power factor improvement techniques.

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Learning Unit 1 – Interpret basic concept in electricity.

LO 1.1 – Identify electrical quantities.

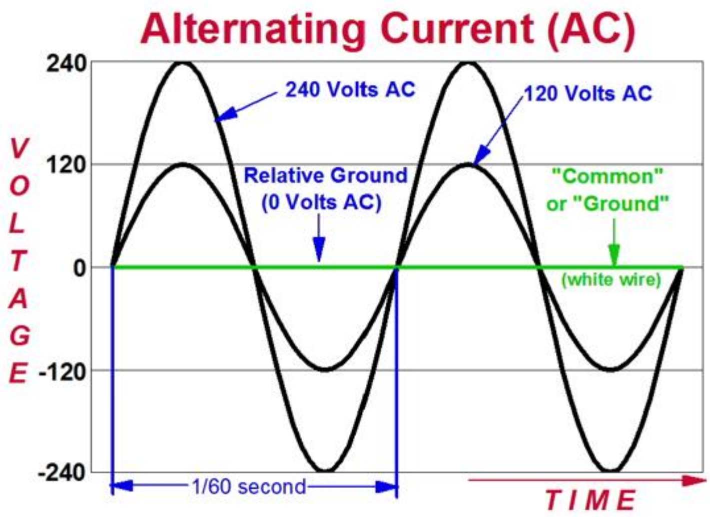
Without electricity, modern life would be impossible. Almost every item on your person from your shoes to your sunglasses its manufactured in terms of electrical power. Indeed, since this is also true of your clothing, without electricity you might not well be completely naked.

The units in which we measure electrical quantities have been assigned the names of famous scientific pioneers, brief details of whom are as follows.

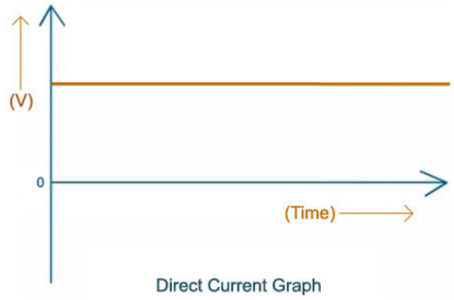
- **André Marie Ampère (1775–1836):** French physicist who showed that a mechanical force exists between two conductors carrying a current.
- **Charles Augustin de Coulomb (1746–1806):** French military engineer and physicist famous for his work on electric charge.
- **Georg Simon Ohm (1789–1854):** German physicist who demonstrated the relationship between current, voltage and resistance.
- **Allessandro Volta (1745–1827):** Italian scientist who developed the electric cell, called the 'voltaic pile', which comprised a series of copper and zinc discs separated by a brine-soaked cloth.
- **Electric current: symbol, *I***; unit, ampere (A): This is the flow or drift of random electrons in a conductor.
- **Electric charge or quantity: symbol, *Q***; unit, coulomb (C): This is the quantity of electricity that passes a point in a circuit in a certain time. One coulomb is said to have passed when one ampere flows for one second: $Q = I\,t$
- **Electromotive force (e.m.f): symbol(*E*)**; unit, volt (V): This is the total potential force available from a source to drive electric current around a circuit.
- **Potential difference (p.d.): symbol(*V*)**; unit, volt (V): Often referred to as 'voltage' or 'voltage across', this is the actual force available to drive current around a circuit.

Content/Topic 1: Introduction to electricity and its means of generation.

A. **Alternative current (AC):** Alternating current is characterized by direction of flow and amount of electricity that changes cyclically over time. Long ago, static electricity was the only type of electricity known, but when batteries were invented, it became possible to use DC electricity. Generators were later invented, and it became possible to use AC as well.



B. Direct current (DC): Direct current such as the power from dry cells is characterized by a uniform direction of flow and amount (voltage) of electricity.



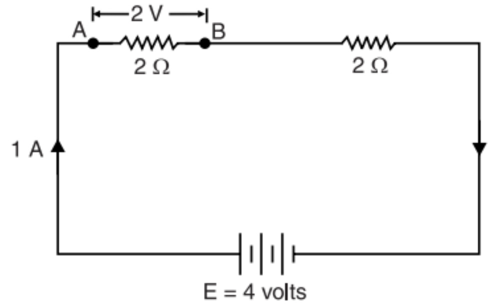
Content /Topic 2: Different electrical quantities.

A. Current: the movement of electrons is from negatively charged atoms to positively charged atoms. This flow of electrons is called ***current (I)***. The symbol "I" is used to represent current. The amount of current is the sum of the charges of the moving electrons past a given point. An electron has a very small charge, so the charge of 6.24 3 1018 electrons is added together and called a ***coulomb (C)***. When 1 coulomb of charge moves past a single point in 1 second, it is called an ***ampere (A)***.

I= V/R

B. Voltage, electrical potential and e.m.f: Anything that is in a state whereby it may give rise to the release of energy is said to have **potential**. For example, a ball held above the ground has potential in that, if it were let go, it would fall and hit the ground. So, a cell or battery with its positive and negative plates have potential to cause electron drift. As there is a difference in the number of electrons on each of the plates, this potential is called the **potential difference** (p.d.).

There is a distinct difference between *e.m.f*. and potential difference. The *e.m.f*. of a device, say a battery, is a measure of the energy the battery gives to each coulomb of charge. Thus, if a battery supplies 4 joules of energy per coulomb, we say that it has an *e.m.f*. of 4 volts. The energy given to each coulomb in a battery is due to the chemical action. The potential difference between two points, say *A* and *B*, is a measure of the energy used by one coulomb in moving from *A* to *B*. Thus, if potential difference between points *A* and *B* is 2 volts, it means that each coulomb will give up an energy of 2 joules in moving from *A* to *B*.



C. Power and Energy: Electric power is the rate at which a device changes electric current to another form of energy. The SI unit of power is the watt. Electric power can be calculated as current times voltage(***P = IV= I²R = V²/R***), the unit of power is the Watt***(W),***while **Electrical energy** use equals the power of the appliance multiplied by the amount of time the appliance is used(***E= Pt =IVt***) the unit of energy is joule ***(J)*** .

D. Resistance and conductance: The ***electrical resistance*** of an electrical conductor is the opposition to the passage of an electric current through that conductor; the inverse quantity is ***electrical conductance***, the ease at which an electric current pass.

Electrical resistance shares some conceptual parallels with the mechanical notion of friction. The SI unit of electrical resistance is the ohm (Ω), while electrical conductance is measured in siemens (S). An object of uniform cross section has a resistance proportional to its resistivity and length and inversely proportional to its cross-sectional area. All materials show some resistance, except for superconductors, which have a resistance of zero. The resistance (R) of an object is defined as the ratio of voltage across it (*V*) to current through it (*I*), while the conductance (G) is the inverse:

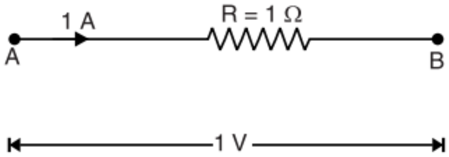
$$R = \frac{V}{I}, \qquad G = \frac{I}{V}$$

The unit of resistance is **ohm (Ω)**

The opposition offered by a substance to the flow of electric current is called its **resistance.** Since current is the flow of free electrons, resistance is the opposition offered by the substance to the flow of free electrons. This opposition occurs because atoms and molecules of the substance obstruct the flow of these electrons. Certain substances (*e.g.* metals such as silver, copper, aluminium etc.) offer very little opposition to the flow of electric current and are called conductors. On the other hand, those substances which offer high opposition to the flow of electric current (*i.e.* flow of free electrons) are called insulators *e.g.* glass, rubber, mica, dry wood etc.

It may be noted here that resistance is the electric friction offered by the substance and causes production of heat with the flow of electric current. The moving electrons collide with atoms or molecules of the substance; each collision resulting in the liberation of minute quantity of heat.

A wire is said to have a resistance of **1 ohm** *if a p.d. of 1 volt across its ends causes 1 ampere to flow through it* (See Fig. below). is another way of defining ohm?



A wire is said to have a resistance of **1 ohm** if it releases 1 joule (or develops 0.24 calorie of heat) when a current of 1 A flows through it for 1 second. A little reflection shows that second definition leads to the first definition. Tus 1 A current flowing for 1 second means that total charge flowing is ***Q=I×t=1×1=1*** coulomb. Now the charge flowing between A and B (See Fig. above) is 1 coulomb and energy released is 1 joule (or 0.24 calorie). Obviously, by definition, p.d. between A and B should be 1 volt.

The resistance *R* of a conductor

i. is directly proportional to its length *i.e.*

$$R \propto l$$

ii. is inversely proportional to its area of *cross*-section *i.e*

$$R \propto \frac{1}{a}$$

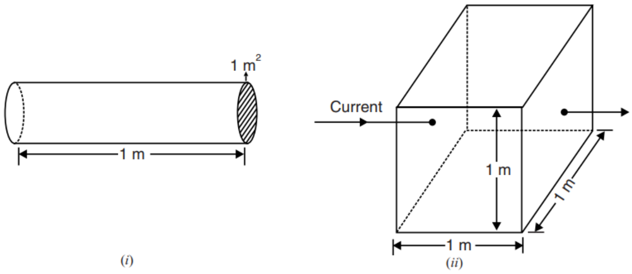
iii. depends upon the nature of material

iv. depends upon temperature. From the first three points (leaving temperature for the time being), we have,

$$R \propto \frac{l}{a} \quad \text{or} \quad R = \rho\frac{l}{a}$$

Here **ρ** (Greek letter 'Rho') is a constant and is known as *resistivity* or *specific resistance* of the material. Its value depends upon the nature of the material.

Hence **specific resistance** of a material is the resistance offered by 1 m length of wire of material having an area of cross-section of 1 m^2



Whereas resistance of a conductor is the opposition to current flow, the conductance of a conductor is the inducement to current flow. The SI unit of conductance is mho (*i.e.*, ohm spelt backward). These days, it is a usual practice to use **siemen** as the unit of conductance. It is denoted by the symbol S.

Conductivity. *The reciprocal of resistivity of a conductor is called its* **conductivity.** It is denoted by the symbol σ. If a conductor has resistivity ρ, then its conductivity is given by; We know that,

$G = \frac{1}{R} = \frac{a}{\rho l} = \sigma \frac{a}{l}$. Clearly, the SI unit of conductivity is *Siemen metre*$^{-1}$ (S m^{-1}).

E. **Conductors, semi-conductors and insulators:** ***Conductors*** are those materials, like silver, copper and graphite, that will allow electrical current to pass. ***Insulators*** are those materials, like pure water and diamond, that will not. In between these two extremes are ***semiconductors***, the difference between the electrical behavior of conductors and insulators are due to the difference between their electronic structures.

LO 1.2 – Apply DC circuits laws and theorems.

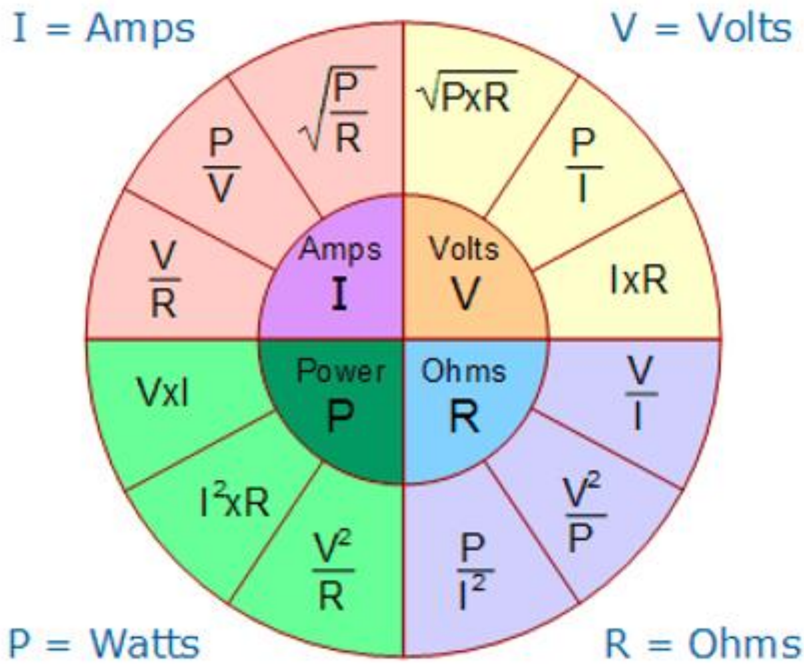
Content/Topic 1: Ohm's law.

Ohm’s law states that the voltage or potential difference between two points is directly proportional to the current or electricity passing through the resistance, and directly proportional to the resistance of the circuit. The formula for Ohm’s law is ***V=IR***. This relationship between current, voltage, and relationship was discovered by German scientist Georg Simon Ohm.

Ohm’s law helps us in determining either voltage, current or impedance or resistance of a linear electric circuit when the other two quantities are known to us. It also makes power calculation simpler.

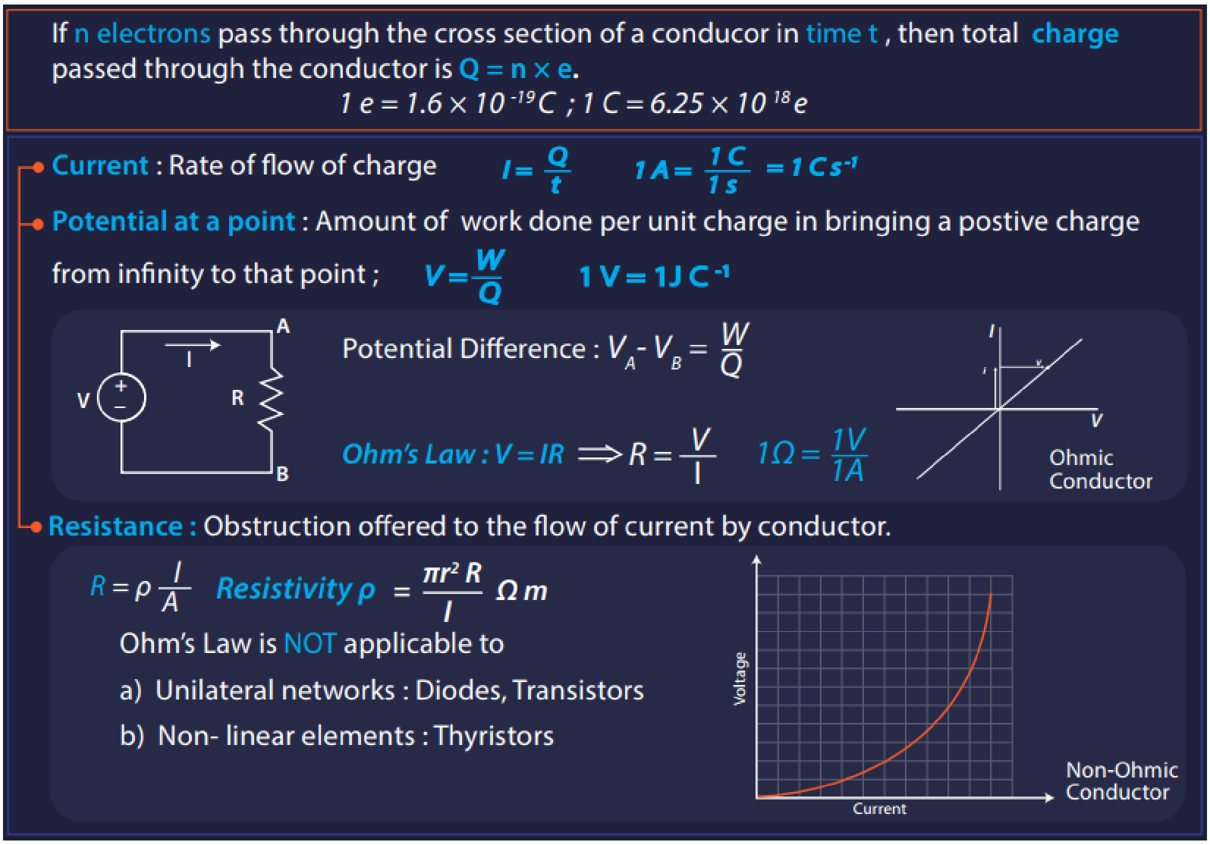
$$Current, (I) = \frac{Voltage, (V)}{Resistance, (R)} \text{ in Amperes, } (A)$$

Ohms law pie chart

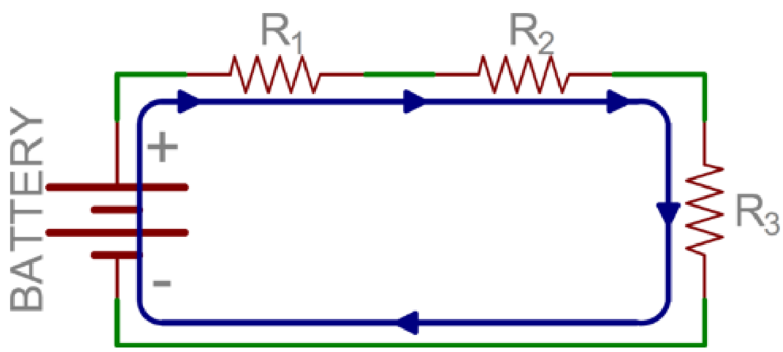


A. Limitations of ohms law

- Ohm's law is not applicable to unilateral networks. Unilateral networks allow the current to flow in one direction. Such types of network consist elements like a diode, transistor, etc.
- Ohm's law is also not applicable to non-linear elements. Non-linear elements are those which do not have current exactly proportional to the applied voltage that means the resistance value of those elements' changes for different values of voltage and current. Examples of non-linear elements are the thyristor.



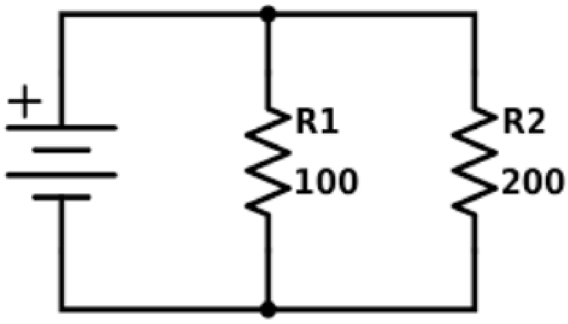
B. **Resistance in series:** A series generally means connected along a line, or in a row, or in an order. In electronics, series resistance means that the resistors are connected one after the other and that there is only one path for current to flow through.



Laws of Series Circuits

1. Individual resistance adds up to the total circuit resistance
   Rt=R1+R2+R3+R4+..........+Rn , Rt=R1+R2+R3
2. Current through the circuit is the same at every point.
3. Individual voltages throughout the circuit add up to the total voltage.

C. **Resistance in parallel:** There are many different ways to organize a parallel circuit. In the practical world, most of the wiring is done in parallel so that the voltage to any one part of the network is the same as the voltage supplied to any other part of it.



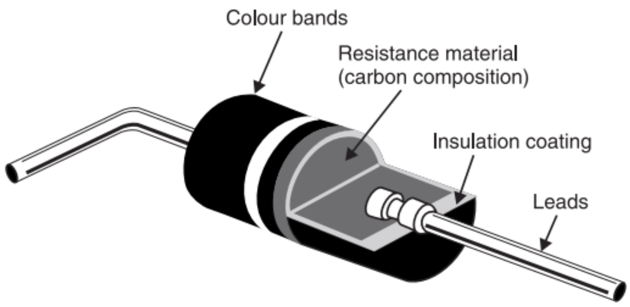
Laws of Parallel Circuits

1. The reciprocals of all the individual resistances add up to the reciprocal of the total circuit resistance. 1/RT = 1/R1 + 1/R2 + 1/R3.
2. Voltage through the circuit is the same at every point.
3. Individual current draws throughout the circuit add up to the total current draw.

Content/Topic 2: Series, parallel and mixed connection of resistors.

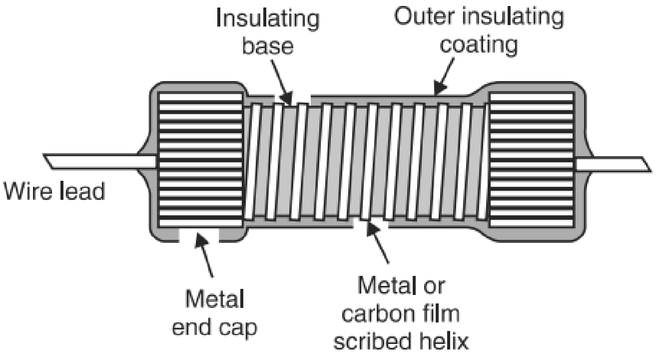
A component whose function in a circuit is to provide a specified value of resistance is called a **resistor**. The principal applications of resistors are to limit current, divide voltage and in certain cases, generate heat. Although there are a variety of different types of resistors, the following are the commonly used resistors in electrical and electronic circuits:

i. **Carbon composition types:** This type of resistor is made with a mixture of finely ground carbon, insulating filler and a resin binder. The ratio of carbon and insulating filler decides the resistance value [See Fig. below]. The mixture is formed into a rod and lead connections are made. The entire resistor is then enclosed in a plastic case to prevent the entry of moisture and other harmful elements from outside.

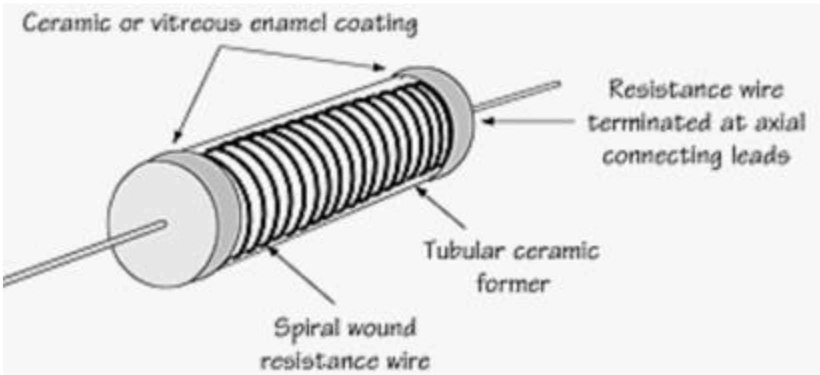


Carbon resistors are relatively inexpensive to build. However, they are highly sensitive to temperature variations. The carbon resistors are available in power ratings ranging from 1/8 to 2 W.

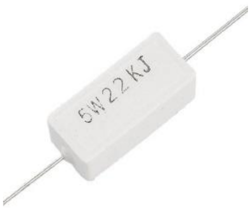
ii. **Film resistors:** In a film resistor, a resistive material is deposited uniformly onto a high-grade ceramic rod. The resistive film may be carbon (carbon film resistor) or nickel-chromium (metal film resistor). In these types of resistors, the desired resistance value is obtained by removing a part of the resistive material in a helical pattern along the rod as shown in Fig below.



iii. **Wire-wound resistors:** A wire-wound resistor is constructed by winding a resistive wire of some alloy around an insulating rod. It is then enclosed in an insulating cover. Generally, Nickle chromium alloy is used because of its very small temperature coefficient of resistance. Wire-wound resistors can safely operate at higher temperatures than carbon types. These resistors have high power ratings ranging from 12 to 225 W.



iv. **Cermet resistors:** A cermet resistor is made by depositing a thin film of metal such as nichrome or chromium cobalt on a ceramic substrate. They are cermet which is a contraction for ceramic and metal. These resistors have very accurate values.



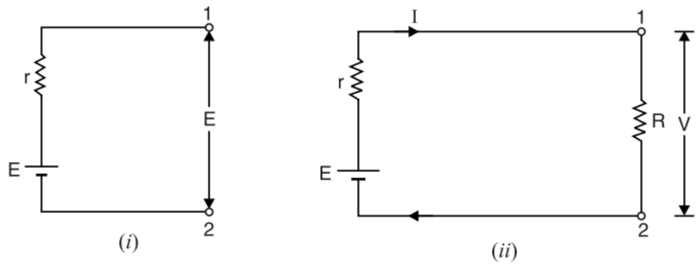
A. **Series connection of resistors:** All supplies (*e.g.* a cell) must have some internal resistance, however small. This is shown as a series resistor external to the supply. Fig 2.20 shows a cell of *e.m.f.* E volts and internal resistance r. When the cell is delivering no current (*i.e.* on no load), the p.d. across the terminals will be equal to *e.m.f.* E of the cell as shown in Fig. 2.20 (*i*). When some load resistance R is connected across the terminals of the cell, the current I start flowing in the circuit. This current causes a voltage drop across internal resistance r of the cell so that terminal voltage V available will be less than E. The relationship between E and V can be easily established [See Fig. 2.20 (*ii*)]

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

$$IR = E - Ir$$

$$IR = V, \text{ the terminal voltage of the cell.}$$

$$V = E - Ir$$



Internal resistance of cell,

$$r = \frac{E-V}{I} = \frac{(E-V)}{V}R$$

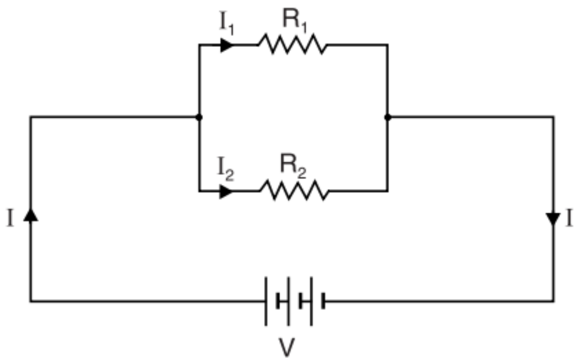
B. Parallel connection of resistors: A frequent special case of parallel resistors is a circuit that contains two resistances in parallel. Fig. below shows two resistances R_1 and R_2 connected in parallel across a battery of V volts. The total current I divides into two parts; I_1 flowing through R_1 and I_2 flowing through R_2.

i. **Total resistance R_P.**

$$\frac{1}{R_P} = \frac{1}{R_1} + \frac{1}{R_2} = \frac{R_2 + R_1}{R_1 R_2}$$

$$R_P = \frac{R_1 R_2}{R_1 + R_2} = \frac{\text{Product}}{\text{Sum}}$$

Hence the total value of two resistors connected in parallel is equal to the product divided by the sum of the two resistors.



ii. **Branch Currents.**

$$R_P = \frac{R_1 R_2}{R_1 + R_2}$$

$$V = I R_P = I \frac{R_1 R_2}{R_1 + R_2}$$

Current through R_1,

$$I_1 = \frac{V}{R_1} = I \frac{R_2}{R_1 + R_2} \qquad \left[\text{Putting } V = I \frac{R_1 R_2}{R_1 + R_2}\right]$$

Current through R_2

$$I_2 = \frac{V}{R_2} = I \frac{R_1}{R_1 + R_2}$$

Hence in a parallel circuit of two resistors, the current in one resistor is the line current (i.e. total current) times the opposite resistor divided by the sum of the two resistors. We can also express currents in terms of conductance's.

$$G_P = G_1 + G_2$$

$$I_1 = \frac{V}{R_1} = VG_1 = \frac{I}{G_P} \times G_1 = I \times \frac{G_1}{G_P} = I \times \frac{G_1}{G_1 + G_2}$$

$$I_2 = \frac{V}{R_2} = VG_2 = \frac{I}{G_P} \times G_2 = I \times \frac{G_2}{G_P} = I \times \frac{G_2}{G_1 + G_2}$$

Note.

When two resistances are connected in parallel and one resistance is much greater than the other, then the total resistance of the combination is very nearly equal to the smaller of the two resistances.

- **Advantages of Parallel Circuits**

The most useful property of a parallel circuit is the fact that potential difference has the same value between the terminals of each branch of parallel circuit. This feature the parallel circuit offers the following advantages:

i. The appliances rated for the same voltage but different powers can be connected in parallel without disturbing each other's performance. Thus a 230 V, 230 W TV receiver can be operated independently in parallel with a 230 V, 40 W lamp.

ii. If a break occurs in any one of the branch circuits, it will have no effect on other branch circuits.

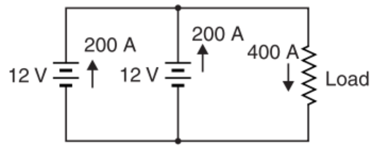
Due to above advantages, electrical appliances in homes are connected in parallel. We can switch on or off any light or appliance without affecting other lights or appliances.

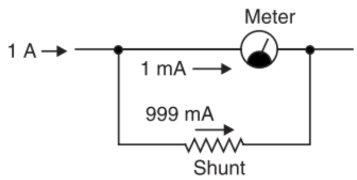
- **Applications of Parallel Circuits**

Parallel circuits find many applications in electrical and electronic circuits. We shall give two applications by way of illustration.

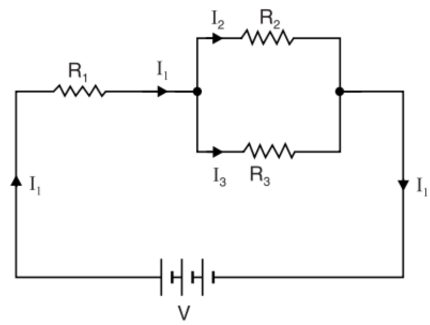
i. Identical voltage sources may be connected in parallel to provide a greater current capacity. Fig. below shows two 12 V automobile storage batteries in parallel. If the starter motor draws 400 A at starting, then each battery will supply half the current *i.e.* 200 A. A single battery might not be able to provide a load current of 400 A. Another benefit is that two batteries in parallel will supply a given load current for twice the time when compared to a single battery before discharge is reached.

ii. Second figure shows another application for parallel connection. A low resistor, called a *shunt*, is connected in parallel with an ammeter to increase the current range of the meter. If shunt is not used, the ammeter is able to measure currents up to 1 mA. However, the use of shunt permits to measure currents up to 1 A. Thus, shunt increases the range of the ammeter.





C. Mixed connection of resistors: As the name suggests, this circuit is a combination of series and parallel circuits. A simple example of such a circuit is illustrated in Fig. below. Note that R_2 and R_3 are connected in parallel with each other and that both together are connected in series with $R1$. One simple rule to solve such circuits is to first reduce the parallel branches to an equivalent series branch and then solve the circuit as a simple series circuit.



Referring to the series-parallel circuit shown in above figure R_P for parallel combination

$$R_P \text{ for parallel combination } = \frac{R_2 R_3}{R_2 + R_3}$$

$$\text{Total circuit resistance } = R_1 + \frac{R_2 R_3}{R_2 + R_3}$$

$$\text{Voltage across parallel combination } = I_1 \times \frac{R_2 R_3}{R_2 + R_3}$$

The reader can now readily find the values of I_1, I_2, I_3. Like series and parallel circuits, the total power dissipated in the circuit is equal to the sum of powers dissipated in the individual resistances *i.e.* Total power dissipated,

$$P = I_1^2 R_1 + I_2^2 R_2 + I_3^2 R_3$$

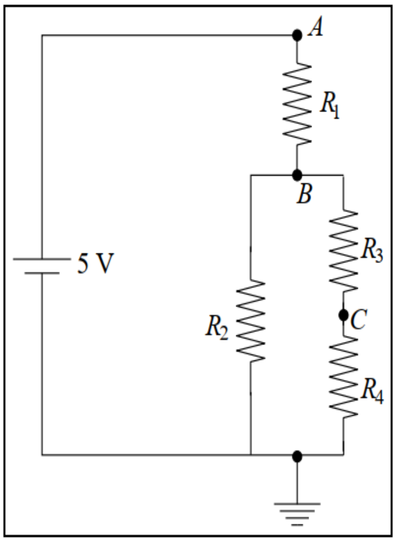
Applications of Series-Parallel Circuits

Series-parallel circuits combine the advantages of both series and parallel circuits and minimize their disadvantages. Generally, less copper is required and a smaller size wire can be used. Such circuits are used whenever various types of circuits must be fed from the same power supply. A few common applications of series-parallel circuits are given below:

i. In an automobile, the starting, lighting and ignition circuits are all individual circuits joined to make a series-parallel circuit drawing its power from one battery.
ii. Radio and television receivers contain a number of separate circuits such as tuning circuits, r.f. amplifiers, oscillator, detector and picture tube circuits. Individually, they may be simple series or parallel circuits. However, when the receiver is considered as a whole, the result is a series-parallel circuit.
iii. Power supplies are connected in series to get a higher voltage and in parallel to get a higher current.

Content/Topic 3: Kirchhoff's laws.

A general electrical circuit could consist of many resistors (and other components), forming a network with combinations of series and parallel connections. The size and complexity of the circuits might go up to tens of thousands of components, requiring the aid of a computer 4 networks of resistances, kirchhoff's laws.



To design and analyze the circuit. But, be it a simple circuit with a handful of components that we analyze by hand or a large-scale integrated circuit that is analyzed by the computer, there are two basic starting-point principles that we use in network analysis. These principles, which are actually results of the law of conservation of energy and the law of conservation of charge, were first formulated by the German scientist Gustav Robert Kirchhoff (1824-1887) around 1846: Kirchhoff's Voltage Law (KVL) and Kirchhoff's Current Law (KCL).

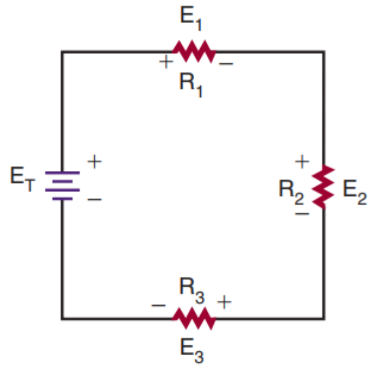
A. *Kirchhoff's Voltage Law states*

Kirchhoff's Voltage Law states

KVL the algebraic sum of the increases and decreases in potential around any closed-circuit loop must be zero.

Kirchhoff 's second law is referred to as **Kirchhoff's voltage law**, and it states the following:

- The algebraic sum of all the voltages around a closed circuit equals 0. Here is another way of stating Kirchhoff's voltage law:
- The sum of all the voltage drops in a closed circuit equals the voltage source.



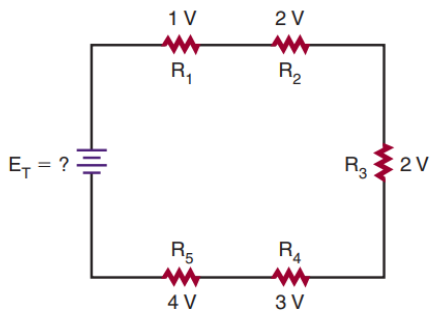
In above Figure there are three voltage drops and one voltage source (voltage rise) in the circuit. If the voltages are summed around the circuit as shown, they equal 0.

$$E_T - E_1 - E_2 - E_3 = 0$$

Notice that the voltage source (E_T) has a sign opposite that of the voltage drops. Therefore, the algebraic sum equals 0. Looking at this another way, the sum of all the voltage drops equals the voltage source.

$$E_T = E_1 + E_2 + E_3$$

Both of the formulas shown are stating the same thing and are equivalent ways of expressing Kirchhoff 's voltage law. The key to remember is that the polarity of the voltage source in the circuit is opposite to that of the voltage drops.



B. Kirchhoff's Current Law states KCL

Kirchhoff's Current Law states KCL
The algebraic sum of all the currents entering or leaving a node must be zero.

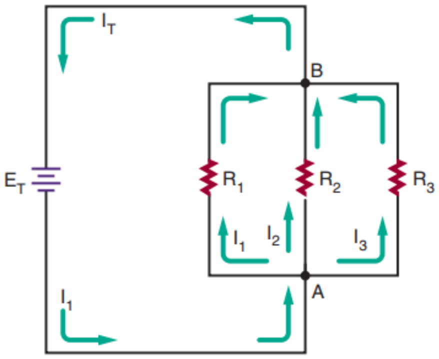
In 1847, G. R. Kirchhoff extended Ohm's law with two important statements that are referred to as Kirchhoff 's laws. The first law, known as **Kirchhoff's current law**, states the following:

- The algebraic sum of all the currents entering and leaving a junction is equal to 0. Here is another way of stating Kirchhoff 's current law:
- The total current flowing into a junction is equal to the sum of the current flowing out of that junction.

A junction is defined as any point of a circuit at which two or more current paths meet. In a parallel circuit, the junction is where the parallel branches of the circuit connect.

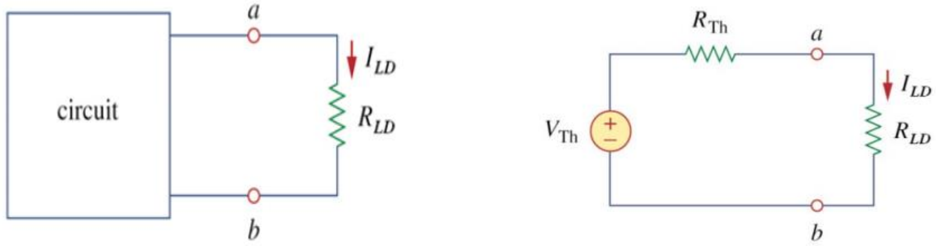
In below Figure, point A is one junction and point B is the second junction. Following the current in the circuit, IT flows from the voltage source into the junction at point A. There the current splits among the three branches as shown. Each of the three branch currents (I_1, I_2, and I_3) flows out of junction A. According to Kirchhoff 's current law, which states that the total current into a junction is equal to the total current out of the junction, the current can be stated as $I_T = I_1+I_2+I_3$.

Following the current through each of the three branches finds them coming back together at point B. Currents I_1, I_2, and I_3 flows out into junction B, and I_T flows out. Kirchhoff 's current law formula at this junction is the same as at junction A: $I_1 + I_2 + I_3 = I_T$



Content/Topic 4: DC circuits analysis theorems.

A. Thevenin: Thevenin's theorem greatly simplifies analysis of complex circuits by allowing us to replace all of the elements with a combination of just one voltage source and one resistor. "A complex two-terminal circuit can be replaced by an equivalent circuit consisting of a voltage source $\boldsymbol{V_{TH}}$ in series with a resistor $\boldsymbol{R_{TH}}$.



Original Circuit

Thevenin Equivalent Circuit

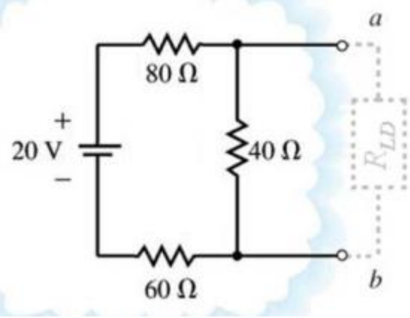
In the new circuit:

- *VTH* is the open circuit voltage at the terminals. ***The Voltage between A and B.***
- *RTH* is the input or equivalent resistance at the terminals when the sources are turned off. ***The equivalent resistance between A and B.***

To draw your new equivalent circuit, follow these steps:

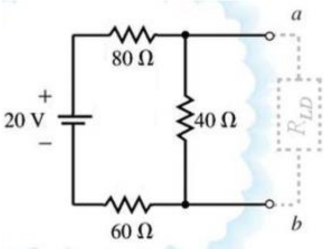
1. Remove your load and label your terminals a and b.
2. Solve for V_{TH}.
3. Solve for R_{TH}.
4. Draw your new equivalent circuit.

1. **Remove your load** and **label** your **terminals a and b**.



2. **Solve for V_{TH}.**

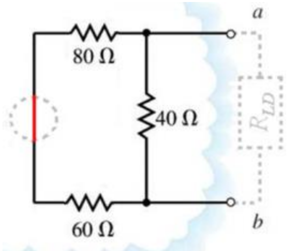
The **Thevenin voltage is the voltage between a and b with the load removed**. Follow the path of current leaving the source to see if it divides and it goes through the 40 Ohms resistor. Note that no matter if you have resistors on the open terminals since no current can flow through them. In this case this is a closed loop where the voltage between a and b, $V_{ab} = V_{TH}$, and is also the voltage drop across the 40Ω resistor, that can be solved using the VDR.



$$V_{ab} = V_{TH} = V_{40\Omega} = 20 \cdot \frac{40}{40+80+60} = 4.4V$$

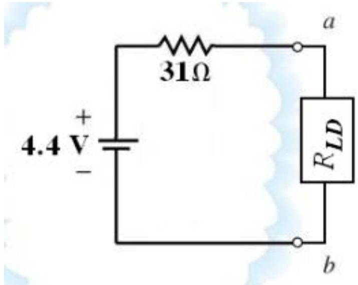
3. Solve for R_{TH}. Turn off your Source.
   - If it is a Voltage source **(Es)** → Short Circuit.
   - If it's a Current source **(Is)** → Open Circuit.

Then your R_{TH} **is the value of resistance between terminals a and b.** To see how to combine the resistors, try to **follow the path of the current from a to b** to check where splits or merge or where simply is not going through because there is an open circuit (due to the current source that you turned off) or a short circuit in the same node (due to the voltage source that you turned off).



$$R_{TH} = R_{ab} = \left(\frac{1}{60+80} + \frac{1}{40}\right)^{-1} = 31\Omega$$

4. Finally**: Draw your new Thevenin equivalent circuit** plugging E_{TH}, R_{TH} and R_{LD}



Advantages of Thevenin's Theorem

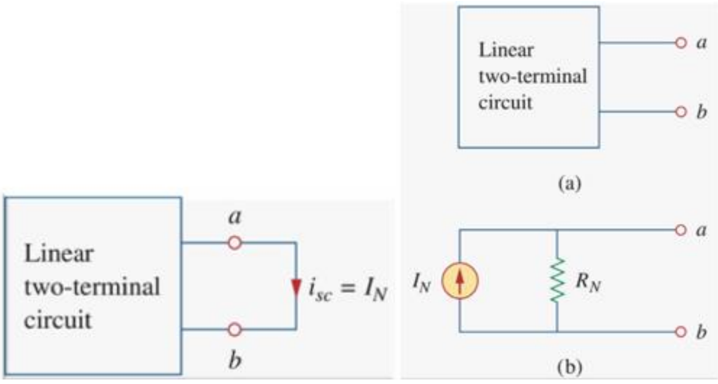
The Thevenin equivalent circuit is *always* an equivalent voltage source (*VTh*) in series with an equivalent resistance (*RTh*) regardless of the original circuit that it replaces. Although the Thevenin equivalent is not the same as its original circuit, it acts the same in terms of output voltage and current. It is worthwhile to give the advantages of Thevenin's theorem.

i. It reduces a complex circuit to a simple circuit *viz.* a single source of e.m.f. V_{Th} in series with a single resistance R_{Th}.
ii. It greatly simplifies the portion of the circuit of lesser interest and enables us to view the action of the output part directly.
iii. This theorem is particularly useful to find current in a particular branch of a network as the resistance of that branch is varied while all other resistances and sources remain constant.
iv. Thevenin's theorem can be applied in successive steps. Any two points in a circuit can be chosen and all the components to one side of these points can be reduced to Thevenin's equivalent circuit.

B. Norton: Norton's theorem states that a linear two-terminal circuit can be replaced by an equivalent circuit consisting of a current source $\mathbf{i_N}$ in parallel with a resistor $\mathbf{R_N}$, where $\mathbf{i_N}$ is the short-circuit current through the terminals and $\mathbf{R_N}$ is the input or equivalent resistance at the terminals when the independent sources are turned off.

- According to Norton theorem, the circuit fig.(a) can be replaced by the one in fig.(b).
- We find R_N in the same way we find $\mathbf{R_{Th}}$. Thevenin and Norton resistances are equal; that **is,** $\mathbf{R_N=R_{Th}}$.
- To find the Norton current we determine the short-circuit current flowing from terminal **a** to **b** in fig.(a), thus, $\mathbf{i_N=i_{sc}}$

$$i_N = \frac{v_{Th}}{R_{Th}}$$



- This is essentially source transformation. For this reason, source transformation is often called Thevenin-Norton transformation.
- To determine the Thevenin or Norton equivalent circuit requires that we find:
  - The open-circuit voltage across terminals a and b.
  - The short-circuit current at terminals a and b.
  - The equivalent or input resistance at terminals a and b when all independent sources are turned off.
- We can calculate any two of the three using the method that takes the least effort and use them to get the third using Ohm's law, since.

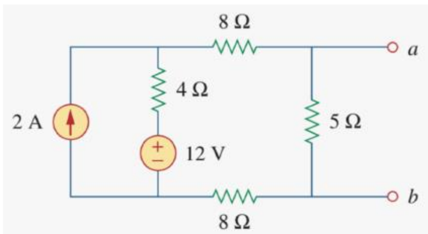
$$v_{Th} = v_{oc}$$

$$i_N = isc$$

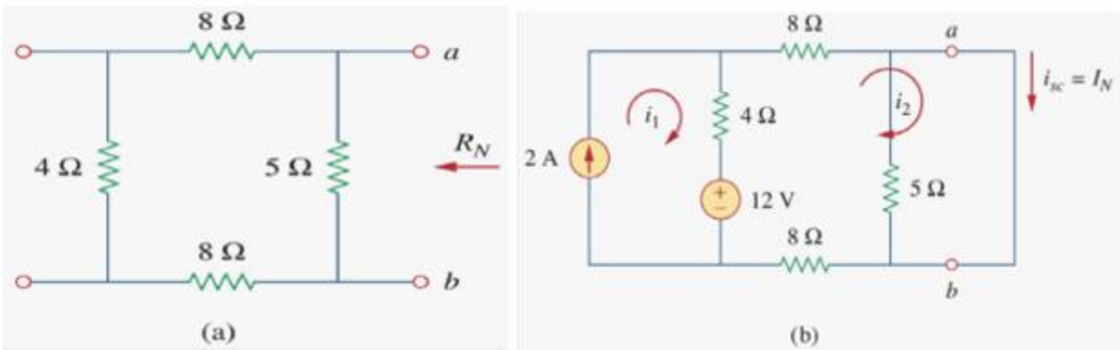
$$R_{Th} = \frac{v_o}{i_{sc}} = R_N$$

Example:

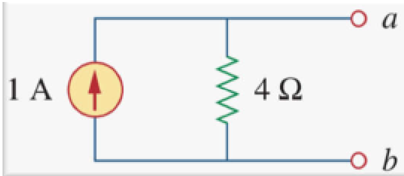
Find the Norton equivalent circuit of the circuit in the shown figure at terminals a-b.



ANSWER:



We find $\mathbf{R_N}$ in the same way we find in the Thevenin equivalent circuit. Set the independent sources equal to zero as shown in fig.(a). from which we find $\mathbf{R_N}$, Thus, $\mathbf{R_N}$=5||(8+4+8)=5||20=(20×5/25) =**4Ω**

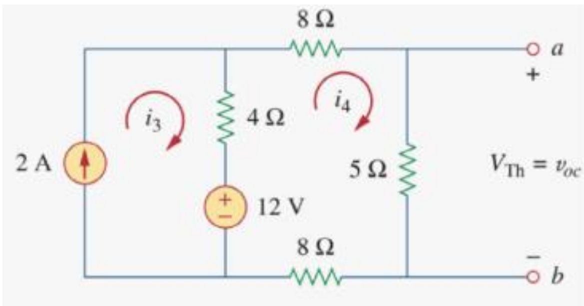


To find $\mathbf{i_N}$ we short-circuit terminals a and b, as shown in fig(b). We ignore the resistor **5Ω** because it has been short-circuited. Applying mesh analysis, we obtain

$$\mathbf{i_1=1A,\ 20i_2-4i_1-12=0}$$

From the above equations we find that: $\mathbf{i_2=1A=isc=i_N}$

Alternatively, we may determine $\mathbf{i_N}$ from $\mathbf{v_{Th}/R_{Th}}$. We obtain $\mathbf{v_{Th}}$ as the open-circuit voltage across terminals a and b in fig.(c). Using mesh analysis, we obtain



(c)

$$\mathbf{i_3=2A}$$

$$\mathbf{25i_4-4i_3-12=0 \Rightarrow i_4=0.8A,\ v_{oc}=v_{Th}=5i_4=4V,\ i_N=v_{Th}/R_{Th}=4/4=1A}$$

Procedure for Finding Norton Equivalent Circuit

- **i.** Open the two terminals (*i.e*. remove any load) between which we want to find Norton equivalent circuit.
- **ii.** Put a short-circuit across the terminals under consideration. Find the short circuit current flowing in the short circuit. It is called Norton current *IN*.
- **iii.** Determine the resistance between the two open terminals with all ideal voltage sources shorted and all ideal current sources opened (a non-ideal source is replaced by its internal resistance). It is called Norton's resistance *RN*. It is easy to see that *RN* = *RTh*.
- **iv.** Connect *IN* and *RN* in parallel to produce Norton equivalent circuit between the two terminals under consideration.
- **v.** Place the load resistor removed in step (*i*) across the terminals of the Norton equivalent circuit. The load current can now be calculated by using current-divider rule. This load current will be the same as the load current in the original circuit

C. Superposition: Superposition is a general principle that allows us to determine the effect of several energy sources (voltage and current sources) acting simultaneously in a circuit by considering the effect of each source acting alone, and then combining (superposing) these effects. This theorem as applied to d.c. circuits may be stated as under : In a linear, bilateral d.c. network containing more than one energy source, the resultant potential difference across or current through any element is equal to the algebraic sum of potential differences or currents for that element produced by each source acting alone with all other independent ideal voltage sources replaced by short circuits and all other independent ideal current sources replaced by open circuits (non-ideal sources are replaced by their internal resistances).

The procedure for using this theorem to solve d.c. networks is as under:

- **i.** Select one source in the circuit and replace all other ideal voltage sources by short circuits and ideal current sources by open circuits.
- **ii.** Determine the voltage across or current through the desired element/branch due to single source selected in step (*i*).
- **iii.** Repeat the above two steps for each of the remaining sources.
- **iv.** *Algebraically* add all the voltages across or currents through the element/branch under consideration. The sum is the actual voltage across or current through that element/branch when all the sources are acting simultaneously.

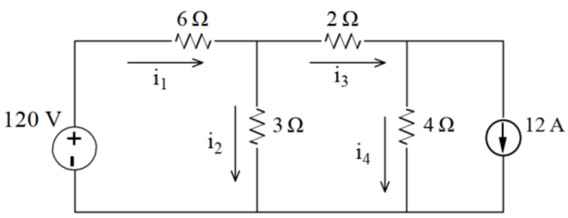
Whenever a linear circuit is excited by more than one independent source, the total response is the algebraic sum of individual responses the idea is to activate one independent source at a time to get individual response. Then add the individual response to get total response.

Note:

- Dependent sources are Never deactivated (always active)
- When an independent voltage source is deactivated, it is set to zero. → Replaced by short circuit
- When an independent current source is deactivated, it is set to zero. → Replaced by open circuit

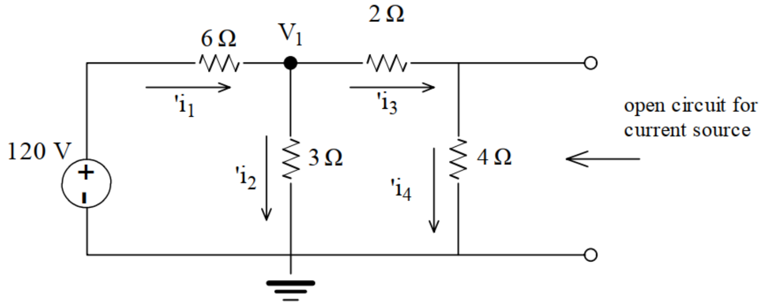
This theorem is called *superposition* because we superpose or algebraically add the components (currents or voltages) due to each independent source acting alone to obtain the total current in or voltage across a circuit element.

Example: Use superposition to find i_1, i_2, i_3, i_4 ?



Answer:

- Activate independent voltage source 120 V only



- Using KCL at V1 (nodal analysis)

$$i_1 - i_2 - i_3 = 0$$

$$\frac{120 - V_1}{6} - \frac{V_1}{3} - \frac{V_1}{2+4} = 0$$

$$20 - V_1\left(\frac{1}{6} + \frac{1}{3} + \frac{1}{6}\right) = 0$$

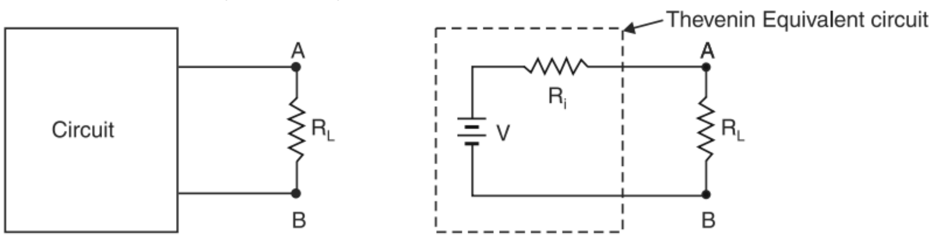
$$\Rightarrow \quad V_1 = 30\ \text{V}$$

$$'i_1 = \frac{120 - V_1}{6} = \frac{90}{6} = 15\ \text{A}$$

$$'i_2 = \frac{V_1}{3} = \frac{30}{3} = 10\ \text{A}$$

$$'i_3 = i_4 = \frac{V_1}{6} = 5\ \text{A}$$

D. Maximum power transfer: This theorem deals with transfer of maximum power from a source to load and may be stated as under: In DC circuits, maximum power is transferred from a source to load when the load resistance is made equal to the internal resistance of the source as viewed from the load terminals with load removed and all e.m.f. sources replaced by their internal resistances.



(*i*) (*ii*)

The above figure (*i*) shows a circuit supplying power to a load *RL*. The circuit enclosed in the box can be replaced by Thevenin's equivalent circuit consisting of Thevenin voltage $V = V_{Th}$ in series with Thevenin resistance R_i ($=R_{Th}$) as shown in Fig. 3.200 (*ii*). Clearly, resistance *Ri* is the resistance measured between terminals *AB* with R_L removed and e.m.f. sources replaced by their internal resistances. According to power transfer theorem, maximum power will be transferred from the circuit to the load when R_L is made equal to R_i, the Thevenin resistance at terminals *AB*.

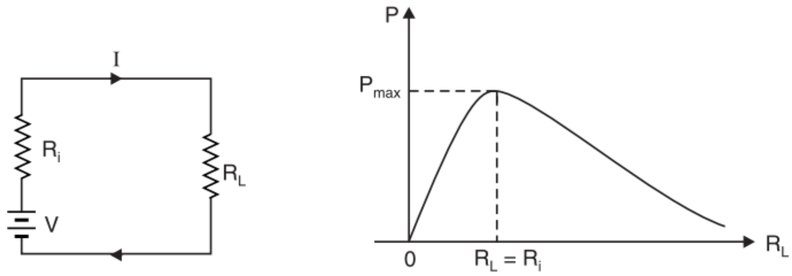
Proof of Maximum Power Transfer Theorem

Consider a voltage source *V* of internal resistance *Ri* delivering power to a load *RL*. We shall prove that when *RL* = *Ri*, the power delivered to *RL* is maximum. Referring to above Fig (*i*), we have

$$\text{Circuit current, } I = \frac{V}{R_L + R_i}$$

$$\text{Power delivered to load, } P = I^2 R_L = \left(\frac{V}{R_L + R_i}\right)^2 R_L$$

For a given source, generated voltage *V* and internal resistance *Ri* are constant. Therefore, power delivered to the load depends upon *RL*. In order to find the value of *RL* for which the value of *P* is maximum, differentiate eq. (*i*) w.r.t. R_L and set the result equal to zero.



(*i*) (*ii*)

$$\text{Thus,} \quad \frac{dP}{dR_L} = V^2\left[\frac{(R_L + R_i)^2 - 2R_L(R_L + R_i)}{(R_L + R_i)^4}\right] = 0$$

$$\text{or} \quad (R_L + R_i)^2 - 2\,R_L\,(R_L + R_i) = 0$$

$$\text{or} \quad (R_L + R_i)\,(R_L + R_i - 2R_L) = 0$$

$$\text{or} \quad (R_L + R_i)\,(R_i - R_L) = 0$$

Since $R_L + R_i$ cannot be zero,

$$\therefore \quad R_i - R_L = 0$$

$$\text{or} \quad R_L = R_i$$

Or, Load resistance = Internal resistance of the source.

Thus, for maximum power transfer, load resistance *RL* must be equal to the internal resistance R_i of the source. Fig. above (*ii*) shows the graph between power delivered (*P*) and R_L. We may extend the maximum power transfer theorem to a linear circuit rather than a single source by means of Thevenin's theorem as under:

The maximum power is obtained from a linear circuit at a given pair of terminals when terminals are loaded by Thevenin's resistance *(R_{Th}) of the circuit.* The above statement is obviously true because by Thevenin's theorem, the circuit is equivalent to a voltage source in series with internal resistance (R_{Th}) of the circuit.

Applications of Maximum Power Transfer Theorem

This theorem is very useful in situations where transfer of maximum power is desirable. Two important applications are listed below:

i. In communication circuits, maximum power transfer is usually desirable. For instance, in a public address system, the circuit is adjusted for maximum power transfer by making load (*i.e*. speaker) resistance equal to source (*i.e*. amplifier) resistance. When source and load have the same resistance, they are said to be *matched*. In most practical situations, the internal resistance of the source is fixed. Also, the device that acts as a load has fixed resistance. In order to make R_L=R_i, we use a transformer. We can use the reflected-resistance characteristic of the transformer to make the load resistance appear to have the same value as the source resistance, thereby ''fooling'' the source into ''thinking'' that there is a match (*i.e.* $RL = Ri$). This technique is called **impedance matching.**

ii. Another example of maximum power transfer is found in starting of a car engine. The power delivered to the starter motor of the car will depend upon the effective resistance of the motor and internal resistance of the battery. If the two resistances are equal (as is the case when battery is fully charged), maximum power will be transferred to the motor to turn on the engine. This is particularly desirable in winter when every watt that can be extracted from the battery is needed by the starter motor to turn on the cold engine. If the battery is weak, its internal resistance is high and the car does not start.

Note.

Electric power systems are never operated for maximum power transfer because the effciency under this condition is only 50%. This means that 50% of the generated power will be lost in the power lines. This situation cannot be tolerated because power lines must operate at much higher than 50% effciency.

Content/Topic 5: Capacitors and capacitance.

It is well known that different bodies hold different charge when given the same potential. This charge holding property of a body is called *capacitance* or *capacity* of the body. In order to store sufficient charge, a device called capacitor is purposely constructed. A capacitor essentially consists of two conducting surfaces (say metal plates) separated by an insulating material (*e.g.*, air, mica, paper etc.). It has the property to store electrical energy in the form of electrostatic charge. The capacitor can be connected in a circuit so that this stored energy can be made to flow in a desired circuit to perform a useful function. Capacitance plays an important role in DC as well as AC circuits. In many circuits (*e.g.*, radio and television circuits), capacitors are intentionally inserted to introduce the desired capacitance. In this chapter, we shall confine our attention to the role of capacitance in DC circuits only.

Capacitor

Any two conducting surfaces separated by an insulating material is called a *capacitor *or* condenser. Its purpose is to store charge in a small space. The conducting surfaces are called the *plates* of the capacitor and the insulating material is called the ***dielectric*.** The most commonly used dielectrics are air, mica, waxed paper, ceramics *etc.* The following points may be noted carefully:

i. The ability of a capacitor to store charge (*i.e.* its capacitance) depends upon the area of plates, distance between plates and the nature of insulating material (or dielectric).
ii. A capacitor is generally named after the dielectric used *e.g.* air capacitor, paper capacitor, mica capacitor *etc.*
iii. The capacitor may be in the form of parallel plates, concentric cylinder or other arrangement.

Capacitance

The ability of a capacitor to store charge is known as its capacitance. It has been found experimentally that charge *Q* stored in a capacitor is directly proportional to the p.d.

$$Q \propto V$$

$$\frac{Q}{V} = \text{Constant} = C$$

The constant *C* is called the capacitance of the capacitor. Hence capacitance of a capacitor can be defined as under: *The ratio of charge on capacitor plates to the p.d. across the plates is called* **capacitance** *of the capacitor*.

Unit of capacitance

We know that:

$$C = Q/V$$

The SI unit of charge is 1 coulomb and that of voltage is 1 volt. Therefore, the SI unit of capacitance is one coulomb/volt which is also called *farad* (Symbol F) in honor of Michael Faraday.

1 farad = 1 coulomb/volt

A capacitor is said to have a capacitance of **1 farad** if a charge of 1 coulomb accumulates on each plate when a p.d. of 1 volt is applied across the plates.

Thus, if a charge of 0·1C accumulates on each plate of a capacitor when a p.d. of 10V is applied across its plates, then capacitance of the capacitor = 0·1/10 = 0·01 F. The farad is an extremely large unit of capacitance. Practical capacitors have capacitances of the order of microfarad (μF) and micro-microfarad (μμF) or picofarad (pF).

$$1\ \mu F = 10^{-6} F \quad ; \quad 1 \mu\mu F \text{ (or 1 pF)} = 10^{-12}\ F$$

Factors Affecting Capacitance

The ability of a capacitor to store charge (*i.e.* its capacitance) depends upon the following factors:

- **Area of plate.** The greater the area of capacitor plates, the larger is the capacitance of the capacitor and *vice-versa.* It is because larger the plates, the greater the charge they can hold for a given p.d. and hence greater will be the capacitance.
- **Thickness of dielectric.** The capacitance of a capacitor is inversely proportional to the thickness (*i.e.* distance between plates) of the dielectric. The smaller the thickness of dielectric, the greater the capacitance and *vice-versa.* When the plates are brought closer, the electrostatic field is intensified and hence capacitance increases.
- **Relative permittivity of dielectric.** The greater the relative permittivity of the insulating material (*i.e.*, dielectric), the greater will be the capacitance of the capacitor and *vice-versa.* It is because the nature of dielectric affects the

electrostatic field between the plates and hence the charge that accumulates on the plates.

A. Electrostatic field: *The branch of engineering which deals with charges at rest is called* **electrostatics**. When a glass rod is rubbed with silk and then separated, the former becomes positively charged and the latter attains equal negative charge. It is because during rubbing, some electrons are transferred from glass to silk. Since glass rod and silk are separated by an insulating medium (*i.e.*, air), they retain the charges. In other words, the charges on them are static or stationary. Note that the word 'electrostatic' means electricity at rest.

Importance of Electrostatics

During the past century, there was considerable increase in the practical importance of electrostatics. A few important applications of electrostatics are given below:

i. Electrostatic generators can produce voltages as high as 10^6 volts. Such high voltages are required for X-ray work and nuclear bombardment.
ii. We use principles of electrostatics for spray of paints, powder, etc.
iii. The principles of electrostatics are used to prevent pollution.
iv. The problems of preventing sparks and breakdown of insulators in high voltage engineering are essentially electrostatic.
v. The development of lightning rod and capacitor are the outcomes of electrostatics.

B. Electric field strength: An electric field is a special state that exists in the space surrounding an electrically charged particle. This special state affects all charged particles placed in the electric field. The true nature of electric fields, as well as the true nature of an electric charge is still unknown to scientists, but the effects of an electric field can be measured and predicted using known equations.

The electric field can be defined as a vector field which describes the relationship between the charge of a test particle introduced in the field and the force exerted upon this charged test particle.

$$\boldsymbol{E} = \frac{\boldsymbol{F}}{q}$$

Where E is the electric field, F is the force exerted on the test particle introduced into the field and q is the charge of the test particle. The unit for electric field is volts per meter [$V \cdot m^{-1}$] or newtons per coulomb [$N \cdot C^{-1}$].

In a simple parallel-plate capacitor, a voltage applied between two conductive plates creates a uniform electric field between those plates. The electric field strength in a capacitor is directly proportional to the voltage applied and inversely proportional to the distance between the plates. This factor limits the maximum rated voltage of a capacitor, since the electric field strength must not exceed the breakdown field strength of the dielectric used in the capacitor. If the breakdown voltage is exceeded, an electrical arc is generated between the plates. This electric arc can destroy some types of capacitors instantly. The standard unit used for electric field strength is volts per meter [$V \cdot m^{-1}$].

C. Types of capacitors: Capacitor is one of mostly used component in electronic circuit design. It plays an important role in many of the embedded applications. It is available at different ratings. It consists of two metal **plates** separated by **a non-conducting substance,** or **dielectric**.

It is often storage depots for analog signals and digital data. The comparisons between the different types of capacitors are generally made with regards to the dielectric used between the plates. Some capacitors look like tubes, small capacitors are often constructed from ceramic materials and then dipped into an epoxy resin to seal them. So here are a few of the more common types of capacitors available. Let's see of them.

i. **Film Capacitors:** Film Capacitors are the most normally ready of numerous types of capacitors, comprising of a generally expansive group of capacitors with the distinction being in their dielectric properties. They are available in almost any value and voltages as high as 1500 volts. They come in any tolerance from 10% to 0.01%. Film capacitors additionally arrive in a combination of shapes and case styles. There are two types of film capacitors, radial lead type and axial lead type. The electrodes of film capacitors may be metalized aluminum or zinc, applied on one or both sides of the plastic film, resulting in metalized film capacitors called film capacitors. The film capacitor is shown in figure below:

Film Capacitors

Film Capacitors are sometimes called plastic capacitors because which use polystyrene, polycarbonate or Teflon as their dielectrics. These film sorts need a much thicker dielectric film to lessen the danger of tears or puncture in the film, and is therefore more suited to lower capacitance values and bigger case sizes. The film capacitors are physically larger and more expensive, they are not polarized, so they can be used in AC voltage applications, and they have much more stable electrical parameters. Dependence of capacitance and dissipation factor, they can be applied in frequency stable Class 1 applications, replacing Class 1 ceramic capacitors.

ii. **Ceramic Capacitors:** Ceramic capacitors are used in high frequency circuits such as audio to RF. They are also the best choice for high frequency compensation in audio circuits. These capacitors are also called as disc capacitors. Ceramic capacitors are made by coating two sides of a small porcelain or ceramic disc with silver and are then stacked together to make a capacitor. One can make both low capacitance and high capacitance in ceramic capacitors by changing the thickness of the ceramic disc used. The ceramic capacitor is shown in figure below:

Ceramic Capacitors

They come in values from a few Pico farads to 1 microfarad. The voltage range is from a few volts up to many thousands of volts. Ceramics are inexpensive to manufacture and they come with several dielectric types. The tolerance of ceramics is not great but for their intended role in life they work just fine.

iii. **Electrolytic Capacitors:** These are the most prevalently used capacitors which have a wide tolerance capacity. Electrolytic capacitors are available with working voltages up to about 500V, although the highest capacitance values are not available at high voltage and higher temperature units are available, but uncommon. There are two types of electrolytic capacitor, tantalum and aluminum in common.

Tantalums capacitors have ordinarily better exhibition, higher value, and are ready just in a more limited extend of parameters. The dielectric properties of tantalum oxide are much superior to those of aluminum oxide giving an easier leakage current and better capacitance strength which makes them suitable for obstructing, decoupling, filtering applications.

The thickness of the aluminum oxide film and heightened breakdown voltage gives the capacitors exceptionally elevated capacitance values for their size. In

a capacitor the foil plates are anodized by a dc current thus setting of the extremity of plat material and confirming polarity of its side.
The tantalum and aluminum capacitors are shown in figure below:

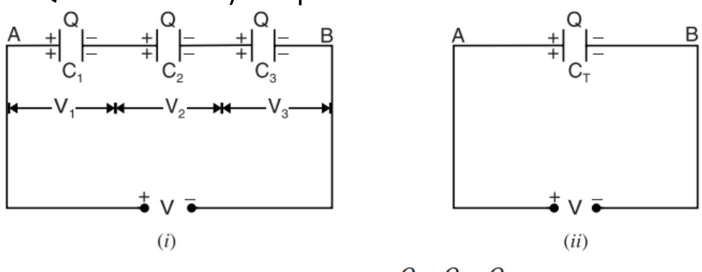
Electrolytic Capacitors

iv. **Variable Capacitors:** A Variable Capacitor is one whose capacitance may be intentionally and repeatedly changed mechanically. This type of capacitors utilized to set frequency of resonance in LC circuits, for instance, to adjust the radio for impedance matching in antenna tuner devices.

Variable Capacitors

D. Series, parallel and mixed connection of capacitors:

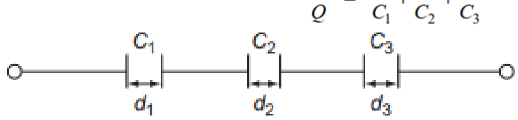
i. **Capacitors in Series:** Consider three capacitors, having capacitances *C*1, *C*2 and *C*3 farad respectively, connected in series across a p.d. of *V* volts [See Fig. (*i*)]. In series connection, charge on each capacitor is the *same (*i.e.* +*Q* on one plate and -*Q* on the other) but p.d. across each is different.



$$V = V_1 + V_2 + V_3 = \frac{Q}{C_1} + \frac{Q}{C_2} + \frac{Q}{C_3}$$

$$= Q\left(\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}\right)$$

$$\frac{V}{Q} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$



Capacitors in series.

smaller when measured a second time. We can therefore state that an increase in dielectric thickness (*d*) causes a decrease in capacitance. **Capacitance is inversely proportional to dielectric thickness**:

$$C \propto \frac{1}{d}$$

If, however, we were to keep the dielectric thickness constant and to vary the area of the plates (a), we would find that a change in plate area would cause a corresponding change in capacitance. The larger the plate area the larger the capacitance. **Capacitance is directly proportional to plate area**:

$$C \propto a$$

Combining these two effects we can see that

$$C \propto \frac{a}{d}$$

Consider the effect of connecting three similar capacitors in above Figure, we know that

$$C \propto \frac{1}{d}$$

$$\therefore d \propto \frac{1}{C} \quad \text{so} \quad d_1 \propto \frac{1}{C_1} \quad d_2 \propto \frac{1}{C_2} \quad d_3 \propto \frac{1}{C_3}$$

If we were to combine all the dielectrics, we would have one capacitor of dielectric thickness *d*t and capacitance *C*:

$$d_t \propto \frac{1}{C}$$

But

$$d_t = d_1 + d_2 + d_3 = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$

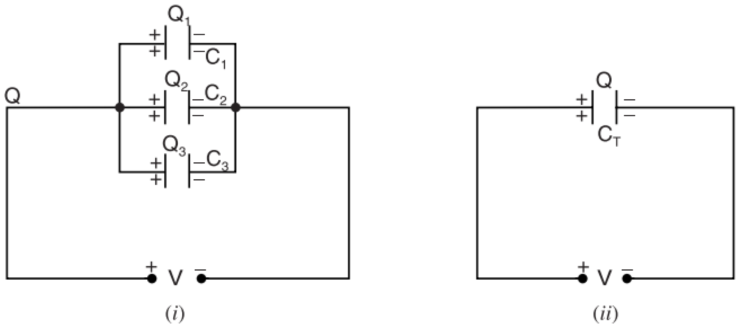
Also

$$d_t = \frac{1}{C} \quad \therefore \frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \cdots$$

Just as the current is common to all parts of a series resistive circuit, so is charge common in a series capacitive circuit. Therefore

$$Q = CV \quad Q = C_1V_1 \quad Q = C_2V_2 \quad Q = C_3V_3 \cdots$$

ii. **Capacitors in Parallel:** Consider three capacitors, having capacitances *C*1, *C*2 and *C*3 farad respectively, connected in parallel across a p.d. of *V* volts [See Fig (*i*)]. In parallel connection, p.d. across each capacitor is the same but charge on each is different.



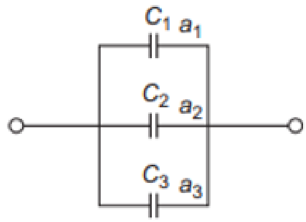
$$Q = Q_1 + Q_2 + Q_3 = C_1 V + C_2 V + C_3 V$$
$$= V(C_1 + C_2 + C_3)$$
$$Q/V = C_1 + C_2 + C_3$$

But *Q*/*V* is the total capacitance *CT* of the parallel combination [See Fig. (*ii*)].

$C_T = C_1 + C_2 + C_3$ Thus, capacitors in parallel are treated in the same manner as are resistors in series.

Note.

Capacitors may be connected in parallel to obtain larger values of capacitance than are available from individual units.



Capacitor in parallel

Let us arrange three similar capacitors in parallel, we know that *C*-*a*. Therefore, *C*1-a_1, C_2-a_2 and C_3-a_3. As the plates connected to either side of the supply are common, we could replace the arrangement with one capacitor ***C*** of plate area a_T.

$aT = a1 + a2 + a3$

$C_T = C_1 + C_2 + C_3$

In this case it is the voltage that is common and the charge *Q* behaves like the current in a parallel resistive circuit. So,

$$Q = CV \quad Q_1 = C_1 V \quad Q_2 = C_2 V \quad Q_3 = C_3 V$$

E. Capacitors' applications: Capacitors are used extensively in electrical engineering.

- In the field of installation work, they are mainly used for motor starting, power factor correction and radio interference suppression and to minimize the stroboscopic effects in fluorescent lighting circuits.
- There are use in power factor correction and fluorescent lighting is dealt.
- Capacitors have applications in both electrical and electronics. They are used in filter applications, energy storage systems, motor starters and signal processing devices.

LO 1.3 – Apply magnetism and electromagnetism.

Content/Topic 1: Introduction to magnetism.

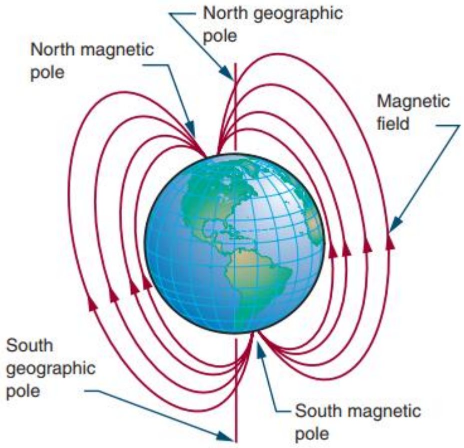
A. Magnetic field: The word ***magnet*** is derived from magnetite, the name of a mineral found in Magnesia, a part of Asia. This mineral is a natural magnet.
Another type of magnet is the ***artificial magnet***. This magnet is created by rubbing a piece of soft iron with a piece of magnetite. A third type of magnet is the ***electromagnet*** created by current flowing through a coil of wire. Magnets come in various shapes (Figure below). Among the more common shapes are the horseshoe, the bar or rectangle, and the ring. Magnets that retain their magnetic properties are called ***permanent magnets***. Magnets that retain only a small portion of their magnetic properties are called ***temporary magnets.*** Magnets are made of metallic or ceramic materials. Alnico (*al*uminum, *ni*ckel, and *co*balt) and Cunife. Magnets come in various sizes and shapes.

(copper [*Cu*], *ni*ckel, and Iron [*Fe*]) are two metallic alloys used for magnets. The earth itself is a huge magnet (Figure below). The earth's magnetic north and south poles are situated close to the geographic North and South Poles. If a bar magnet is suspended, the magnet aligns in a north–south direction, with one end pointing toward the North Pole of the earth and the other toward the South Pole. This is the principle behind the compass.

It is also the reason the two ends of the magnet are called the north pole and the south pole. Magnets align in a north–south direction because of laws similar to those of positive and negative charges: Unlike magnetic poles attract each other and like magnetic poles repel each other. The color code for a magnet is red for the north pole and blue for the south pole.

Magnetism, the property of the magnet, can be traced to the atom. As electrons orbit around the nucleus of the atom, they spin on their axis, like the earth as it orbits the sun. This moving electrostatic charge produces a magnetic field. The direction of the magnetic field depends on the electron's direction of spin. Iron, nickel, and cobalt are the only naturally magnetic elements. Each of these materials has two valences.

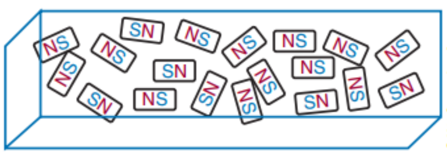
The earth's magnetic north and south poles are situated close to the geographic North and South Poles.



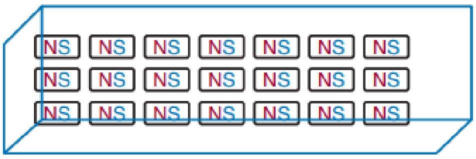
electrons that spin in the same direction. Electrons in other materials tend to spin in opposite directions and this cancels their magnetic characteristics.

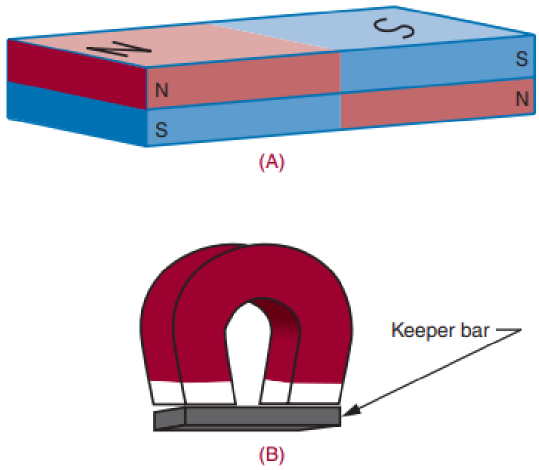
Ferromagnetic materials are materials that respond to magnetic fields. In ferromagnetic materials, the atoms combine into **domains**, or groups of atoms arranged in the form of magnets. In an unmagnetized material, the magnetic domains are randomly arranged, and the net magnetic effect is zero (Figure 18-3). When the material becomes magnetized, the domains align in a common direction and the material becomes a magnet (Figure below).

If the magnetized material is divided into smaller pieces, each piece becomes a magnet with its own poles. Evidence of this "domain theory" is that if a magnet is heated or hit repeatedly with a hammer, it loses its magnetism (the domains are jarred back into a random arrangement). Also, if an artificial magnet is left by itself, it slowly loses its magnetism. To prevent this loss, bar magnets should be stacked on top of each other with opposite poles together; keeper bars should be placed across horseshoe magnets (Figure below). Both methods maintain the magnetic field.

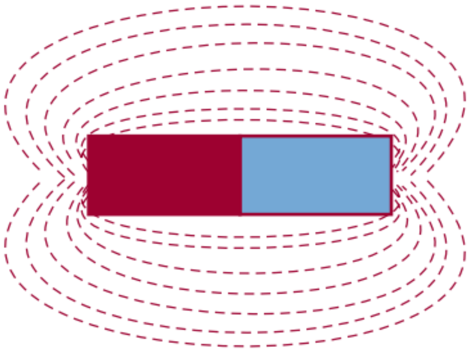
The domains in unmagnetized material are randomly arranged with no overall magnetic effect 	To prevent loss of magnetism, (A) bar magnets are stacked on top of each other, and (B) keeper bars are placed across horseshoe magnets.

When material becomes magnetized, all the domains align in a common direction.





A **magnetic field** consists of invisible lines of force that surround a magnet. These lines of force are called **flux lines**.



Magnetic lines of flux can be seen in patterns of iron filings, they can be "seen" by placing a sheet of paper over a magnet and sprinkling iron filings on the paper. When the paper is lightly tapped, the iron filings arrange themselves into a definite pattern that reflects the forces attracting them (Figure above).

Flux lines have several important characteristics:

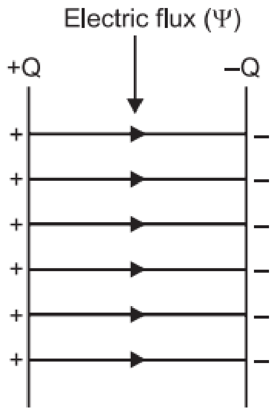
- They have polarity from north to south.
- They always form a complete loop.
- They do not cross each other because like polarities repel.
- They tend to form the smallest loop possible, because unlike poles attract and tend to pull together.
- The characteristic that determines whether a substance is ferromagnetic is called **permeability**. Permeability is the ability of a material to accept magnetic lines of force. A material with great permeability offers less resistance to flux lines than air.

B. Magnetic flux and flux density: The Figure below show electric field between two equal and oppositely charged parallel plates. The electric field is considered to be filled with electric flux and each unit of charge is assumed to give rise to one unit of electric flux. The symbol for electric flux is the Greek letter Ψ(psi) and it is measured in coulombs. Thus in Fig. below, the charge on each plate is *Q* coulombs so that electric flux between the plates is

Electric flux, Ψ **= *Q*** coulombs

Electric flux is a measure of electric lines of force. The greater the electric flux passing through an area, the greater is the number of electric lines of force passing through that area and *vice-versa*. Suppose there is a charge of ***Q*** coulombs in a medium of absolute permittivity $\boldsymbol{\varepsilon = \varepsilon_0 \varepsilon_r}$, *where* $\boldsymbol{\varepsilon_r}$ is the relative permittivity of the medium. Then number of electric lines of force ***N*** produced by this charge is

$$N = \frac{Q}{\varepsilon} = \frac{Q}{\varepsilon_0 \varepsilon_r}$$



i. The electric flux through a surface area has maximum value when the surface is perpendicular to the electric field.
ii. The electric flux through the surface is zero when the surface is parallel to the electric field.

Flux density: symbol *D*; unit tesla (T) Just as population densities are measured in people per km2, flux density is measured in flux per m2 or Wb/m2. This unit, however, is known as the **tesla** (T). The **electric flux density** at any section in an electric field is the electric flux crossing normally per unit area of that section i.e.

Electric flux density $D = \frac{\Psi}{A}$

For example, when we say that electric flux density in an electric field is 4C/m^2, it means that 4C of electric flux passes normally through an area of 1m^2. Electric flux density is a vector quantity; possessing both magnitude and direction. Its direction is the same as the direction of electric intensity.

C. Magneto-motive force and magnetic field strength:

i. Magnetomotive force, also known as magnetic potential, is the property of certain substances or phenomena that gives rise to magnetic field s. Magnetomotive force is analogous to electromotive force or voltage in electricity.

The standard unit of magnetomotive force is the ampere-turn (AT), represented by a steady, direct electrical current of one ampere (1 A) flowing in a single-turn loop of electrically conducting material in a vacuum . Sometimes a unit called the gilbert (G) is used to quantify magnetomotive force. The gilbert is defined differently, and is a slightly smaller unit than the ampere-turn. To convert from ampere-turns to gilberts, multiply by 1.25664. Conversely, multiply by 0.795773.

Although the standard definition of magnetomotive force involves current passing through an electrical conductor, permanent magnet s also exhibits magnetomotive force. The same is true for planets with magnetic fields, such as the Earth, Jupiter, Saturn, Uranus, and Neptune. The Sun also generates magnetomotive forces, particularly in the vicinity of sunspots.

ii. **Magnetic field strength**, also called **magnetic intensity** or **magnetic field intensity**, the part of the magnetic field in a material that arises from an external current and is not intrinsic to the material itself. It is expressed as the vector **H** and is measured in units of amperes per meter.

$$\mathbf{H} = \mathbf{B}/\boldsymbol{\mu} - \mathbf{M},$$

where **B** is the magnetic flux density, a measure of the actual magnetic field within a material considered as a concentration of magnetic field lines, or flux, per unit cross-sectional area; **μ** is the magnetic permeability; and **M** is the magnetization. The magnetic field **H** might be thought of as the magnetic field produced by the flow of current in wires and the magnetic field **B** as the total magnetic field including also the contribution **M** made by the magnetic properties of the materials in the field. When a current flow in a wire wrapped on a soft-iron cylinder, the magnetizing field **H** is quite weak, but the actual average magnetic field **(B)** within the iron may be thousands of times stronger because B is greatly enhanced by the alignment of the iron's myriad tiny natural atomic magnets in the direction of the field.

D. Permeability and Reluctance: The reluctance (S), of a material is a measure of how difficult it is to produce flux within it. Permeability, on the other hand, is a measure of how easily a magnetic field can be set up in a material. However, rather than just being a measure of the ratio of the m.m.f. to the flux it produces, permeability considers the distribution of the flux within the material. Permeability is the ratio of the flux density of the magnetic field within the material, to its field strength.

$$\mu = B/H.$$

- μ = the permeability of the material measured in Henries per meter (Hm^{-1}).
- B = flux density measured in Tesla (T).
- H = the field strength measured in Amperes per meter (Am^{-1}).

Relative permeability: When we refer to the permeability of a material, then rather than actually stating its absolute permeability, we tend to quote what is referred to, as its relative permeability. Relative permeability refers to how much more permeable the material is, in comparison to the absolute permeability of free space (i.e. a vacuum). The permeability of the material can be calculated by multiplying its relative permeability, by the permeability of free space.

$$\mu = \mu_o \times \mu_r.$$

- μ = the permeability of the material measured in Henries per meter (Hm^{-1}).
- μ_o = the permeability of free space measured in Henries per meter (Hm^{-1}).

- μ_r = the relative permeability of the material (no units).

Note: the permeability of free space μ_o is 4 PI x10^{-7} H/m. The relative permeability of air is very close to 1, so in practice we can use the same value for the permeability of air.

In both AC and DC fields, the **reluctance** is the ratio of the magnetomotive force (MMF) in a magnetic circuit to the magnetic flux in this circuit. In a pulsating DC or AC field, the reluctance also pulsates. The definition can be expressed as follows:

$$\mathcal{R} = \frac{\mathcal{F}}{\Phi}$$

Where

- (R) is the reluctance in ampere-turns per weber (a unit that is equivalent to turns per henry). "Turns" refers to the winding number of an electrical conductor comprising an inductor.
- (F) is the magnetomotive force (MMF) in ampere-turns
- *Φ* ("Phi") is the magnetic flux in webers.

Magnetic flux always forms a closed loop, as described by *Maxwell's equations*, but the path of the loop depends on the reluctance of the surrounding materials. It is concentrated around the path of least reluctance. Air and vacuum have high reluctance, while easily magnetized materials such as soft iron have low reluctance. The concentration of flux in low-reluctance materials forms strong temporary poles and causes mechanical forces that tend to move the materials towards regions of higher flux so it is always an attractive force (pull). The reluctance of a uniform magnetic circuit can be calculated as:

$$\mathcal{R} = \frac{l}{\mu_0 \mu_r A} = \frac{l}{\mu A}$$

where

- *L* is the length of the circuit in meters
- μ_o is the permeability of vacuum, equal to

$$4\pi \times 10^{-7} \, \frac{\text{henry}}{\text{metre}} \text{ (or, } \frac{\text{kilogram} \times \text{meter}}{\text{ampere}^2 \times \text{second}^2} = \frac{\text{second} \times \text{volt}}{\text{ampere} \times \text{meter}} = \frac{\text{joule}}{\text{ampere}^2 \times \text{meter}}\text{)}$$

- μr is the relative magnetic permeability of the material (dimensionless)
- μ is the permeability of the material ($\mu = \mu_o \mu_r$)
- *A* is the cross-sectional area of the circuit in square meters.

E. **Types magnetic materials (Ferromagnetic, Paramagnetic, Ferri-magnetic, Electromagnet):** To study magnetic properties of magnetic materials, the material is usually placed in a uniform magnetic field and then the magnetic field is varied. There are three major kinds of magnetic behavior:

i. **Diamagnetic materials:** These materials are barely magnetized when placed in a magnetic field. Magnetic dipoles in these substances tend to align in opposition to the applied field. In effect, they produce an internal magnetic field that opposes the applied field and the substance tends to repel the external field around it. This opposing field disappears as soon as the external field is removed. Ex: Gold, water, mercury and even animals!

ii. **Paramagnetic materials:** In these materials the magnetic dipoles in the Magnetic Materials tend to align along the applied magnetic field and thus reinforcing the applied magnetic field. Such substances are attracted by a magnet if it applies a sufficiently strong field. It must be noted that such materials are still feeble magnetized and the magnetization disappears as soon as the external field is removed. The magnetization (**M**) of such materials was discovered by Madam Curie and is dependent on the external magnetic field (**B**) and temperature T as:

$$\overrightarrow{M} = C\frac{\overrightarrow{B}}{T}$$

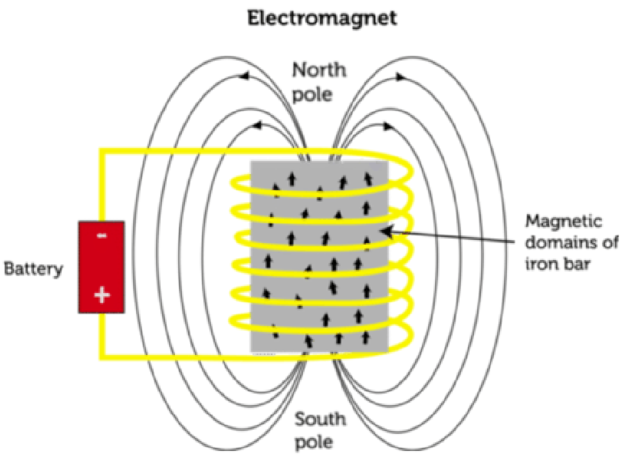
Where C= Curie Constant,
Ex: Liquid oxygen, sodium, platinum, salts of iron and nickel.

iii. **Ferromagnetic materials**: We are most familiar with these materials as they exhibit the strongest magnetic behavior. Magnetic dipoles in these materials are arranged into domains where the arrangements of individual magnetic dipoles are essentially perfect that can produce strong magnetic fields. Normally, these domains are usually randomly arranged and thus the magnetic field of each domain is cancelled by another and the entire material does not show any magnetic behavior.

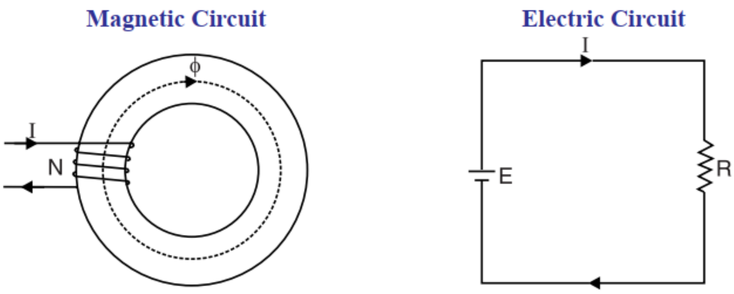
However, when an external field is applied, the domains reorient themselves to reinforce the external field and produce a strong internal magnetic field that is along the external field. Upon, removal of the external field, most of the domains stay put and continues to be aligned in the direction of the (erstwhile) magnetic field. Thus, the magnetic field of the Magnetic Materials persists even when the external field disappears. This property is used to produce Permanent magnets that we use every day. Iron, cobalt, nickel, neodymium and their alloys are usually highly ferromagnetic and are used to make permanent magnets.

iv. **Ferri-magnetic material**: In physics, a ferrimagnetic material is one that has populations of atoms with opposing magnetic moments, as in anti-ferromagnetism; however, in ferrimagnetic materials, the opposing moments are unequal and a spontaneous magnetization remains. This happens when the populations consist of different materials or ions.

v. **Electromagnet material**: An electromagnet is a type of magnet in which the magnetic field is produced by an electric current. **Electromagnets** usually consist of wire wound into a coil. A current through the wire creates a magnetic field which is concentrated in the hole, denoting the center of the coil.



F. Comparison between electrical and magnetic quantities: There are many points of similarity between magnetic and electric circuits. However, the two circuits are not analogous in all respects. A comparison of the two circuits is given below in the tabular form.



Similarities

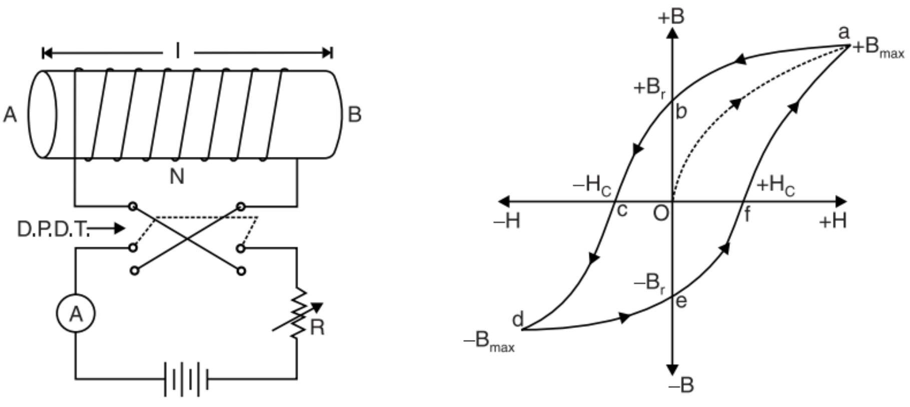
1.	The closed path for magnetic flux is called a magnetic circuit.	1.	The closed path for electric current is called an electric circuit.
2.	Flux, $\phi = \dfrac{\text{m.m.f.}}{\text{reluctance}}$	2.	Current, $I = \dfrac{\text{e.m.f.}}{\text{resistance}}$
3.	m.m.f. (ampere-turns)	3.	e.m.f. (volts)
4.	Reluctance, $S = \dfrac{l}{a\mu_0\mu_r}$	4.	Resistance, $R = \rho\dfrac{l}{a}$
5.	Flux density, $B = \dfrac{\phi}{a}\,\text{Wb/m}^2$	5.	Current density, $J = \dfrac{I}{a}\,\text{A/m}^2$
6.	m.m.f. drop $= \phi\, S$	6.	Voltage drop $= I\,R$
7.	Magnetic intensity, $H = N\,I/l$	7.	Electric intensity, $E = V/d$
8.	Permeance	8.	Conductance.
9.	Permeability	9.	Conductivity

Dissimilarities

1. Truly speaking, magnetic flux does not flow.	**1.** The electric current acutally flows in an electric circuit.
2. There is no magnetic insulator. For example, flux can be set up even in air (the best known magnetic insulator) with reasonable m.m.f.	**2.** There are a number of electric insulators. For instance, air is a very good insulator and current cannot pass through it.
3. The value of μ_r is not constant for a given magnetic material. It varies considerably with flux density (*B*) in the material. This implies that reluctance of a magnetic circuit is not constant rather it depends upon *B*.	**3.** The value of resistivity (ρ) varies very slightly with temperature. Therefore, the resistance of an electric circuit is practically constant. This salient feature calls for different approach to the solution of magnetic and electric circuits.
4. No energy is expended in a magnetic circuit. In other words, energy is required in creating the flux, and not in maintaining it.	**4.** When current flows through an electric circuit, energy is expended so long as the current flows. The expended energy is dissipated in the form of heat.

G. Hysteresis and hysteresis losses: When a magnetic material is subjected to a cycle of magnetization (*i.e*. it is magnetized first in one direction and then in the other), it is found that flux density *B* in the material lags behind the applied magnetizing force *H*. This phenomenon is known as hysteresis. The phenomenon of lagging of flux density (B) behind the magnetizing force (H) in a magnetic material subjected to cycles of magnetization is known as **magnetic hysteresis.**

The term 'hysteresis' is derived from the Greek word *hysterein* meaning to lag behind. If a piece of magnetic material is subjected to *one cycle of magnetization, the resultant ***B-H*** curve is a closed loop *abcdefa* called *hysteresis loop* [See Fig. below (*ii*)]. Note that ***B*** always lags behind ***H***. Thus, at point **'b', *H*** is zero but flux density *B* has a positive finite value *ob*. Similarly, at point **'*e*', *H*** is zero, but flux density has a finite negative value *one*. This tendency of flux density *B* to lag behind magnetizing force *H* is known as magnetic hysteresis



(*i*) (*ii*)

- **Hysteresis Loop:** Consider an unmagnetized iron bar *AB* wound with *N* turns as shown in Fig. above (*i*). The magnetizing force *H* (= *NI*/*l*) produced by this solenoid can be changed by varying the current through the coil. The double-pole, double-throw switch (DPDT) is used to reverse the direction of current through the coil. We shall see that *when the iron piece is subjected to a cycle of magnetization, the resultant B-H curve traces a loop abcdefa called hysteresis loop.*

i. We start with unmagnetized solenoid *AB*. When the current in the solenoid is zero, $H = 0$ and hence B in the iron piece is 0. As H is increased (by increasing solenoid current), the flux density ($+ B$) also increases until the point of maximum flux density ($+ B_{max}$) is reached. The material is saturated and beyond this point, the flux density will not increase regardless of any increase in current or magnetizing force. Note that *B-H* curve of the iron follows the path *oa*.

ii. If now H is gradually reduced (by reducing solenoid current), it is found that the flux density B does not decrease along the same line by which it had increased but follows the path *ab*. At point *b*, the magnetizing force H is zero but flux density in the material has a finite value $+ B_r$ (= *ob*) called **residual flux density.** It means that after the removal of *H,* the iron piece still retains some magnetism (*i.e*. $+ Br$). In other words, B lags behind H. The greater the lag, the greater is the residual magnetism (*i.e*. ordinate *ob*) retained by the iron piece. The power of retaining residual magnetism is called **retentivity** of the material.

The hysteresis effect (*i.e*. lagging of B behind H) in a magnetic material is due to the opposition offered by the magnetic domains (or molecular magnets) to the turning effect of magnetizing force. Once arranged in an orderly position by the magnetizing force, the magnetic domains do not return exactly to the original positions. In other words, the material retains some magnetism even after the removal of magnetizing force. This results in the lagging of B behind H.

iii. To demagnetize the iron piece (*i.e*. to remove the residual magnetism *ob*), the magnetizing force H is reversed by reversing the current through the coil. When H is gradually increased in the reverse direction, the *B-H* curve follows the path *bc* so that when $H = oc$, the residual magnetism is zero. The value of H (= *oc*) required to wipe out residual magnetism is known as **coercive force** (H_c).

iv. If H is further increased in the reverse direction, the flux density increases in the reverse direction ($- B$). This process continues (curve *cd*) till the material is saturated in the reverse direction (-*Bmax* point) and can hold no more flux.

v. If *H* is now gradually decreased to zero, the flux density also decreases and the curve follows the path *de*. At point *e*, the magnetizing force is zero but flux density has a finite value -*Br* (= *oe*) — the residual magnetism.

vi. In order to neutralize the residual magnetism *oe*, magnetizing force is applied in the positive direction (*i.e*. original direction) so that when *H* = *of* (coercive force *Hc*), the flux density in the iron piece is zero. Note that the curve follows the path *ef*. If *H* is further increased in the positive direction, the curve follows the path *fa* to complete the loop *abcdefa.*

Thus, when a magnetic material is subjected to one cycle of magnetization, B always lags behind H so that the resultant B-H curve forms a closed loop, called **hysteresis loop.**

- **Hysteresis Loss:** When a magnetic material is subjected to a cycle of magnetization (*i.e.* it is magnetized first in one direction and then in the other), an energy loss takes place due to the molecular friction in the material. That is, the domains (or molecular magnets) of the material resist being turned first in one direction and then in the other. Energy is thus expended in the material in overcoming this opposition. This loss is in the form of heat and is called *hysteresis loss*. Hysteresis loss is present in all those electrical machines whose iron parts are subjected to cycles of magnetization. The obvious effect of hysteresis loss is the rise of temperature of the machine.
  - **i.** Transformers and most electric motors operate on alternating current. In such devices, the flux in the iron changes continuously, both in value and direction. Hence hysteresis loss occurs in such machines.
  - **ii.** Hysteresis loss also occurs when an iron part rotates in a constant magnetic field *e.g.* d.c. machines.

- **Calculation of Hysteresis Loss:** We will now show that area of hysteresis loop represents the †energy loss/m3/cycle. Let

  l = length of the iron bar

  A = area of *X*-section of bar

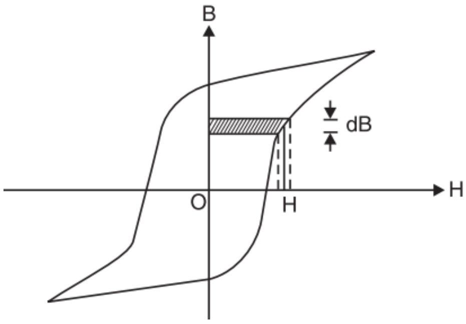
  N = No. of turns of wire of solenoid

  Suppose at any instant the current in the solenoid is *i*. Then

$$H = \frac{Ni}{l} \quad \text{or} \quad i = \frac{Hl}{N}$$

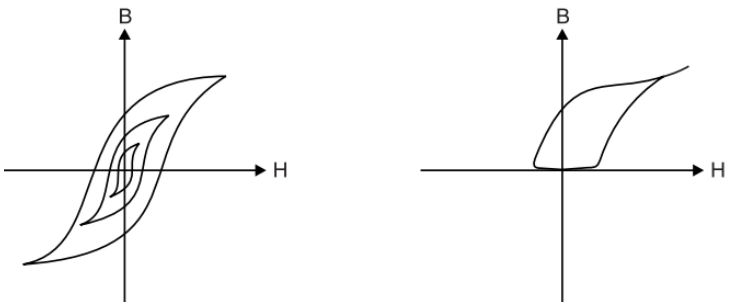
Suppose the current increases by *di* in a small time *dt*. Tis will cause the flux density to increase by *dB* [See Fig. below] and hence an increase in flux *d*ϕ (= *AdB*). This causes an e.m.f. *e* to be induced in the solenoid.

$$e = N\frac{d\phi}{dt} = NA\frac{dB}{dt}$$



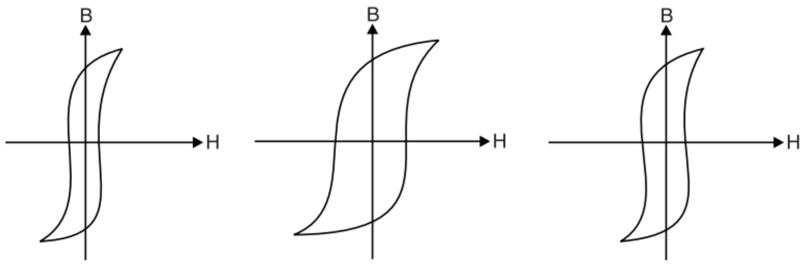
By Lenz's law, this e.m.f. opposes the current *i* so that energy *dW* is spent in overcoming this opposing e.m.f.

- **Factors Affecting the Shape and Size of Hysteresis Loop:** There are three factors that affect the shape and size of hysteresis loop.
  i. **The material.** The shape and size of the hysteresis loop largely depends upon the nature of the material. If the material is easily magnetized, the loop will be narrow. On the other hand, if the material does not get magnetized easily, the loop will be wide. Further, different materials will saturate at different values of magnetic flux density thus affecting the height of the loop.
  ii. **The maximum flux density.** The loop area also depends upon the maximum flux density that is established in the material. This is illustrated in Fig. below. It is clear that the loop area increases as the alternating magnetic field has progressively greater peak values.



  iii. **The initial state of the specimen.** The shape and size of the hysteresis loop also depends upon the initial state of the specimen. To illustrate this point, refer to Fig. above. It is clear that the specimen is already saturated to start with. The magnetic flux density is then reduced to zero and finally the specimen is returned to the saturated condition.

- **Importance of Hysteresis Loop**: The shape and size of the hysteresis loop largely depends upon the nature of the material. The choice of a magnetic material for a particular application often depends upon the shape and size of the hysteresis loop. A few cases are discussed below by way of illustration.
    i. The smaller the hysteresis loop area of a magnetic material, the less is the hysteresis loss. The hysteresis loop for silicon steel has a very small area [See Fig. below (i)]. For this reason, silicon steel is widely used for making transformer cores and rotating machines which are subjected to rapid reversals of magnetization.

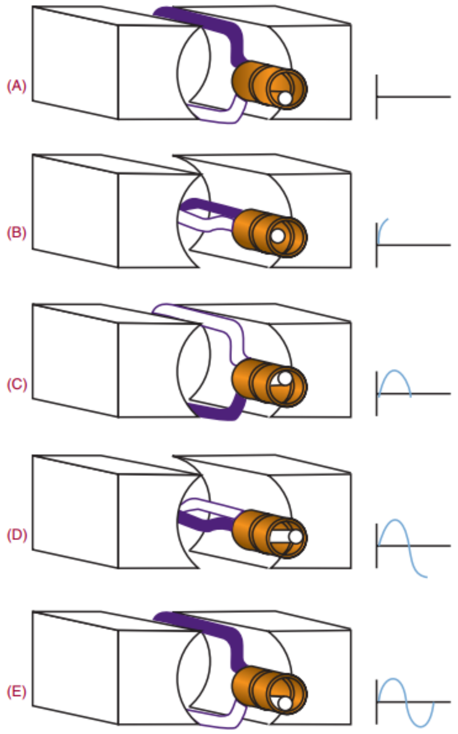
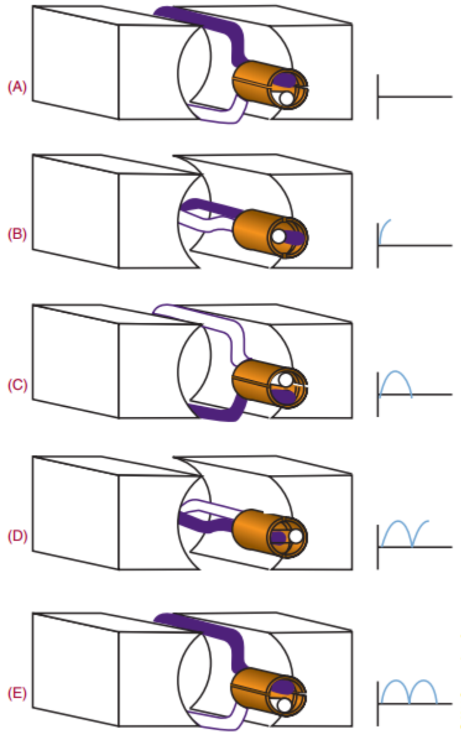


    ii. The hysteresis loop for hard steel [See Fig. above (*ii*)] indicates that this material has high retentivity and coercivity. Therefore, hard steel is quite suitable for making permanent magnets. But due to the large area of the loop, there is greater hysteresis loss. For this reason, hard steel is not suitable for the construction of electrical machines.
    iii. The hysteresis loop for wrought iron [See Fig. above (*iii*)] shows that this material has fairly good residual magnetism and coercivity. Hence, it is suitable for making cores of electromagnets.

H. Applications of magnetism: An alternating current (AC) generator converts mechanical energy to electrical energy by utilizing the principle of electromagnetic induction. The mechanical energy is needed to produce motion between the magnetic field and the conductor.

The below Figure shows a loop of wire (conductor) being rotated (moved) in a magnetic field. The loop has a light and dark side for ease of explanation. At the point shown in part A, the dark half is parallel to the lines of force, as is the light half. No voltage is induced. As the loop is rotated toward the position shown in part B, the lines of force are cut and a voltage is induced. The induced voltage is greatest at this position, when the motion is at right angles to the magnetic field. As the loop is rotated to position C, fewer lines of force are cut and the induced voltage decreases from the maximum value to zero volts. At this point, the loop has rotated 180º, or half a circle.

The direction of current flow can be determined by applying the left-hand rule for generators. The arrow shows the direction of current flow at position B. When the loop is rotated to position D, the action reverses. As the dark half moves up through the magnetic lines of force and the light half moves down, applying the left-hand rule for generators shows that the induced voltage changes polarities. The voltage reaches a peak.

Induced voltage in an AC generator	Induced voltage in a DC generator.
	

at position D and decreases until the loop reaches the original position. The induced voltage has completed one cycle of two alternations. The Rotating loop is called an **armature**, and the source of the electromagnetic field is called the **field**. The armature can have any number of loops.

The term *armature* refers to the part that rotates in the magnetic field, regardless of whether it consists of one loop or multiple loops. The **frequency** of the alternating current or voltage is the number of complete cycles completed per second. The speed of rotation determines the frequency. An **ac generator** is often called an **alternator** because it produces alternating current.

A DC (direct current) generator also converts mechanical energy into electrical energy. It functions like an AC generator with the exception that it converts AC voltage to DC voltage. It does this with a device called a **commutator**, as shown in Figure above.

The output is taken from the commutator, a split ring. When the loop is rotated from position A to position B, a voltage is induced. The induced voltage is greatest as the motion is at right angles to the magnetic field. As the loop is rotated to position C, the induced voltage decreases from the maximum value to zero. As the loop continues to rotate to position D, a voltage is induced, but the commutator reverses the output polarity so that it remains the same as before.

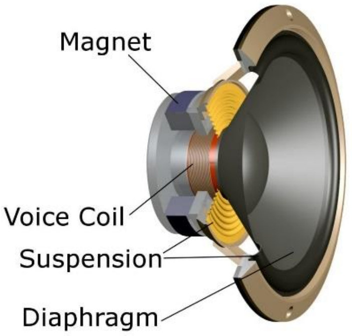
Examples of various types of relays	Examples of types of solenoids.
	

The loop then returns to the original position, E. The voltage generated from the commutator pulsates, but in one direction only, varying twice during each revolution between zero and maximum.

i. A **relay** is an electromechanical switch that opens and closes with an electromagnetic coil (Figure above). As a current flow through the coil, it generates a magnetic field that attracts the plunger, pulling it down. As the plunger is pulled down, it closes the switch contacts. When the current through the coil stops, a spring pulls the armature back to its original position and opens the switch. A relay is used where it is desirable to have one circuit control another circuit. It electrically isolates the two circuits. A small voltage or current can control a large voltage or current. A relay can also be used to control several circuits some distance away. A doorbell is an application of the relay. The striker to ring the bell is attached to the plunger. As the doorbell is pressed, the relay coil is energized, pulling down the plunger and striking the bell. As the plunger moves down, it opens the circuit, de-energizing the relay. The plunger is pulled back by the spring closing the switch contacts, energizing the circuit again, and the cycle repeats until the button is released.

ii. A **solenoid** is similar to a relay (Figure above). A coil, when energized, pulls a plunger that does some mechanical work. This is used on some door chimes where the plunger strikes a metal bar. It is also used on automotive starters. The plunger pulls the starter gear in to engage the flywheel to start the engine. Phonograph pickups use the electromagnetic principle. A magnetic field is produced by a permanent magnet that is attached to a stylus (needle). The permanent magnet is placed inside a small coil. As the stylus is tracked through the groove of a record, it moves up and down and from side to side in response to the audio signal recorded. The movement of the magnet in the coil induces a small voltage that varies at the audio signal response. The induced voltage is then amplified and used to drive a loudspeaker, reproducing the audio signal.

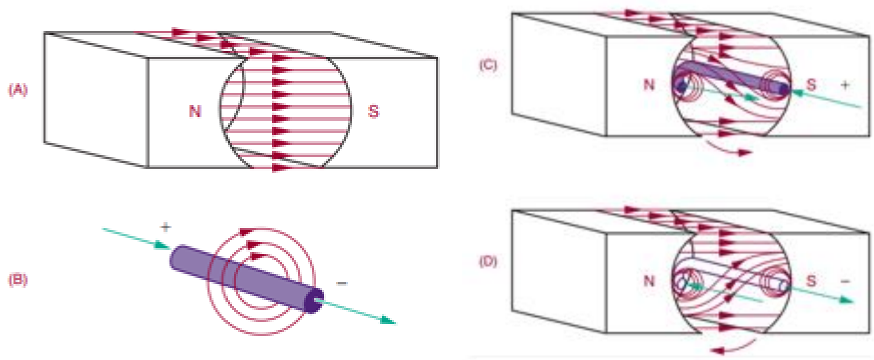
iii. **loudspeakers** are used for all types of audio amplification. Most speakers today are constructed of a moving coil around a permanent magnet. The magnet produces a stationary magnetic field. As current is passed through the coil, it produces a magnetic field that varies at the rate of the audio signal. The varying magnetic field of the coil is attracted and repelled by the magnetic field of the permanent magnet. The coil is attached to a cone that moves back and forth in response to the audio signal. The cone moving back and forth moves the air, reproducing the audio sound.



Magnetic recording is used for cassette recorders, video recorders, reel-to-reel recorders, floppy disk drives, and hard disk drives. All these devices use the same electromagnetic principle to store information. A signal is stored on the tape or disk with a record head, to be read back later with a playback head. In some equipment, the record and playback head are combined in one package or they may be the same head. The record and playback head are a coil of wire with a ferromagnetic core. In a tiny gap between the ends of the core is a magnetic field. As the storage medium, a piece of material covered with iron oxide, is pulled across the record head, the magnetic field penetrates the tape, magnetizing it. The information is written on it in a magnetic pattern that corresponds to the original information. To play back or read the information, the medium is moved past the gap in the playback head. The changing magnetic field induces a small voltage into the coil winding. When this voltage is amplified, the original information is reproduced.

The operation of a DC motor (Figure below) depends on the principle that a current-carrying conductor, placed in and at right angles to a magnetic field, tends to move at right angles to the direction of the field. Figure 18-18A shows a magnetic field extending between a north pole and a south pole. Figure 18-18B shows the magnetic field that exists around a current carrying conductor. The plus sign implies that the current flows inward. The direction of the flux lines can be determined using the left-hand rule. Figure 18-18C shows the conductor placed in the magnetic field. Note that both fields become distorted. Above the wire, the field is weakened, and the conductor tries to move upward. The amount of force exerted upward depends on the strength of the field between the poles and the amount of current flowing through the conductor. If the current through the conductor is reversed (Figure below D), the direction of the magnetic flux around the conductor is reversed. If this occurs, the field below the conductor is weakened and the conductor tends to move downward. A method of determining the direction of a current-carrying conductor in a magnetic field uses the **right-hand motor rule**: When the thumb, index finger, and middle finger of the right hand are extended at right angles to each other, the middle finger points in the direction of current flow in the conductor; the index finger indicates the magnetic field from the north pole to the south pole; the thumb points in the direction of the motion of the conductor. The force acting on a current-carrying conductor in a magnetic field depends on the strength of the magnetic field, the length of the conductor, and the amount of current flowing in the conductor. If a loop of wire, free to rotate horizontally, is placed between the two poles of a magnet, the loop spins as the poles repel each other. The current flows in one direction on one side of the loop and in the other direction on the other side of the loop. One side of the loop moves down and the other side of the loop moves upward. The loop rotates in a counterclockwise direction around its axis. A commutator reverses the direction of current flow in the loop every time it reaches the top or zero torque position. This is how a DC motor rotates. The loop or armature rotates in a magnetic field. Permanent magnets or electromagnets may produce this field. The commutator reverses the direction of current through the armature. Note the resemblance between a DC motor and a **dc generator**.

Operation of a DC motor.

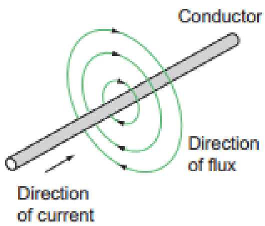


The basic meter movement uses the principle of the DC motor. It consists of a stationary permanent magnet and a moveable coil. When the current flows through the coil, the resulting magnetic field reacts with the field of the permanent magnet and causes the coil to rotate. The greater the current flow through the coil, the stronger the magnetic field produced. The stronger the magnetic field produced, the greater the rotation of the coil. To determine the amount of current flow, a pointer is attached to the rotating coil. As the coil turns, the pointer also turns. The pointer moves across a graduated scale and indicates the amount of current flow. This type of meter movement is used for analog meters such as voltmeters, ammeters, and ohmmeters. A conductor carrying a current can be deflected (moved) by a magnetic field. It is not the conductor that is deflected, but the electrons traveling in the conductor. The electrons are restricted to the conductor, so the conductor also moves. Electrons can travel through other media. In the case of television picture tubes, electrons travel through a vacuum to strike a phosphor screen where they emit light. The

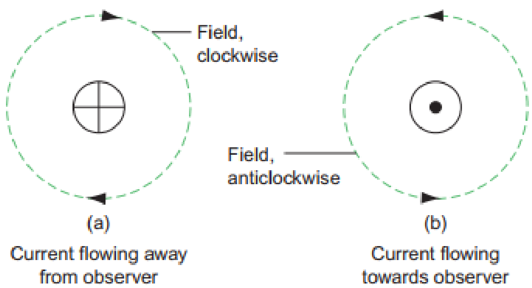
electrons are produced by an electron gun. By varying the electron beam over the surface of the picture screen, a picture can be created. To move the beam back and forth across the screen, two magnetic fields deflect the beam. One magnetic field moves the beam up and down the screen, and the other magnetic field moves the beam from side to side. This method is used in television, radar, oscilloscopes, computer terminals, and other applications where a picture is desired on a screen.

Content/Topic 2: Introduction to electromagnetism.

When a conductor carries a current, a magnetic field is produced around that conductor (Fig. below).

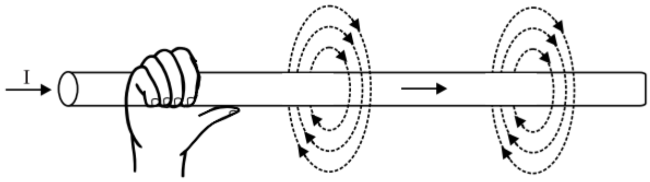


This field is in the form of concentric circles along the whole length of the conductor. The direction of the field depends on the direction of the current – clockwise for a current flowing away from the observer and anti-clockwise for a current flowing towards the observer. In order to show these directions, certain signs are used.



Symbols for current direction.

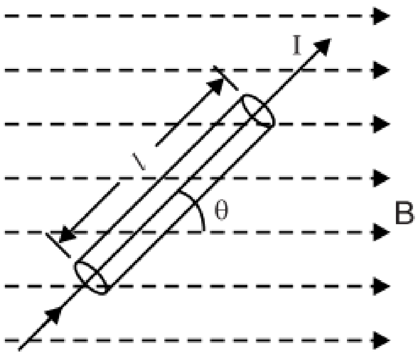
A. Magnetic field due to an electric current: When an electric current flows through a conductor, magnetic field is set up all along the length of the conductor. Fig. below shows the magnetic field produced by the current flowing in a straight wire. The magnetic lines of force are in the form of concentric circles around the conductor. The direction of lines of force depends upon the direction of current and may be determined by **right-hand rule.** Hold the conductor in the right-hand with the thumb pointing in the direction of current (See Fig. below). Then the fingers will point in the direction of magnetic field around the *conductor.* it is clear that when viewed from left-hand side, the direction of magnetic lines of force will be clockwise.



The following points may be noted about the magnetic effect of electric current:

- **i.** The greater the current through the conductor, the stronger the magnetic field and *vice versa.*
- **ii.** The magnetic field neart the conductor is stronger and becomes weaker and weaker as we move away from the conductor.
- **iii.** The magnetic lines of force around the conductor will be either clockwise or anticlockwise, depending upon the direction of current. One may use *right-hand rule* to determine the direction of magnetic field around the conductor.
- **iv.** The shape of the magnetic field depends upon the shape of the conductor.

B. Force on current carrying conductor: When a current-carrying conductor is placed at right angles to a magnetic field, it is found that the conductor experiences a force which acts in a direction perpendicular to the direction of both the field and the current. Consider a straight current-carrying conductor placed in a uniform magnetic field as shown in Fig. below.



Let

- *B* = magnetic flux density in Wb/m2
- *I* = current through the conductor in amperes
- *l* = effective length of the conductor in meters

i.e. the length of the conductor lying in the magnetic field

- θ = angle which the conductor makes with the direction of the magnetic field

It has been found experimentally that the magnitude of force (*F*) acting on the conductor is directly proportional to the magnitudes of flux density (*B*), current (*I*), length (*l*) and sin θ *i.e.*

$$F \propto BIl \sin\theta \text{ newtons}$$
$$F = k\,BIl \sin\theta$$

where *k* is a constant of proportionality. Now SI unit of *B* is so defined that value of *k* becomes unity.

$$F = BIl \sin\theta$$

By experiment, it is found that the direction of the force is always perpendicular to the plane containing the conductor and the magnetic field. Both magnitude and direction of the force will be given by the following vector equation:

$$\vec{F} = I\left(\vec{l} \times \vec{B}\right)$$

The direction of this force is perpendicular to the plane containing *l* and *B* . It can be found by using right-hand rule for cross product.

Special Cases.

$$F = BIl \sin\theta$$

i. When $\theta = 0°$ or $180°$; $\sin\theta = 0$

$$F = BIl \times 0 = 0$$

Therefore, if a current-carrying conductor is placed parallel to the direction of magnetic field, the conductor will experience no force.

ii. When $\theta = 90°$; $\sin\theta = 1$

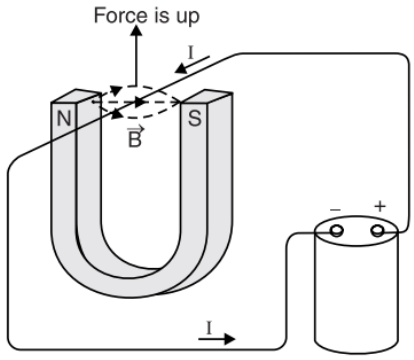
$$F = BIl$$

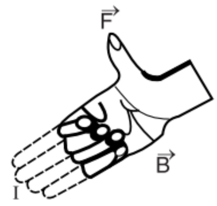
maximum value, Therefore, a current-carrying conductor will experience a maximum force when it is placed at right angles to the direction of the magnetic field.

Direction of force.

The direction of force F is always perpendicular to the plane containing l and B and can be determined by right-hand rule for cross product stated below:

Orient your right hand so that your outstretched fingers point along the direction of the conventional current; the orientation should be such that when you bend your fingers, they must point along the direction of the magnetic field B, then your extended thumb will point in the direction of the force on the conductor





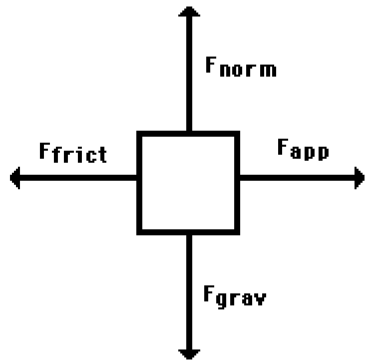
Right-hand rule

Thus, applying right-hand rule for cross product to Fig. above, it is clear that magnetic force on the conductor is vertically upward.

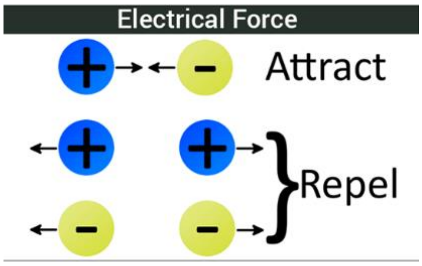
C. Force on a charge: An electric force is exerted between any two charged objects. Objects with the same charge, both positive and both negative, will repel each other, and objects with opposite charges, one positive and one negative, will attract each other.

The repulsive or attractive interaction between any two charged bodies is called as an electric force. Similar to any force, its impact and effects on the given body are described by *Newton's laws of motion.* The electric force is among the list of other forces that exert over objects.

Newton's laws are applicable to analyze the motion under the influence of that kind of force or combination of forces. The analysis begins by the construction of a free body image wherein the direction and type of the individual forces are shown by the vector to calculate the resultant sum which is called the net force that can be applied to determine the body's acceleration.



The electric force between two electrons is equal to the electric force between two protons when placed at equal distances. This describes that the electric force is not based on the mass of the object, but depends on the quantity known as the electric charge.



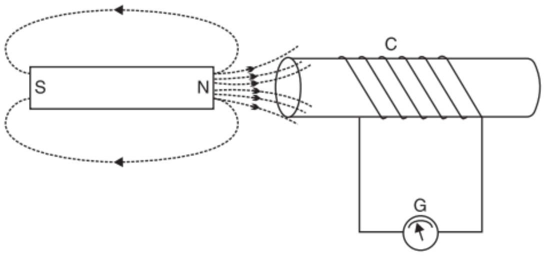
D. Applications of electromagnetism: In many practical **applications of electromagnets**, such as motors, generators, transformers, lifting magnets, and loudspeakers, the iron core is in the form of a loop or magnetic circuit, possibly broken by a few narrow air gaps. This is because the magnetic field lines are in the form of closed loops.

The main advantage of an electromagnet over a permanent magnet is that the magnetic field can be quickly changed by controlling the amount of electric current in the winding. However, unlike a permanent magnet that needs no power, an electromagnet requires a continuous supply of current to maintain the magnetic field.

Electromagnets are widely used as components of other electrical devices, such as motors, generators, electromechanical solenoids, relays, loudspeakers, hard disks, MRI machines, scientific instruments, and magnetic separation equipment. Electromagnets are also employed in industry for picking up and moving heavy iron objects such as scrap iron and steel.

Content /Topic 3: Introduction to electromagnetic induction.

When the magnetic flux linking a conductor changes, an e.m.f. is induced in the conductor. If the conductor forms a complete loop or circuit, a current will flow in it. This phenomenon is known as electromagnetic induction. The phenomenon of production of e.m.f. and hence current in a conductor or coil when the magnetic flux linking the conductor or coil changes is called **electromagnetic induction.**



If two electrically isolated coils are placed next to each other and an AC voltage is put across one coil, a changing magnetic field result. This changing magnetic field induces a voltage into the second coil. This action is referred to as electromagnetic induction. The device is called a **transformer**.

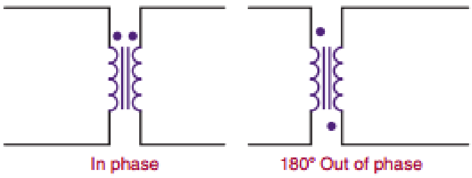
In a transformer, the coil containing the AC voltage is referred to as the **primary winding**. The other coil, in which the voltage is induced, is referred to as the **secondary winding**. The amount of voltage induced depends on the amount of mutual induction between the two coils. The amount of mutual induction is determined by the **coefficient of coupling**.

The coefficient of coupling is a number from 0 to 1, with 1 indicating that all the primary flux lines cut the secondary windings and 0 indicating that none of the primary flux lines cut the windings.

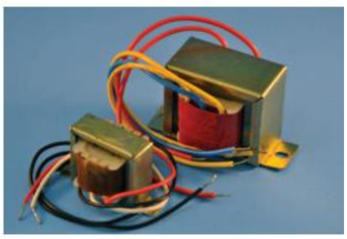
The design of a transformer is determined by the frequency at which it will be used, the power it must handle, and the voltage it must handle. For example, the application of the transformer determines the type of core material that the coils are wound on. For low frequency applications, iron cores are used. For high frequency applications, air cores with nonmetallic cores used to reduce losses associated with the higher frequencies.

Transformers are rated in **volt-amperes (Va)** rather than in power (watts). This is because of the loads that can be placed on the secondary winding. If the load is a pure capacitive load, the reactance could cause the current to be excessive. The power rating has little meaning where a volt-ampere rating can identify the maximum current the transformer can handle. Figure below shows the schematic symbol of a transformer. The direction of the primary and secondary windings on the core determines the polarity of the induced voltage in the secondary winding. The AC voltage can either be in phase or 180° out of phase with the induced voltage. Dots are used on the schematic symbol of the transformer to indicate polarity.

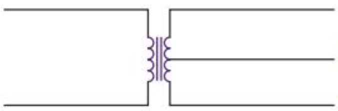
Transformer schematic symbol showing phase indication



a) Transformers with a center-tapped secondary.
b) Schematic symbol showing transformer with a center-tapped secondary.



(A)



(B)

Transformers are wound with tapped secondaries (above Figure). A **center-tapped secondary** is the equivalent of two secondary windings, each with half of the total voltage across them. The center tap is used for power supply to convert AC voltages to DC voltages. A transformer may have taps on the primary to compensate for line voltages that are too high or too low.

- **Flux Linkages:** The product of number of turns (N) of the coil and the magnetic flux (ϕ) linking the coil is called flux linkages i.e.

Flux linkages = $N\phi$

Experiments show that the magnitude of e.m.f. induced in a coil is directly proportional to the rate of change of flux linkages. If N is the number of turns of the coil and the magnetic flux linking the coil changes (say increases) from ϕ_1 to ϕ_2 in t seconds, then, Induced e.m.f., $e \propto$ Rate of change of flux linkages

$$e \propto \frac{N\phi_2 - N\phi_1}{t}$$

A. Laws of electromagnetic induction (Faraday's law Lenz's law, coulomb's law): performed a series of experiments to demonstrate the phenomenon of electromagnetic induction. He summed up his conclusions into two laws, known as Faraday's laws of electromagnetic induction.

- **First Law:** It tells us about the condition under which an e.m.f. is induced in a conductor or coil and may be stated as under: *When the magnetic flux linking a conductor or coil changes, an e.m.f. is induced in it.* It does not matter how the change in magnetic flux is brought about. The essence of the first law is that the induced e.m.f. appears in a circuit subjected to a changing magnetic field.
- **Second Law:** It gives the magnitude of the induced e.m.f. in a conductor or coil and may be stated as under: *The magnitude of the e.m.f. induced in a conductor or coil is directly proportional to the rate of change of flux linkages i.e*

$$\text{Induced e.m.f., } e \propto \frac{N\phi_2 - N\phi_1}{t}$$

$$e = k\frac{N\phi_2 - N\phi_1}{t}$$

where the value of k is *unity in SI units.

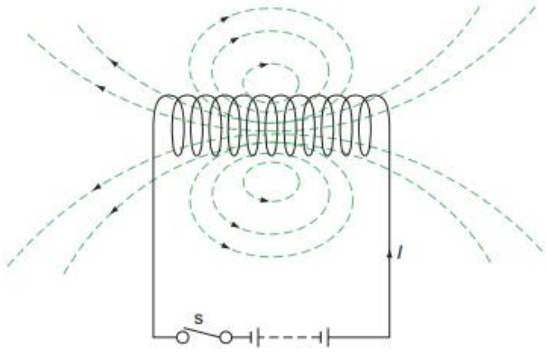
$$e = \frac{N\phi_2 - N\phi_1}{t}$$ In differential form, we have $$e = N\frac{d\phi}{dt}$$

The direction of induced e.m.f. (and hence of induced current if the circuit is closed) is given by **Lenz's law.** The magnitude and direction of induced e.m.f. should be written as:

$$e = -N\frac{d\phi}{dt}$$

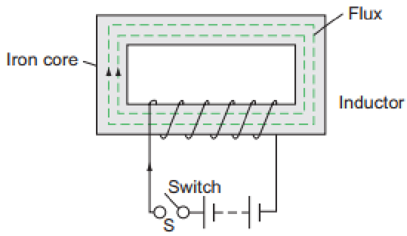
The minus sign on the R.H.S. represents Lenz's law mathematically. In SI units, e is measured in volts, ϕ in webers and t in seconds

B. Inductance and inductors: inductance: symbol(L); unit, henry (H)**,** Let us consider the effect of forming a coil from a length of wire and connecting it to a DC source of supply.



Fiux distribution for a coil.

This shows the distribution of the magnetic lines of force, or flux, produced by such a circuit. We know that if we wind the same coil on to an iron core, the lines of force tend to be confined to that core and the flux is much greater, and that when a conductor is cut by magnetic lines of force, a current, and hence an e.m.f, is produced in that conductor. Consider what happens when the switch S is first closed.

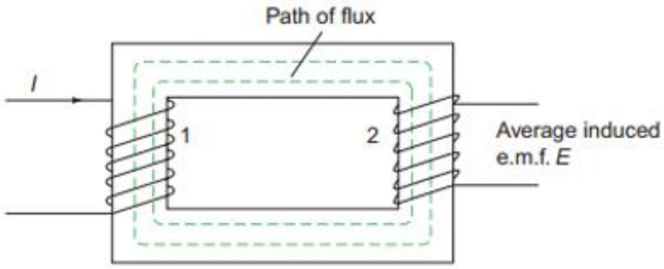


Self-inductance.

As the current increases from zero to a maximum, the flux in the core also increases, and this growing magnetic field cuts the conductors of the coil, inducing an e.m.f. in them. This e.m.f., called the **back e.m.f***,* operates in the reverse direction to the supply voltage and opposes the change in the circuit current that is producing it. The effect of this opposition is to slow down the rate of change of current in the circuit. When the switch S is opened, the current falls to zero and the magnetic field collapses. Again, lines of force cut the conductors of the coil inducing an e.m.f. in them. In this case, the e.m.f. appears across the switch contacts in the form of an arc.

C. Mutual inductance: mutual inductance: symbol(*M)*; unit, henry (H), Let us consider the effect of winding two coils on the same iron core (Fig below). A change of current in coil 1 produces a change of flux which links with coil 2, thus inducing an e.m.f. in that coil. These two coils are said to possess the property of **mutual inductance***,* which is defined as: 'A mutual inductance of 1H exists between two coils when a uniformly varying current of 1A/s in one coil produces an e.m.f. of 1V in the other coil'. If a change of current (I_2-I_1)*,* in the first coil induces an average e.m.f. E in the second coil, then

$$E = -\frac{M(I_2 - I_1)}{t} \text{ volts}$$



Mutual inductance.

But E can also be expressed as

$$E = -\frac{(\Phi_2 - \Phi_1)N}{t} \text{ volts}$$

Then

$$\frac{M(I_2 - I_1)}{t} = \frac{(\Phi_2 - \Phi_1)}{t} \times N$$

$$\therefore M = \frac{(\Phi_2 - \Phi_1)}{(I_2 - I_1)} \times N \text{ henrys}$$

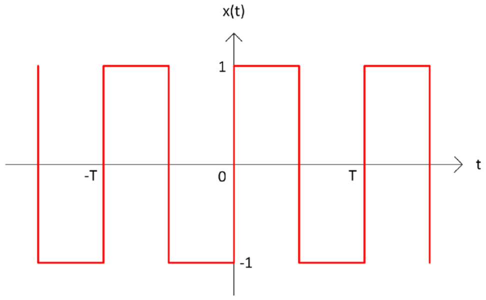
Learning Unit 2 – Analyze characteristics of AC Signals.

LO 2.1 – Identify waveform signals.

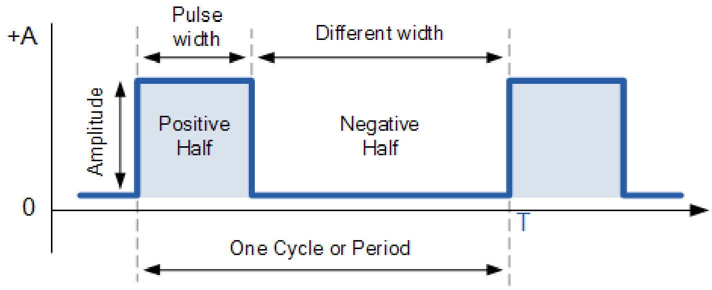
Content/Topic 1: Introduction to alternating voltages and currents waveforms.

The shape of the curve obtained by plotting the instantaneous values of voltage or current as ordinate against time as abscissa is called its *waveform* or *waveshape.*

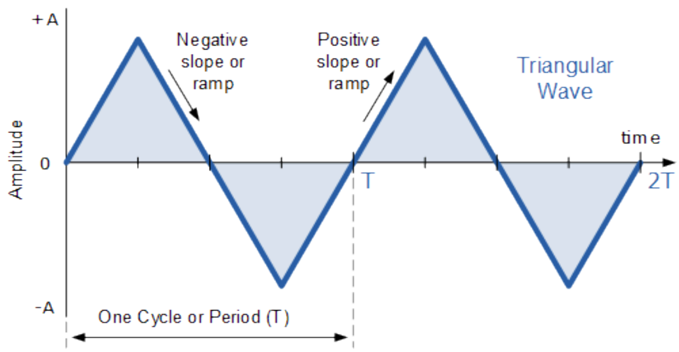
A. **Square wave:** A **square wave** is a non-sinusoidal periodic **waveform** in which the amplitude alternates at a steady frequency between fixed minimum and maximum values, with the same duration at minimum and maximum. In an ideal **square wave**, the transitions between minimum and maximum are instantaneous.



B. **Rectangular:** A periodic **wave** that alternately and suddenly changes from one to the other of two fixed values. Also known as **rectangular wave** train.

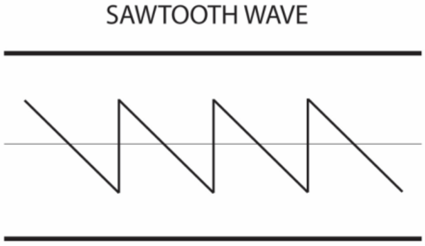


C. **Triangle:** A triangular wave or triangle wave is a non-sinusoidal waveform named for its triangular shape. However, the higher harmonics roll off much faster than in a square wave (proportional to the inverse square of the harmonic number as opposed to just the inverse).

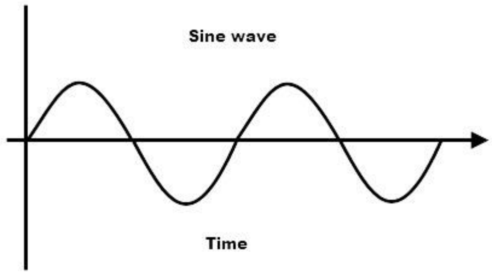


D. **Saw tooth:** The sawtooth wave is a kind of non-sinusoidal waveform. It is so named based on its resemblance to the teeth of a plain-toothed saw with a zero-rake angle.

A single sawtooth, or an intermittently triggered sawtooth, is called a ramp waveform. The convention is that a sawtooth wave ramps upward and then sharply drops.



E. Sinusoidal: A sine wave or sinusoid is a mathematical curve that describes a smooth periodic oscillation. A sine wave is a continuous wave. It is named after the function sine, of which it is the graph. It occurs often in both pure and applied mathematics, as well as physics, engineering, signal processing and many other fields.

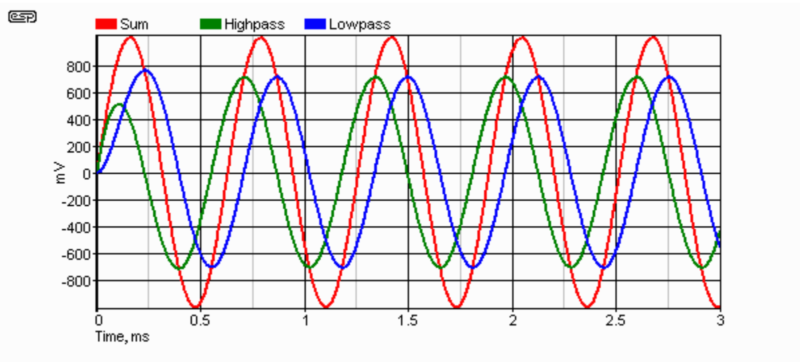


Content/Topic 2: Types of waveform distortion.

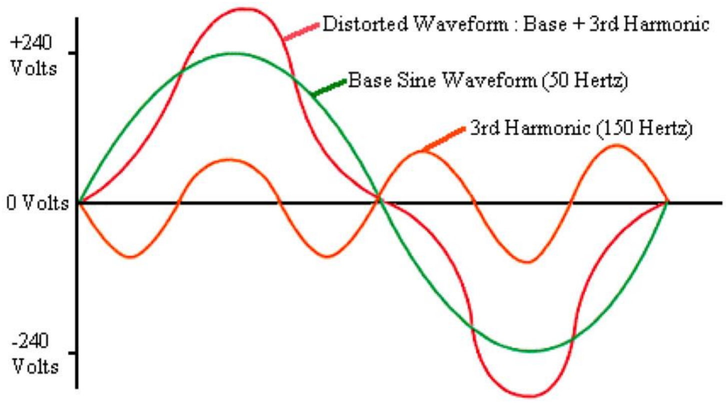
A. Phase distortion: In signal processing, phase distortion or phase-frequency distortion is distortion, that is, change in the shape of the waveform, that occurs when

a) A filter's phase response is not linear over the frequency range of interest, that is, the phase shift introduced by a circuit or device is not directly proportional to frequency, or

b) The zero-frequency intercept of the phase-frequency characteristic is not 0 or an integral multiple of 2π radians.



B. Harmonic distortion: distortion in which harmonics of an input signal are produced in an amplifier and appear in the output along with the amplified input signal.
The total harmonic distortion (THD or THDi) is a measurement of the harmonic distortion present in a signal and is defined as the ratio of the sum of the powers of all harmonic components to the power of the fundamental frequency. Distortion factor, a closely related term, is sometimes used as a synonym.



LO 2.2 – Interpret waveforms signals.

Content/Topic 1: Components of AC waveforms.

A. **Period:** The time taken by the waveform to complete one full cycle is called the Periodic Time of the waveform, and is given the symbol "T". The number of complete cycles that are produced within one second (cycles/second) is called the Frequency, symbol ƒ of the alternating waveform.
The period of a wave is the amount of time it takes to complete one cycle. Frequency is the number of complete cycles that a wave completes in a given amount of time. Usually measured in Hertz (Hz), 1 Hz being equal to one complete wave cycle per second.

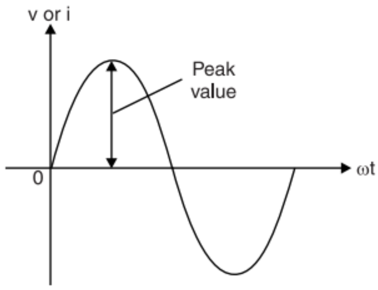
B. **Frequency:** Frequency: – This is the number of times the waveform repeats itself within a one second time period. Frequency is the reciprocal of the time period, (ƒ = 1/T) with the standard unit of frequency being the **Hertz, (Hz**). Amplitude: – This is the magnitude or intensity of the signal waveform measured in volts or amps.

C. **Current:** Any part of an AC type waveform which lies above the horizontal zero axis represents a voltage or current flowing in one direction. Likewise, any part of the waveform which lies below the horizontal zero axis represents a voltage or current flowing in the opposite direction to the first.

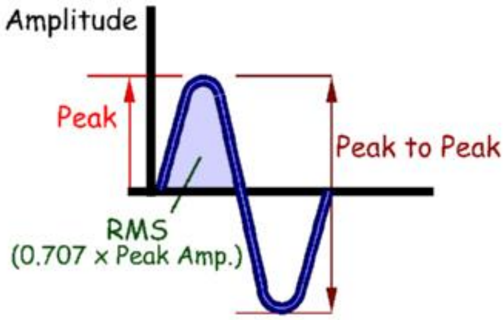
D. **Voltage:** A sinusoidal **waveform** is defined as: V_m = 169.8 sin(377t) volts. Calculate the RMS **voltage** of the **waveform**, its frequency and the instantaneous value of the **voltage**, (V_i) after a time of six milliseconds (6ms).

Content/Topic 2: Amplitude.

A. **Peak value:** It is the maximum value attained by an alternating quantity. The peak or maximum value of an alternating voltage or current is represented by *Vm* or *Im*. The knowledge of peak value is important in case of testing materials. However, peak value is not used to specify the magnitude of alternating voltage or current. Instead, we generally use r.m.s. values to specify alternating voltages and currents.



B. **Peak -to-peak:** Peak-to-peak amplitude (abbreviated p–p) is the change between peak (highest amplitude value) and trough (lowest amplitude value, which can be negative). With appropriate circuitry, peak-to-peak amplitudes of electric oscillations can be measured by meters or by viewing the waveform on an oscilloscope.



C. **Effective value (RMS):** The average value cannot be used to specify a sinusoidal voltage or current. It is because its value over one-cycle is zero and cannot be used for power calculations. Therefore, we must search for a more suitable criterion to measure the effectiveness of an alternating current (or voltage). The obvious choice would be to measure it in terms of direct current that would do work (or produce heat) at the same average rate under similar conditions. This equivalent direct current is called the root-mean-square (r.m.s.) or effective value of alternating current.

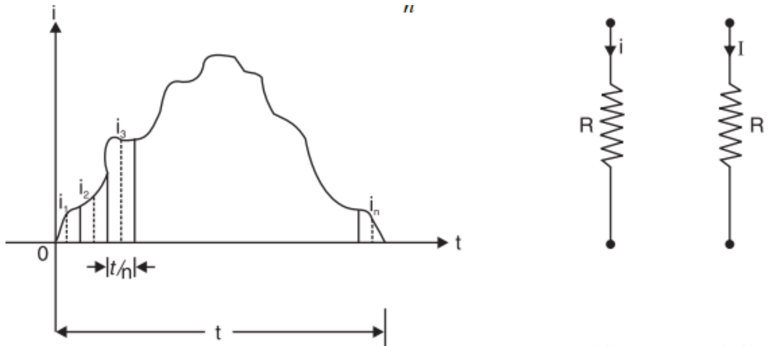
The **effective or r.m.s. value** of an alternating current is that steady current (d.c.) which when flowing through a given resistance for a given time produces the same amount of heat as produced by the alternating current when flowing through the same resistance for the same time.
For example, when we say that the r.m.s. or effective value of an alternating current is 5A, it means that the alternating current will do work (or produce heat) at the same rate as 5A direct current under similar conditions.

Illustration.
The r.m.s. or effective of alternating current (or voltage) can be determined as follows. Consider the half-cycle of a non-sinusoidal alternating current i [See Fig. below (*i*)] flowing through the resistance $R\Omega$ for t seconds. Divide the time t in n equal intervals of time, each of duration t/n second. Let the mid-ordinates be i_1, i_2, i_3,..i_n. Each current i_1, i_2, i_3,.....i_n will produce heating effect when passed through the resistance R as shown in Fig. below (*ii*). Suppose the heating effect produced by current i in R is the same as produced by some direct current I flowing through the resistance R for the

same time t. Then direct current I is the r.m.s. or effective value of alternating current i.

The heating effect of various components of alternating current will be i_1^2Rt/n......i_n^2Rt/n joules. Since the alternating current is varying, the heating effect will also vary. Total heat produced by alternating current i=

$$= (i_1^2R + i_2^2R + i_3^2R + ... + i_n^2R)\ t/n$$
$$= \frac{(i_1^2R + i_2^2R + i_3^2R + ... + i_n^2R)}{n} t \text{ joules}$$



(i) (ii) (iii)

Heat produced by equivalent direct current I, = $I^2\ R\ t$ joules
Since heat produced in both cases is the same

$$I^2 R\ t = \left(\frac{i_1^2R + i_2^2R + i_3^2R + ... + i_n^2R}{n}\right) t$$

$$I = \sqrt{\frac{i_1^{\ 2} + i_2^{\ 2} + i_3^{\ 2} + ... + i_n^{\ 2}}{n}} \qquad ...(i)$$

$$= \sqrt{\text{*mean value of } i^2}$$

= Square **root** of the **mean** of the **squares** of the current
= **root-mean-square (r.m.s.)** value

It hardly needs any explanation as to why the equivalent direct current (generally written as $I_{r.m.s.}$) is called the root-mean-square value. It is also called **effective value** because it is this value which tells the energy transfer capability of AC source. The following points may be noted:

i. For symmetrical waves, the r.m.s. or effective value can be found by considering half-cycle or full-cycle. It is because second half is the negative of the first half and the r.m.s. value depends upon the squares of the instantaneous values. However, for unsymmetrical waves, full-cycle should be considered.
ii. The r.m.s. value of symmetrical wave can also be expressed as:

$$\text{R.M.S. value} = \sqrt{\frac{\text{Area of half-cycle of squared wave}}{\text{Half-cycle base}}}$$

iii. The r.m.s. or effective value of an alternating voltage can similarly be expressed as:

$$V_{r.m.s.} = \sqrt{\frac{v_1^2 + v_2^2 + v_3^2 + \ldots + v_n^2}{n}}$$

Note. In case of an unsymmetrical wave, full-cycle should be considered to find the r.m.s. value.

Content /Topic 3: Application of waveform.

In acoustics, it is usually applied to steady periodic sounds—variations of pressure in air or other media. In these cases, the **waveform** is an attribute that is independent of the frequency, amplitude, or phase shift of the signal. The term can also be used for non-periodic signals, like chirps and pulses.

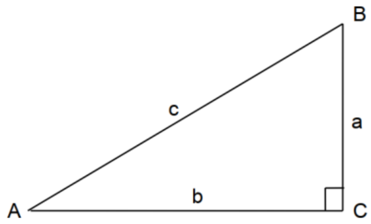
Signal wave generators are used in the following cases

- To test and characterize the electronic device and circuit.
- The signals generated are usually periodic.
- Information carriers for communication system.
- Control systems and time clock for computers.

LO 2.3 – Determine instantaneous equation of AC voltages and currents.

Content/Topic 1: Introduction to trigonometric functions.

The following figure indicates the conventional method for designating sides and angles:



- Side **a** is the altitude of the triangle.
- Side **b** is the base of the triangle.
- Side **c** is the hypotenuse of the triangle.

Pythagorean Theorem

The Pythagorean theorem is a rule or formula that allows us to calculate the length of one side of a right triangle when we are given the lengths of the other two sides. Although the formula is named after the ancient Greek mathematician Pythagoras, it was known to Babylonian engineers and surveyors more than a thousand years before Pythagoras lived.

Pythagorean Theorem - For any right triangle, the square of the hypotenuse is equal to the sum of the squares of the other two sides.

$$c^2 = a^2 + b^2$$

Refer to the observed relationship of the side lengths of a right triangle based upon the Pythagorean Theorem. There is also a relationship between the ratio of the opposite side to the hypotenuse for a fixed angle. The ratio will always be constant regardless the unit of measure of the sides. The same applies to the ratio of the adjacent side to the hypotenuse and the ratio of the opposite side to the adjacent side.

These ratios are useful in solving right triangles and certain other scientific calculations. These ratios are called *trigonometric functions*. Using the labeling techniques from the previous page, these functions are shown as follows:

A. **Sine:**

$$sine\ \angle\theta = \frac{OppositeSide}{Hypotenuse}$$

B. **Cosine:**

$$cosine\ \angle\theta = \frac{Adjacent\ Side}{Hypotenuse}$$

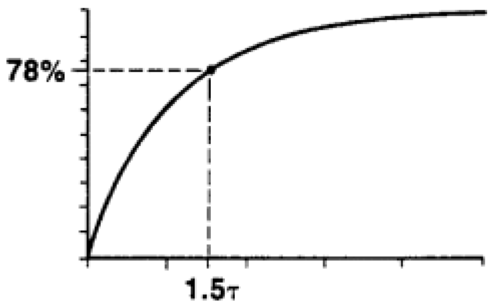
C. **Tangent:**

$$tangent\ \angle\theta = \frac{OppositeSide}{Adjacent\ Side}$$

D. **Cotangent:** is the inverse of tangent.

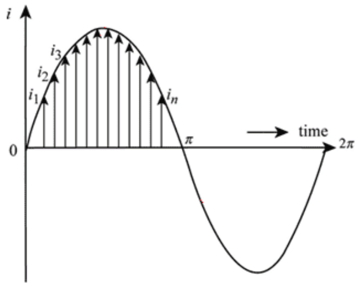
Content /Topic 2: Instantaneous values.

A. **Voltage:** Let an **instantaneous voltage** v be represented by v = V_M sin 2πft volts. This is a waveform which varies sinusoidally with time t, has a frequency f, and a maximum value, V_M. Alternating **voltages** are usually assumed to have wave-shapes which are sinusoidal where only one frequency is present.



B. **Current: Instantaneous current** is the amount of charge passing through a conductor at the moment. Time averaged **current** is the total amount of charge passing through a conductor in a time interval.

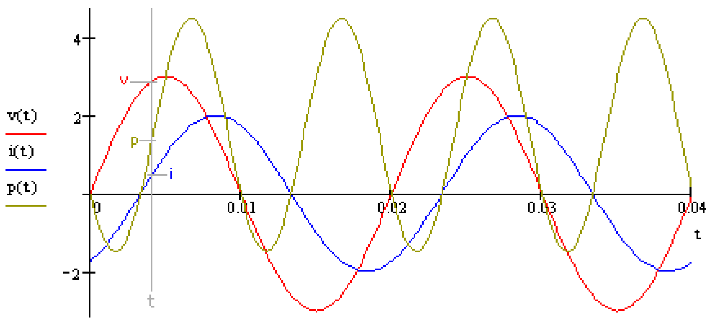
Instantaneous value



i1, i2, i3.....i n at instant time of
t1, t2, t3....t n

Content /Topic 3: Graphical interpretation of instantaneous equation of voltage and current.

Measurement is an act or the result of evaluation between the quantity and a predefined standard. Electrical measurements are the methods, devices and calculations used to measure electrical quantities. Measurement of electrical quantities may be done to measure electrical parameters of a system. Specifying a voltage measurement wants explicit or implicit specification of the points across which the voltage is measured. Whichever two points with the same potential may be connected by a conductor and no current will flow among them. Voltage and Current measurement or monitoring within electronic circuitry is a common requirement covering various types of applications. These may include anything from portable, handheld equipment through to automotive applications. The Current Measurement block is used to measure the instantaneous current flowing in any electrical block or connection line. The Voltage Measurement block measures the prompt voltage between two electric nodes. An electric current is a flow of electric charge. In electric circuits this charge is often carried by moving electrons in a wire. Electric current is measured using Series/Parallel RLC resonant circuits using MATLAB Simulink graphical representation. In the future work the different level voltage circuits data will be tested with Hyperspectral data processing to find out the accurate voltage magnification difference and analyze through signal processing.



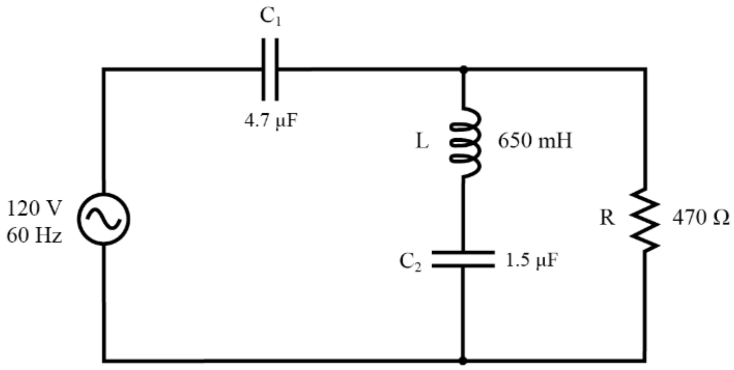
Learning Unit 3 – Study the behavior of different AC circuits.

LO 3.1 – Analyze AC circuits.

Content/Topic 1: Series, parallel and mixed connection of resistors, capacitors and inductors.

Analysis of series-parallel AC circuits is much the same as series-parallel DC circuits. The only substantive difference is that all figures and calculations are in complex (not scalar) form.

Now that we've seen how ***series and parallel*** AC circuit analysis is not fundamentally different than DC circuit analysis, it should come as no surprise that series-parallel analysis would be the same as well, just using complex numbers instead of a scalar to represent voltage, current, and impedance. Take this series-parallel circuit for example:



The first order of business, as usual, is to determine values of impedance (Z) for all components based on the frequency of the AC power source. To do this, we need to first determine values of reactance (X) for all ***inductors*** and ***capacitors***, then convert reactance (X) and resistance (R) figures into proper impedance (Z) form:

$$X_{C1} = \frac{1}{2\pi f C_1}$$

$$X_{C1} = \frac{1}{(2)(\pi)(60\text{Hz})(4.7\mu\text{F})}$$

$$X_{C1} = 564.38\ \Omega$$

$$X_L = 2\pi f L$$

$$X_L = (2)(\pi)(60\text{Hz})(650\text{mH})$$

$$X_L = 245.04\ \Omega$$

$$X_{C2} = \frac{1}{2\pi f C_2}$$

$$X_{C2} = \frac{1}{(2)(\pi)(60\text{Hz})(1.5\mu\text{F})}$$

$$X_{C2} = 1.7684\ \text{k}\Omega$$

$$R = 470\ \Omega$$

$$Z_{C1} = 0 - j564.38\Omega \text{ or } 564.38\Omega \angle -90°$$

$$Z_L = 0 + j245.04\Omega \text{ or } 245.04\Omega \angle 90°$$

$$Z_{C2} = 0 - j1.7684k\Omega \text{ or } 1.7684k\Omega \angle -90°$$

$$Z_R = 470 + j0\Omega \text{ or } 470\Omega \angle 0°$$

Content/Topic 2: Single-phase series AC circuit:

A. Purely resistive circuit: The instantaneous value of the current though the circuit (Fig. 14.1a) is given by,

$$i = \frac{v}{R} = \frac{V_m}{R} \sin \omega t = I_m \sin \omega t$$

where,

Im and Vm are the maximum values of current and voltage respectively.

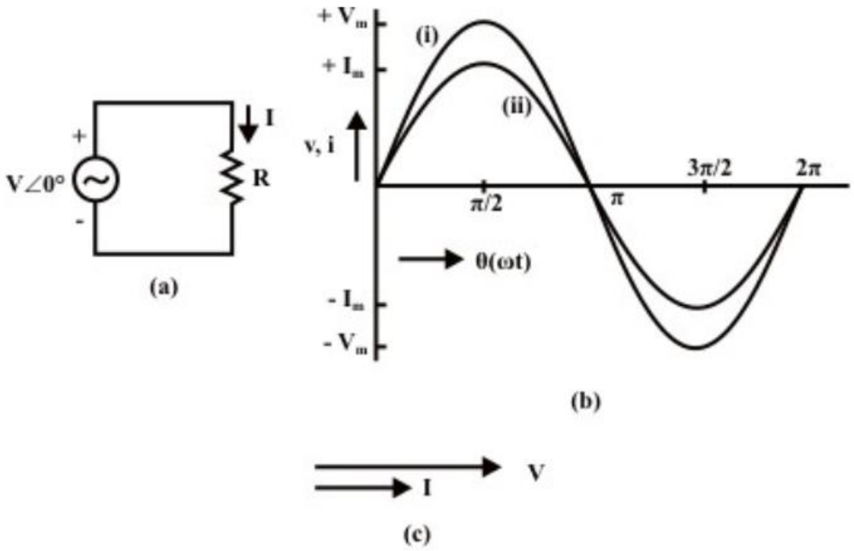


Fig. 14.1: Circuit with Resistance (R)
(a) Circuit diagram
(b) Waveforms: (i) Voltage (ii) Current
(c) Phasor diagram

The rms value of current is given by

$$\bar{I} = \frac{I_m}{\sqrt{2}} = \frac{V_m/\sqrt{2}}{R} = \frac{\bar{V}}{R}$$

In phasor notation

$$\bar{V} = V\angle 0° = V(1 + j0) = V + j0$$

$$\bar{I} = I\angle 0° = I(1 + j0) = I + j0$$

The impedance or resistance of the circuit is obtained as,

$$\frac{\bar{V}}{\bar{I}} = \frac{V\angle 0°}{I\angle 0°} = Z\angle 0° = R + j0$$

Please note that the voltage and the current are in phase (Φ = 0°), which can be observed from phasor diagram (Fig. 14.1b) with two (voltage and current) phasors, and also from the two waveforms (Fig. 14.1c). In ac circuit, the term, Impedance is defined as voltage/current, as is the resistance in DC circuit, following Ohm's law. The impedance, Z is a complex quantity. It consists of real part as resistance R, and imaginary part as reactance X, which is zero, as there is no inductance/capacitance. All the components are taken as constant, having linear V-I characteristics. In the three cases being considered, including this one, the power consumed and also power factor in the circuits, are not taken up now, but will be described later in this lesson.

B. Purely capacitive circuit: The current i, in the circuit (Fig. 14.3a), is,

$$i = C\frac{dv}{dt}$$

Substituting

$v = \sqrt{2}\,V\sin\omega t = V_m \sin\omega t$, i is

$$i = C\frac{d}{dt}\left(\sqrt{2}\,V\sin\omega t\right) = \sqrt{2}\,\omega C V\cos\omega t = \sqrt{2}\,\omega C V\sin(\omega t + 90°) = \sqrt{2}\,I\sin(\omega t + 90°)$$

$$= I_m \sin(\omega t + 90°)$$

The rms value, I is

$$\bar{I} = \omega C\bar{V} = \frac{\bar{V}}{1/(\omega C)} = I\angle 90° \qquad \bar{V} = V\angle 0° = V + j\,0 \quad ; \qquad \bar{I} = I\angle 90° = 0 + j\,I$$

The impedance of the circuit is

$$Z\angle\phi = \frac{\bar{V}}{\bar{I}} = \frac{V\angle 0°}{I\angle 90°} = \frac{V}{jI} = \frac{1}{j\omega C} = -\frac{j}{\omega C} = 0 - jX_C = X_C\angle -90° = \frac{1}{\omega C}\angle 90°$$

where, the capacitive reactance is,

$$X_C = \frac{1}{\omega C} = \frac{1}{2\pi f C}.$$

Note that the current leads the voltage by Φ = 90° (this value is negative, i.e. Φ = -90°), as per convention being followed here. This can be observed both from phasor diagram (Fig. 14.3b), and waveforms (Fig. 14.3c). As the circuit has no resistance, but only capacitive reactance, **X = (1/ω*C*),** (negative, as per convention), the impedance **Z** is only in the y-axis (imaginary).

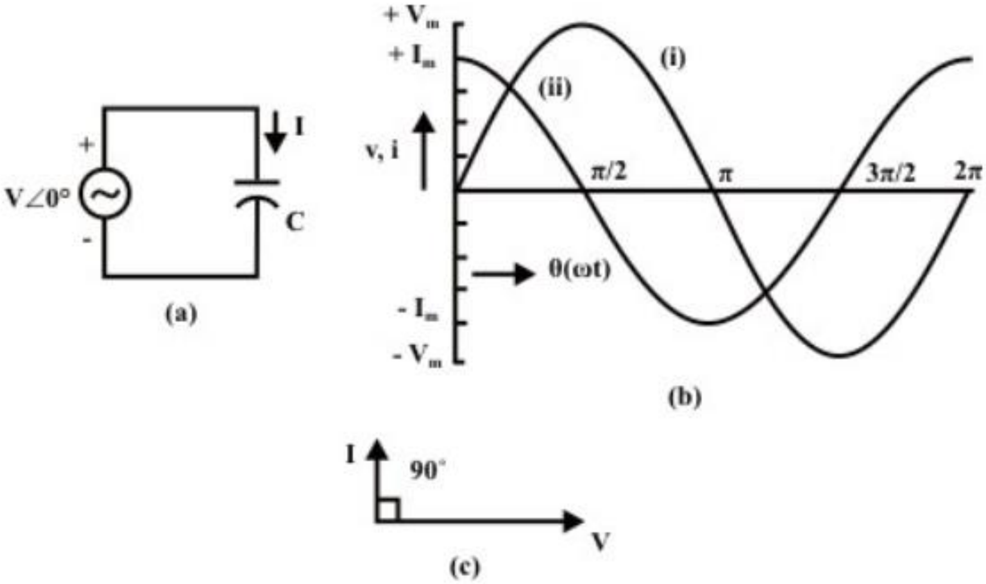


Fig. 14.3: Circuit with Capacitance (C)
(a) Circuit diagram
(b) Waveforms: (i) Voltage (ii) Current
(c) Phasor diagram

C. Purely inductive circuit: For the circuit (Fig. 14.2a), the current i, is obtained by the procedure described here.

$$\text{As } v = L\frac{di}{dt} = V_m \sin \omega t = \sqrt{2}V \sin \omega t,$$

$$di = \frac{\sqrt{2}V}{L}\sin(\omega t)\, dt$$

Integrating,

$$i = -\frac{\sqrt{2}V}{\omega L}\cos \omega t = \frac{\sqrt{2}V}{\omega L}\sin(\omega t - 90°) = I_m \sin(\omega t - 90°) = \sqrt{2}I \sin(\omega t - 90°)$$

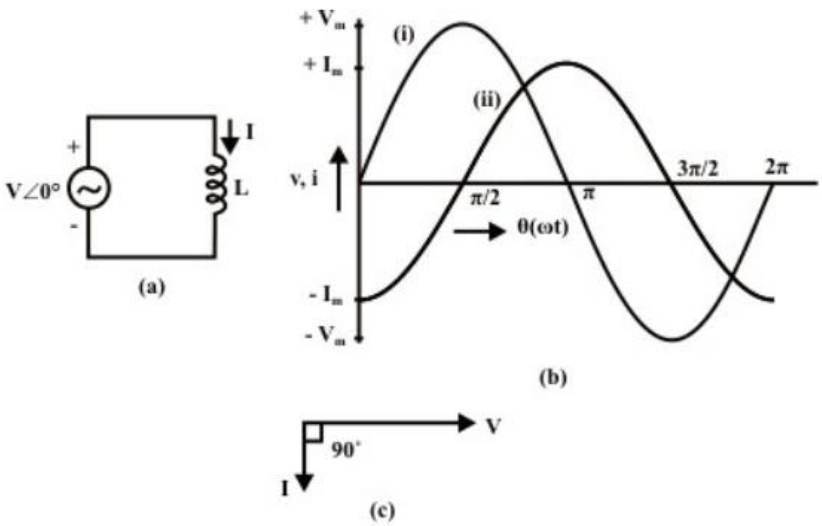


Fig. 14.2: Circuit with Inductance (L)
(a) Circuit diagram
(b) Waveforms: (i) Voltage (ii) Current
(c) Phasor diagram

It may be mentioned here that the current i, is the steady state solution, neglecting the constant of integration. The rms value, I is

$$\bar{I} = \frac{\bar{V}}{\omega L} = I\angle -90^\circ$$

$$\bar{V} = V\angle 0^\circ = V + j0 \quad ; \qquad \bar{I} = I\angle -90^\circ = 0 - jI$$

The impedance of the circuit is

$$Z\angle\phi = \frac{\bar{V}}{\bar{I}} = \frac{V\angle 0^\circ}{I\angle -90^\circ} = \frac{V}{-jI} = j\omega L = 0 + jX_L = X_L\angle 90^\circ = \omega L\angle 90^\circ$$

where, the inductive reactance is

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

Note that the current lags the voltage by Φ = +90°. This can be observed both from phasor diagram (Fig. 14.2b), and waveforms (Fig. 14.2c). As the circuit has no resistance, but only inductive reactance $X_L = \omega L$ (positive, as per convention), the impedance **Z** is only in the y-axis (imaginary).

D. RLC circuit: This is a general series AC circuit. Fig. 12.32 shows *R*, *L* and *C* connected in series across a supply voltage *V* (*r.m.s.*). The resulting circuit current is *I* (*r.m.s.*).

Voltage across R, $V_R = IR$ ... V_R is in phase with I

Voltage across L, $V_L = IX_L$ ... where V_L leads I by 90°

Voltage across C, $V_C = IX_C$ ... where V_C lags I by 90°

As before, the phasor diagram is drawn taking current as the reference phasor. In the phasor

diagram (See Fig. 12.33), *OA* represents *VR*, *AB* represents *VL* and *AC* represents V_C. It may be seen that V_L is in phase opposition to V_C. It follows that the circuit can either be effectively inductive or capacitive depending upon which voltage drop (V_L or V_C) is predominant. For the case considered, $V_L > V_C$ so that net voltage drop across *L-C* combination is $V_L - V_C$ and is represented by *AD*. Therefore, the applied voltage *V* is the phasor sum of V_R and $V_L - V_C$ and is represented by *OD*.

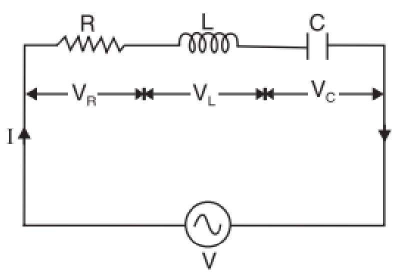


Fig. 12.32

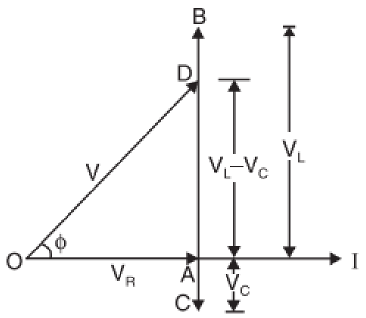


Fig. 12.33

$$V = \sqrt{V_R^2 + (V_L - V_C)^2} = \sqrt{(IR)^2 + (IX_L - IX_C)^2}$$
$$= I\sqrt{R^2 + (X_L - X_C)^2}$$
$$I = \frac{V}{\sqrt{R^2 + (X_L - X_C)^2}}$$

The quantity $\sqrt{R^2 + (X_L - X_C)^2}$ offers opposition to current flow and is called **impedance** of the circuit.

$$\text{Circuit power factor, } \cos\phi = \frac{R}{Z} = \frac{R}{\sqrt{R^2 + (X_L - X_C)^2}} \quad ...(i)$$

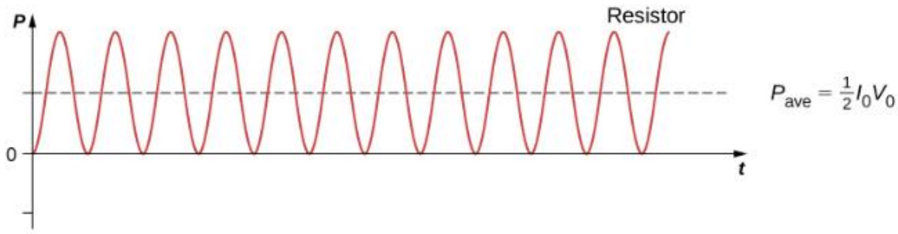
$$\text{Also, } \tan\phi = \frac{V_L - V_C}{V_R} = \frac{X_L - X_C}{R} \quad ...(ii)$$

Since X_L, X_C and R are known, phase angle ϕ of the circuit can be determined.

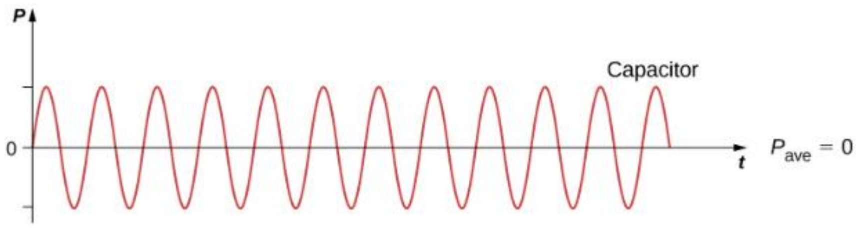
$$\text{Power consumed, } P = VI\cos\phi = {*}I^2 R$$

E. Power in AC circuit: The average ac power is found by multiplying the rms values of current and voltage. Ohm's law for the rms ac is found by dividing the rms voltage by the impedance. In an AC circuit, there is a phase angle between the source voltage and the current, which can be found by dividing the resistance by the impedance.

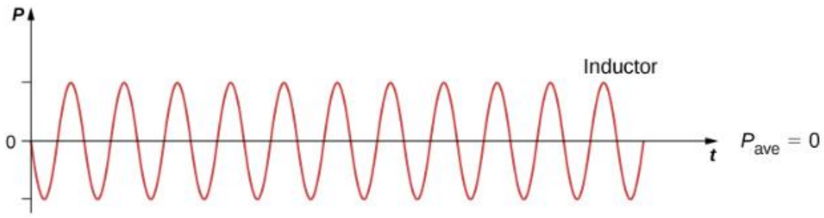
A circuit element dissipates or produces power according to **P=IV**, where ***I*** is the current through the element and *V* is the voltage across it. Since the current and the voltage both depend on time in an ac circuit, the instantaneous power **P(t) = I(t) V(t)** is also time dependent. A plot of $p(t)$ for various circuit elements is shown in figure below, for a resistor, $i(t)$ and $v(t)$ are in phase and therefore always have the same sign (see figure below). For a capacitor or inductor, the relative signs of $i(t)$ and $v(t)$ vary over a cycle due to their phase differences (see figure below).
Consequently, $p(t)$ is positive at some times and negative at others, indicating that capacitive and inductive elements produce power at some instants and absorb it at others.
Graph of instantaneous power for various circuit elements. (a) For the resistor, $\mathbf{P_{ave} = I_oV_o/2}$, whereas for (b) the capacitor and (c) the inductor, $\mathbf{P_{ave} = 0}$, (d) For the source, $\mathbf{P_{ave} = I_oV_o\ (\cos\ \Phi)/2}$, which may be positive, negative, or zero, depending on Φ.



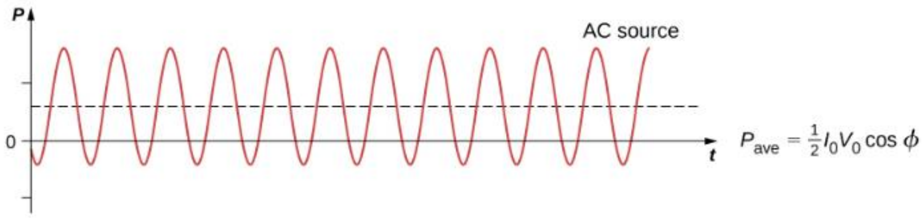
(a)



(b)



(c)



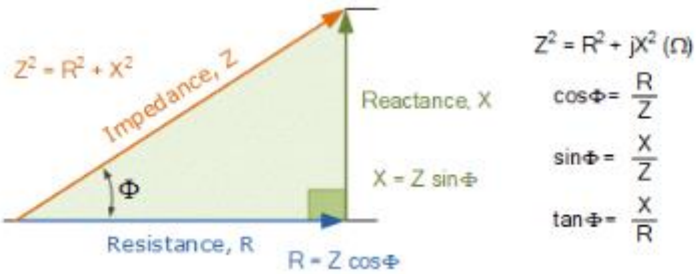
(d)

F. Power triangle and power factor: Electrical power consumed in an AC circuit can be represented by the three sides of a right-angled triangle, known commonly as a power triangle.

We saw in our tutorial about Electrical Power that AC circuits which contain resistance and capacitance or resistance and inductance, or both, also contain real power and reactive power. So, in order for us to calculate the total power consumed, we need to know the phase difference between the sinusoidal waveforms of the voltage and current.

In an AC circuit, the voltage and current waveforms are sinusoidal so their amplitudes are constantly changing over time. Since we know that power is voltage times the current (P = V*I), maximum power will occur when the two voltage and current waveforms are lined up with each other. That is, their peaks and zero crossover points occur at the same time. When this happens the two waveforms are said to be "in-phase".

The three main components in an AC circuit which can affect the relationship between the voltage and current waveforms, and therefore their phase difference, by defining the total impedance of the circuit are the resistor, the capacitor and the inductor.
The impedance, (Z) of an AC circuit is equivalent to the resistance calculated in DC circuits, with impedance given in ohms. For AC circuits, impedance is generally defined as the ratio of the voltage and current phasors produced by a circuit component. Phasor's are straight lines drawn in such a way as to represents a voltage or current amplitude by its length and its phase difference with respect to other phasor lines by its angular position relative to the other phasor's.
AC circuits contain both resistance and reactance that are combined together to give a total impedance (Z) that limits current flow around the circuit. But an AC circuits impedance is not equal to the algebraic sum of the resistive and reactive ohmic values as a pure resistance and pure reactance are 90^o out-of-phase with each other. But we can use this 90^o phase difference as the sides of a right-angled triangle, called an impedance triangle, with the impedance being the hypotenuse as determined by Pythagoras theorem.



From the waveform of instantaneous power **(W= *iv*)** also shown in Fig. 14.4c for the above circuit, the average power is,

$$W = \frac{1}{\pi}\int_0^{\pi} v \cdot i\, d\theta = \frac{1}{\pi}\int_0^{\pi} \sqrt{2}V\sin\theta \sqrt{2}I\sin(\theta-\phi)\, d\theta = \frac{1}{\pi}\int_0^{\pi} VI[\cos\phi - \cos(2\theta-\phi)]\, d\theta$$

$$= \frac{1}{\pi}\left[VI\cos\phi\,\theta\Big|_0^{\pi} - \frac{VI}{2}\sin(2\theta-\phi)\Big|_0^{\pi}\right]$$

$$= \frac{1}{\pi}\left[VI\cos\phi(\pi-0) - \frac{VI}{2}[\sin(2\pi-\phi)+\sin\phi]\right] = VI\cos\phi$$

Note that power is only consumed in resistance, R only, but not in the inductance, L. So, W= RI^2.

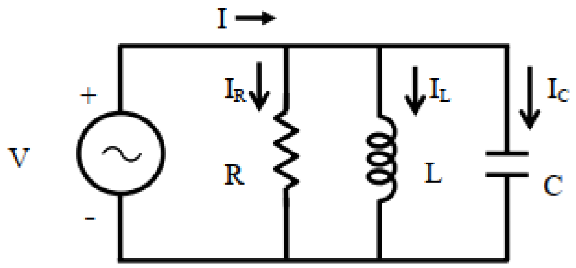
$$\text{Power factor} = \frac{\textit{average power}}{\textit{apparent power}} = \frac{VI\cos\phi}{VI} = \cos\phi = \frac{R}{Z} = \frac{R}{\sqrt{R^2+(\omega L)^2}}$$

The power factor in this circuit is less than 1 (one), as ° ≤ ϕ ≤ 900 °, ϕ being positive as given above. For the resistive (R) circuit, the power factor is 1 (one), as ϕ = 0°, and the average power is *IV.*
For the circuits with only inductance, L or capacitance, C as described earlier, the power factor is 0 (zero), as ϕ =± 90° For inductance, the phase angle, or the angle of the impedance, ϕ = +90° (lagging), and for capacitance, ϕ = -90° (leading). It may be noted that in both cases, the average power is zero (0), which means that no power is

consumed in the elements, L and C. The complex power, Volt-Amperes (VA) and reactive power will be discussed after the next section.

Content /Topic 3: Single-phase parallel AC circuit:

A. RLC circuit: The circuit with all three elements, R, L & C connected in parallel (Fig. 15.4a), is fed to the ac supply. The current from the supply can be computed by various methods, of which two are described here.



First method

The current in three branches are first computed and the total current drawn from the supply is the phasor sum of all three branch currents, by using Kirchhoff's first law related to the currents at the node. The voltage phasor (*V*) is taken as reference. All currents, i.e. three branch currents and total current, in steady state, are sinusoidal in nature, as the input (supply voltage is sinusoidal of the form,

$$v = \sqrt{2}\ V \sin \omega t$$

Three branch currents are obtained by the procedure given in brief.

$v = R \cdot i_R$, or $i_R = v / R = \sqrt{2}\ (V / R)\ \sin \omega t = \sqrt{2}\, I_R \sin \omega t$,

where, $|I_R| = |(V / R)|$

Similarly, $v = L \dfrac{d\, i_L}{dt}$

So, i_L is,

$i_L = (1/L) \int v\, dt = (1/L) \int \sqrt{2}\ V(\sin \omega t)\ dt = -\sqrt{2}[V/(\omega L)] \cos \omega t = -\sqrt{2}\, I_L \cos \omega t$

$= \sqrt{2}\, I_L \sin(\omega t - 90°)$

where, $|I_L| = |(V / X_L)|$ with $X_L = \omega L$

$v = (1/C) \int i_C\, dt$, from which i_C is obtained as,

$i_C = C \dfrac{dv}{dt} = C \dfrac{d}{dt}(\sqrt{2}\ V \sin \omega t) = \sqrt{2}\ (V \cdot \omega C) \cos \omega t = \sqrt{2}\, I_C \cos \omega t$

$= \sqrt{2}\, I_C \sin(\omega t + 90°)$

where, $|I_c| = |(V / X_C)|$ with $X_C = (1/\omega C)$

Total (supply) current, i is

$i = i_R + i_L + i_C = \sqrt{2}\, I_R \sin \omega t - \sqrt{2}\, I_L \cos \omega t + \sqrt{2}\, I_C \cos \omega t$

$= \sqrt{2}\, I_R \sin \omega t - \sqrt{2}(I_L - I_C) \cos \omega t = \sqrt{2}\, I \sin(\omega t \mp \phi)$

The two equations given here are obtained by expanding the trigonometric form appearing in the last term on RHS, into components of cosωt and sinωt, and then equating the components of cosωt and sinωt from the last term and last but one (previous).

$$I\cos\phi = I_R \text{ and } I\sin\phi = (I_L - I_C)$$

From these equations, the magnitude and phase angle of the total (supply) current are,

$$|I| = \sqrt{(I_R)^2 + (I_L - I_C)^2} = |V|\cdot\sqrt{\left(\frac{1}{R}\right)^2 + \left(\frac{1}{X_L} - \frac{1}{X_C}\right)^2}$$

$$= |V|\cdot\sqrt{\left(\frac{1}{R}\right)^2 + \left(\frac{1}{\omega L} - \omega C\right)^2} = |V|\cdot|Y|$$

$$\phi = \tan^{-1}\left(\frac{I_L - I_C}{I_R}\right) = \tan^{-1}\left(\frac{(1/X_L) - (1/X_C)}{(1/R)}\right) = \tan^{-1}\left[R\cdot\left(\frac{1}{X_l} - \frac{1}{X_C}\right)\right]$$

$$= \tan^{-1}\left[R\cdot\left(\frac{1}{\omega L} - \omega C\right)\right]$$

where, the magnitude of the term (admittance of the circuit) is,

$$|Y| = \sqrt{\left(\frac{1}{R}\right)^2 + \left(\frac{1}{X_L} - \frac{1}{X_C}\right)^2} = \sqrt{\left(\frac{1}{R}\right)^2 + \left(\frac{1}{\omega L} - \omega C\right)^2}$$

Please note that the admittance, which is reciprocal of impedance, is a complex quantity. The angle of admittance or impedance, is same as the phase angle, ϕ of the current *I*, with the input (supply) voltage taken as reference phasor, as given earlier. Alternatively, the steps required to find the rms values of three branch currents and the total (supply) current, using complex form of impedance, are given here. Three branch currents are

$$I_R \angle 0° = I_R = \frac{V}{R}; \quad I_L \angle -90° = -j\,I_L = \frac{V}{j\,X_L} = \frac{V}{j\,\omega L} = -j\frac{V}{\omega L}$$

$$I_C \angle +90° = j\,I_C = \frac{V}{-j\,X_C} = \frac{V}{-j\,(1/\omega C)} = j\,\omega C\,V$$

Of the three branches, the first one consists of resistance only, the current, $\boldsymbol{I_R}$ is in phase with the voltage (V). In the second branch, the current, $\boldsymbol{I_L}$ lags the voltage by 90°, as there is inductance only, while in the third one having capacitance only, the current I_C, leads the voltage 90°. All these cases have been presented in the previous lesson. The total current is

$$I\angle\pm\phi = I_R + j(I_c - I_L) = V\left[\frac{1}{R} + j\left(\omega C - \frac{1}{\omega L}\right)\right]$$

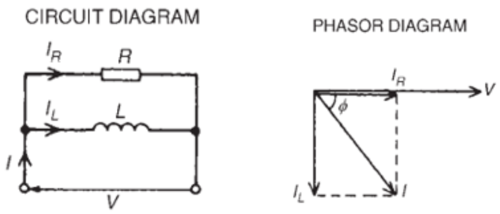
where,

$$I = \sqrt{I_R^2 + (I_C - I_L)^2} = V\sqrt{\left[\frac{1}{R^2} + \left(\omega C - \frac{1}{\omega L}\right)^2\right]}, \text{ and}$$

$$\phi = \tan^{-1}\left(\frac{I_C - I_L}{I_R}\right) = \tan^{-1}\left[R\left(\omega C - \frac{1}{\omega L}\right)\right]$$

B. Power in AC Circuit: The true power in an ac circuit is obtained by multiplying the apparent power by the power factor and is expressed in watts or kilo-watts (kW). The product of apparent power, VI and the sine of the angle between voltage and current, sin ϕ is called the reactive power.

In parallel circuits, such as those shown in Figures below, the voltage is common to each branch of the network and is thus taken as the reference phasor when drawing phasor diagrams. For any parallel AC circuit:



$$\text{True or active power, } P = VI\cos\phi \text{ watts (W)}$$

$$\text{or } P = I_R{}^2 R \text{ watts}$$

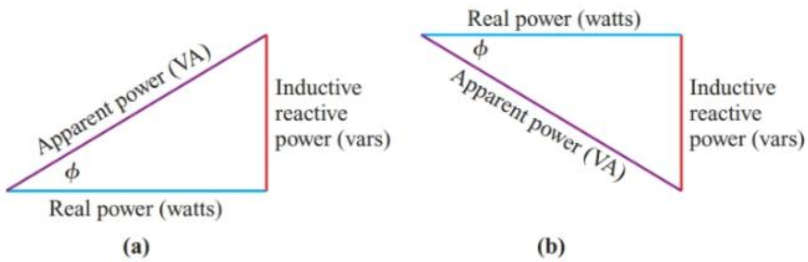
$$\text{Apparent power, } S = \text{VI voltamperes (VA)}$$

$$\text{Reactive power, } Q = VI\sin\phi \text{ reactive voltamperes (var)}$$

$$\text{Power factor} = \frac{\text{true power}}{\text{apparent power}} = \frac{P}{S} = \cos\phi$$

These formulae are the same as for series AC circuits.

C. Power triangle and power factor: Electrical power consumed in an AC circuit can be represented by the three sides of a right-angled triangle, known commonly as a power triangle.



We saw in our tutorial about Electrical Power that AC circuits which contain resistance and capacitance or resistance and inductance, or both, also contain real power and reactive power. So, in order for us to calculate the total power consumed, we need to know the phase difference between the sinusoidal waveforms of the voltage and current.

In an AC circuit, the voltage and current waveforms are sinusoidal so their amplitudes are constantly changing over time. Since we know that power is voltage times the current (P = V*I), maximum power will occur when the two voltage and current waveforms are lined up with each other. That is, their peaks and zero crossover points occur at the same time. When this happens the two waveforms are said to be "in-phase".

The three main components in an AC circuit which can affect the relationship between the voltage and current waveforms, and therefore their phase difference, by defining the total impedance of the circuit are the resistor, the capacitor and the inductor.

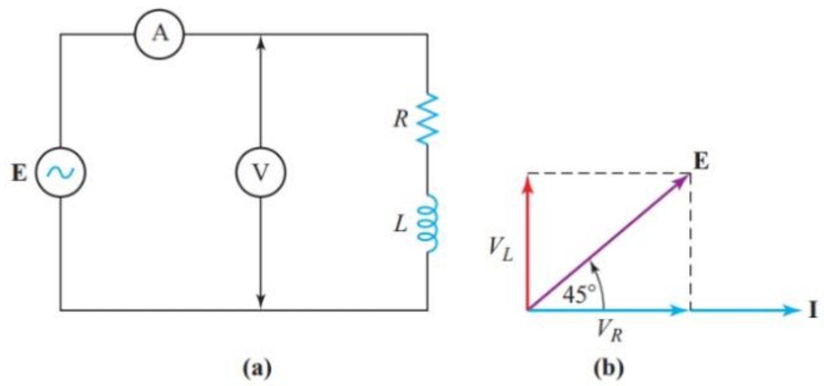
The impedance, (Z) of an AC circuit is equivalent to the resistance calculated in DC circuits, with impedance given in ohms. For AC circuits, impedance is generally defined as the ratio of the voltage and current phasors produced by a circuit component. Phasor's are straight lines drawn in such a way as to represents a voltage or current amplitude by its length and its phase difference with respect to other phasor lines by its angular position relative to the other phasor's.

AC circuits contain both resistance and reactance that are combined together to give a total impedance (Z) that limits current flow around the circuit. But an AC circuits impedance is not equal to the algebraic sum of the resistive and reactive ohmic values as a pure resistance and pure reactance are 90° out-of-phase with each other. But we can use this 90° phase difference as the sides of a right-angled triangle, called an impedance triangle, with the impedance being the hypotenuse as determined by Pythagoras theorem.

This geometric relationship between resistance, reactance and impedance can be represented visually by the use of an impedance triangle as shown.

The real power in the circuit of figure below can be found from the product of V_R and I, and the reactive power from the product of V_L and I. Since V_L leads V_R by 90°,

$$V_T = \sqrt{V_R^2 + V_L^2} \qquad (1)$$



Multiplying each side of **Equation 1** by the common current gives

$$V_T I = \sqrt{(V_R I)^2 + (V_L I)^2}$$

$$S = \sqrt{P^2 + Q^2} \qquad (2)$$

Power Factor

Since the hypotenuse of a right triangle must be longer than either of the other two sides, the apparent power that a generator must supply to a reactive load is always greater than the real power that the load can convert into some other form of energy. This relationship can be quite important since most industrial loads have appreciable inductive reactance.

Power factor is the ratio between the real power and the apparent power of a load in an ac circuit.

Content / topic 4: Power factor improvement in single phase AC circuit.

Power factor improvement in three phase system by connecting a capacitor bank in

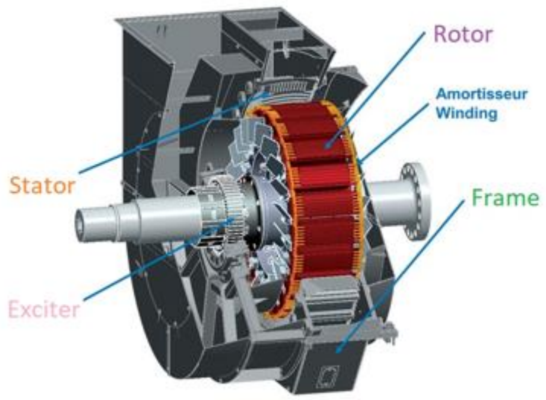
i. Delta connection.
ii. Star Connection.

The following devices and equipment are used for Power Factor Improvement.

1. **Static Capacitor:** We know that most of the industries and power system loads are inductive that take lagging current which decrease the system power factor (See Disadvantages of Low Power factor) . For Power factor improvement purpose, Static capacitors are connected in parallel with those devices which work on low power factor.

   These static capacitors provide leading current which neutralize (totally or approximately) the lagging inductive component of load current (i.e. leading component neutralize or eliminate the lagging component of load current) thus power factor of the load circuit is improved.

2. **Synchronous Condenser:** When a Synchronous motor operates at No-Load and over-exited then it’s called a synchronous Condenser. Whenever a Synchronous motor is over-exited then it provides leading current and works like a capacitor.
   When a synchronous condenser is connected across supply voltage (in parallel) then it draws leading current and partially eliminates the re-active component and this way, power factor is improved. Generally, synchronous condenser is used to improve the power factor in large industries.



3. **Phase Advancer:** Phase advancer is a simple AC exciter which is connected on the main shaft of the motor and operates with the motor's rotor circuit for power factor improvement. Phase advancer is used to improve the power factor of induction motor in industries.

   As the stator windings of induction motor takes lagging current 90° out of phase with Voltage, therefore the power factor of induction motor is low. If the exciting ampere-turns are excited by external AC source, then there would be no effect of exciting current on stator windings. Therefore, the power factor of induction motor will be improved. This process is done by Phase advancer.

LO 3.2 – Analyze resonance in AC circuit.

Content/Topic 1: Series RLC circuit resonance.

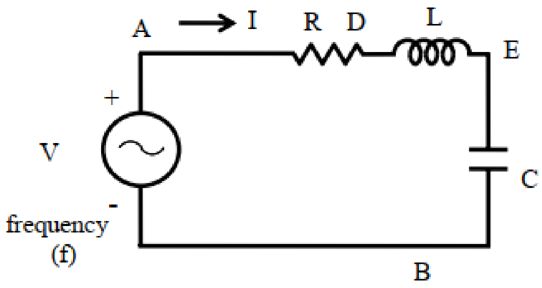


Fig. 17.1 (a) Circuit diagram.

The circuit, with resistance R, inductance L, and a capacitor, C in series (Fig. 17.1a) is connected to a single phase variable frequency (f) supply. The total impedance of the circuit is

$$Z\angle\phi = R + j\left(\omega L - \frac{1}{\omega C}\right)$$

where,

$$Z = \sqrt{\left[R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2\right]} \; ; \quad \phi = \tan^{-1}\frac{(\omega L - 1/\omega C)}{R} \; ; \quad \omega = 2\pi f$$

The current is

$$I\angle -\phi = \frac{V\angle 0°}{Z\angle\phi} = (V/Z)\angle -\phi$$

where $I = \dfrac{V}{\left[R^2 + (\omega L - (1/\omega C))^2\right]^{\frac{1}{2}}}$

The current in the circuit is maximum, if

$$\omega L = \frac{1}{\omega C} \, .$$

The frequency under the above condition is

$$f_o = \frac{\omega_o}{2\pi} = \frac{1}{2\pi\sqrt{LC}}$$

This condition under the magnitude of the current is maximum, or the magnitude of the impedance is minimum, is called resonance. The frequency under this condition with the constant values of inductance L, and capacitance C, is called resonant frequency. If the capacitance is variable, and the frequency, is kept constant, the value of the capacitance needed to produce this condition is

$$C = \frac{1}{\omega^2 L} = \frac{1}{(2\pi f)^2 L}$$

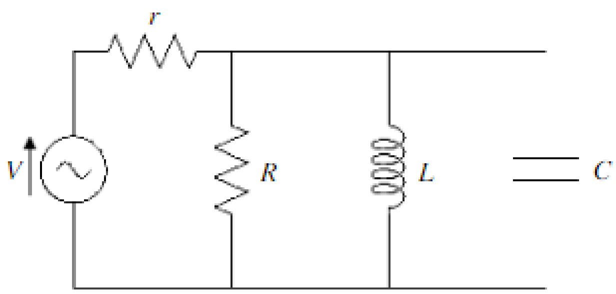
The magnitude of the impedance under the above condition is R=Z, with the reactance X = 0, as the inductive reactance x_1 = ωL is equal to capacitive reactance

X = 1/1ωc. The phase angle is Φ = 0°, and the power factor is unity (cosΦ = 1), which means that the current is in phase with the input (supply) voltage. So, the magnitude of the current (*V/R*) in the circuit is only limited by resistance, R. The phasor diagram is shown in Fig. 17.1b. The magnitude of the voltage drops in the inductance L/capacitance C (both are equal, as the reactance are equal) is **$I\omega_o L = I(1/\omega_o C)$.** The magnification of the voltage drops as a ratio of the input (supply) voltage is

$$Q = \frac{\omega_o L}{R} = \frac{2\pi f_o L}{R} = \frac{1}{R}\sqrt{\frac{L}{C}}$$

A. Calculation of resonance frequency: We now know that at the **resonant frequency**, f_r the admittance of the **circuit** is at its minimum and is equal to the conductance, G given by 1/R because in a **parallel resonance circuit** the imaginary part of admittance, i.e. the susceptance, B is zero because $B_L = B_C$.
Resonance in a parallel RLC Circuit is much like to a series one but with an exactly opposite characteristic. At a specific frequency (resonance frequency), the two reactance cancel each other leaving the maximum impedance however in the circuit.

This circuit in a simple sense, consists of a set of parallel connected resistor, conductor, and capacitor to an AC power source. Hence, they have common voltage about their end points and we need to find the current flowing through each branch. Unlike series RLC circuit this time we would rather consider” admittance “instead of” impedance” for the former case. Similarly, for this case also we would use phasor diagram to obtain an equation between the total current and the supply voltage in the circuit.

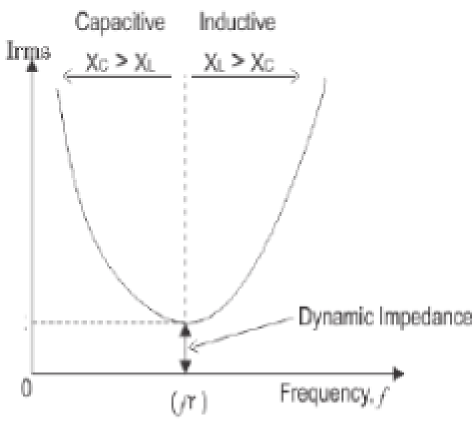


$$\left(\frac{1}{X_L}\right)^2 = \left(\frac{1}{X_C}\right)^2$$

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

$$w_r = \frac{1}{\sqrt{LC}}$$

At the resonance frequency the only contributing (dynamic) impedance would be the resistance while the rest of the circuit would act as an open circuit. As it can be seen from the below figure, the admittance has its lowest value while $\mathbf{Z_{max}}$ at the resonance point:



At the resonance frequency both I_L and I_C become equal at the opposite direction hence the total current would be the one passing through the resistor.

B. Calculation of Q factor: Parallel resonant circuits

- For a parallel RLC circuit, the Q factor is the inverse of the series case:
- Q = R C L = R $\omega 0$ = $\omega 0$ RC
- Consider a circuit where R, L and C are all in parallel. The lower the parallel resistance, the more effect it will have in damping the circuit and thus the lower the Q.

i. Q-Factor in Series and Parallel A.C. Circuits

- The Q, quality factor, of a resonant circuit is a measure of the "goodness" or quality of a resonant circuit. A higher value for this figure of merit corresponds to a narrower bandwidth, which is desirable in many applications. More formally, Q is the ratio of power stored to power dissipated in the circuit reactance and resistance, respectively.
- Q = P stored/P dissipated = I2X/I2R Q = X/R where: X = Capacitive or Inductive reactance at resonance R = Series resistance.
- This formula is applicable to series resonant circuits, and also parallel resonant circuits if the resistance is in series with the inductor. This is the case in practical applications, as we are mostly concerned with the resistance of the inductor limiting the Q.
- Series Resonant Circuits • In an ideal series RLC circuit, and in a tuned radio frequency receiver (TRF) the Q factor is:
    a. Q = 1 R L C = $\omega 0$ L R
    b. where R, L and C are the resistance, inductance and capacitance of the tuned circuit, respectively. The larger the series resistance, the lower the circuit Q.
- A series resonant circuit looks like a resistance at the resonant frequency. Since the definition of resonance is XL=XC, the reactive components cancel, leaving only the resistance to contribute to the impedance. The impedance is also at a minimum at resonance. Below the resonant frequency, the series resonant

circuit looks capacitive since the impedance of the capacitor increases to a value greater than the decreasing inductive reactance, leaving a net capacitive value. Above resonance, the inductive reactance increases, capacitive reactance decreases, leaving a net inductive component.

- Parallel resonant circuits
  a. For a parallel RLC circuit, the Q factor is the inverse of the series case:
  b. Q = R C L = R $\omega 0$ = $\omega 0$ RC
  c. Consider a circuit where R, L and C are all in parallel. The lower the parallel resistance, the more effect it will have in damping the circuit and thus the lower the Q. This is useful in filter design to determine the bandwidth.
  d. In a parallel LC circuit where the main loss is the resistance of the inductor, R, in series with the inductance, L, Q is as in the series circuit. This is a common circumstance for resonators, where limiting the resistance of the inductor to improve Q and narrow the bandwidth is the desired result.
- A parallel resonant circuit is resistive at the resonant frequency. At resonance XL=XC, the reactive components cancel. The impedance is maximum at resonance. Below the resonant frequency, the parallel resonant circuit looks inductive since the impedance of the inductor is lower, drawing the larger proportion of current. Above resonance, the capacitive reactance decreases, drawing the larger current, thus, taking on a capacitive characteristic.
- A parallel resonant circuit is resistive at resonance, inductive below resonance, capacitive above resonance.
- Impedance is maximum at resonance in a parallel resonant circuit, but decreases above or below resonance. Voltage is at a peak at resonance since voltage is proportional to impedance (E=IZ)
- Parallel resonant circuit: Impedance peaks at resonance.
  a. A low Q due to a high resistance in series with the inductor produces a low peak on a broad response curve for a parallel resonant circuit. Conversely, a high Q is due to a low resistance in series with the inductor. This produces a higher peak in the narrower response curve. The high Q is achieved by winding the inductor with larger diameter (smaller gauge), lower resistance wire.

Content/Topic 2: Parallel RLC circuit resonance.

The circuit, with resistance R, inductance L, and a capacitor, C in parallel (Fig. 17.4a) is connected to a single phase variable frequency (f) supply. The total admittance of the circuit is

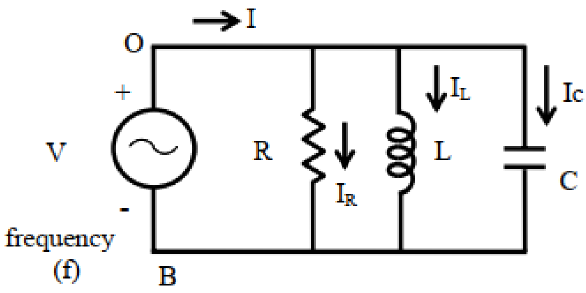


Fig. 17.4 (a) Circuit diagram.

$$Y\angle\phi = \frac{1}{R} + j\left(\omega C - \frac{1}{\omega L}\right)$$ where,

$$Y = \sqrt{\left[\frac{1}{R^2} + \left(\omega C - \frac{1}{\omega L}\right)^2\right]} \;;\quad \phi = \tan^{-1}\left[R\left(\omega C - \frac{1}{\omega L}\right)\right] \;;\quad \omega = 2\pi f$$

The impedance is $Z\angle-\phi = 1/Y\angle\phi$

The current is

$I\angle\phi = V\angle 0°\cdot Y\angle\phi = (V\cdot Y)\angle\phi = V\angle 0°/Z\angle-\phi = (V/Z)\angle\phi$

where, $I = V\sqrt{\left[\frac{1}{R^2} + \left(\omega C - \frac{1}{\omega L}\right)^2\right]}$

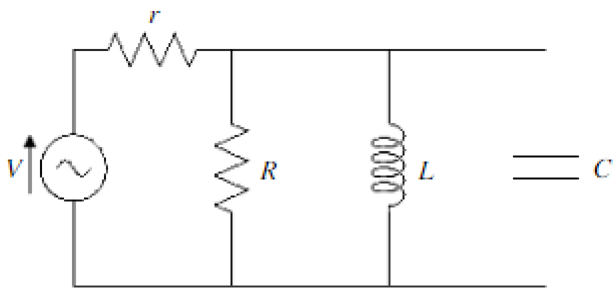
The current in the circuit is minimum, if $\omega C = \frac{1}{\omega L}$

The frequency under the above condition is

$$f_o = \frac{\omega_o}{2\pi} = \frac{1}{2\pi\sqrt{LC}}$$

A. **Calculation of resonance frequency:** We now know that at the **resonant frequency**, f_r the admittance of the **circuit** is at its minimum and is equal to the conductance, G given by 1/R because in a **parallel resonance circuit** the imaginary part of admittance, i.e. the susceptance, B is zero because $B_L = B_C$.
Resonance in a parallel RLC Circuit is much like to a series one but with an exactly opposite characteristic. At a specific frequency (resonance frequency), the two reactance cancel each other leaving the maximum impedance however in the circuit.

This circuit in a simple sense, consists of a set of parallel connected resistor, conductor, and capacitor to an AC power source. Hence, they have common voltage about their end points and we need to find the current flowing through each branch. Unlike series RLC circuit this time we would rather consider" admittance "instead of" impedance" for the former case. Similarly, for this case also we would use phasor diagram to obtain an equation between the total current and the supply voltage in the circuit.

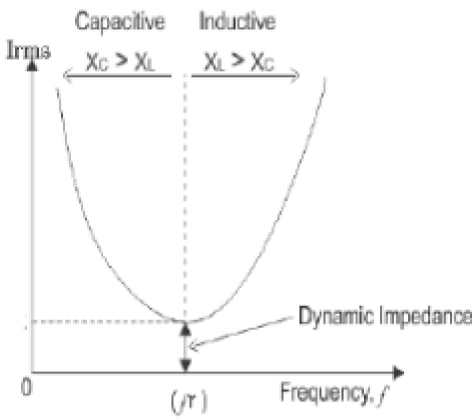


$$\left(\frac{1}{X_L}\right)^2 = \left(\frac{1}{X_C}\right)^2$$

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

$$w_r = \frac{1}{\sqrt{LC}}$$

At the resonance frequency the only contributing (dynamic) impedance would be the resistance while the rest of the circuit would act as an open circuit. As it can be seen from the below figure, the admittance has its lowest value while $\mathbf{Z_{max}}$ at the resonance point:



At the resonance frequency both $\mathbf{I_L}$ and $\mathbf{I_C}$ become equal at the opposite direction hence the total current would be the one passing through the resistor.

B. Calculation of Q factor: Parallel resonant circuits

- For a parallel RLC circuit, the Q factor is the inverse of the series case:
- Q = R C L = R $\omega 0$ = $\omega 0$ RC
- Consider a circuit where R, L and C are all in parallel. The lower the parallel resistance, the more effect it will have in damping the circuit and thus the lower the Q.

ii. Q-Factor in Series and Parallel A.C. Circuits

- The Q, quality factor, of a resonant circuit is a measure of the “goodness” or quality of a resonant circuit. A higher value for this figure of merit corresponds to a narrower bandwidth, which is desirable in many applications. More formally, Q is the ratio of power stored to power dissipated in the circuit reactance and resistance, respectively.

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- This formula is applicable to series resonant circuits, and also parallel resonant circuits if the resistance is in series with the inductor. This is the case in practical applications, as we are mostly concerned with the resistance of the inductor limiting the Q.
- Series Resonant Circuits • In an ideal series RLC circuit, and in a tuned radio frequency receiver (TRF) the Q factor is:
    c. Q = 1 $R\ L\ C = \omega 0\ L\ R$
    d. where R, L and C are the resistance, inductance and capacitance of the tuned circuit, respectively. The larger the series resistance, the lower the circuit Q.
- A series resonant circuit looks like a resistance at the resonant frequency. Since the definition of resonance is XL=XC, the reactive components cancel, leaving only the resistance to contribute to the impedance. The impedance is also at a minimum at resonance. Below the resonant frequency, the series resonant circuit looks capacitive since the impedance of the capacitor increases to a value greater than the decreasing inductive reactance, leaving a net capacitive value. Above resonance, the inductive reactance increases, capacitive reactance decreases, leaving a net inductive component.
- Parallel resonant circuits
    e. For a parallel RLC circuit, the Q factor is the inverse of the series case:
    f. Q = R $C\ L = R\ \omega 0 = \omega 0\ RC$
    g. Consider a circuit where R, L and C are all in parallel. The lower the parallel resistance, the more effect it will have in damping the circuit and thus the lower the Q. This is useful in filter design to determine the bandwidth.
    h. In a parallel LC circuit where the main loss is the resistance of the inductor, R, in series with the inductance, L, Q is as in the series circuit. This is a common circumstance for resonators, where limiting the resistance of the inductor to improve Q and narrow the bandwidth is the desired result.
- A parallel resonant circuit is resistive at the resonant frequency. At resonance XL=XC, the reactive components cancel. The impedance is maximum at resonance. Below the resonant frequency, the parallel resonant circuit looks inductive since the impedance of the inductor is lower, drawing the larger proportion of current. Above resonance, the capacitive reactance decreases, drawing the larger current, thus, taking on a capacitive characteristic.
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- Parallel resonant circuit: Impedance peaks at resonance.
  b. A low Q due to a high resistance in series with the inductor produces a low peak on a broad response curve for a parallel resonant circuit. Conversely, a high Q is due to a low resistance in series with the inductor. This produces a higher peak in the narrower response curve. The high Q is achieved by winding the inductor with larger diameter (smaller gauge), lower resistance wire.

Content /Topic 3: Basic of RLC filters.

A. Bandwidth and selectivity: Consider the current versus frequency graph of a *R-L-C* series circuit shown in Fig. 12.44. It is clear from the graph that the current reaches maximum value (= *Ir*) at resonance. It is also clear that at frequencies close to resonance, the current level is only a little below its maximum value. Thus, the resonant circuit is said to select a *band* (*i.e.*, range) of frequencies rather than just one frequency *fr*. We **arbitrarily* select frequency *f*1 below *fr* and frequency *f*2 above *fr* such that at *f*1 and *f*2, the circuit current = 0.707 *Ir* where *Ir* is the circuit current at resonance as shown in Fig. 12.44. Then, Bandwidth of the series resonant circuit is

$$\text{Bandwidth, } BW = \Delta f = f_2 - f_1$$

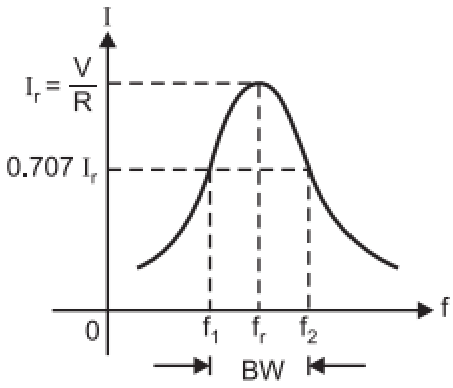


Fig. 12.44

Hence **bandwidth** of a series resonant circuit is the range of frequencies for which the circuit current is equal to or greater than 70.7% of the circuit current at resonance (i.e., Ir). Note that f1 and f_2 are the limiting frequencies at which current is exactly equal to 70.7% of the maximum value. The frequency f_1 (i.e., on the lower side) is called the **lower cut off frequency** and the frequency f_2 (i.e., on the higher side) is called the **upper cut off frequency.** The frequencies f_1 and f_2 are also called **half-power frequencies** (or **half-power points**) or **–3dB frequencies.**

i. The frequencies *f*1 and *f*2 are called half-power frequencies as explained hereafter. At series resonance, the circuit current is maximum (= I_r) and circuit impedance is R. Also, power delivered at resonance is maximum (P_{max}) and is given by;

$$P_{max} = I_r^2 R$$

At f_1 or f_2, circuit current $= 0.707\, I_r$ so that power delivered at f_1 or f_2 is

$$P_{f_1 \text{ or } f_2} = (0.707\, I_r)^2 R = \frac{I_r^2 R}{2} = \frac{P_{max}}{2}$$

Hence frequencies f1 and f2 may also be defined as those frequencies at which the power delivered to the circuit is half the power delivered at resonance.

ii. The frequencies $f1$ and $f2$ are also called – 3dB frequencies as explained hereafter. Power delivered at resonance = P_{max}

$$\text{Power delivered at } f_1 \text{ or } f_2 = \frac{P_{max}}{2}$$

Change in power level from resonance to f_1 or f_2

$$= 10 \log_{10} \frac{P_{max}}{P_{max}/2} = 10 \log_{10} 2$$

$$= 3 \text{ dB below resonance} = -3 \text{ dB}$$

Hence frequencies f1 and f2 can also be defined as those frequencies at which the power is 3 dB below the power at resonance.

Other names for $f1$ and $f2$ are *critical frequencies* and *band frequencies*. **Important points about $f1$ and $f2$.** At $f1$ and $f2$,

(*a*) Circuit current is $\frac{I_r}{\sqrt{2}}$ where I_r = current at resonance.

(*b*) Circuit impedance is $\sqrt{2}R$ or $\sqrt{2}\,Z_r$.

(*c*) $P_1 = P_2 = \frac{P_{max}}{2}$

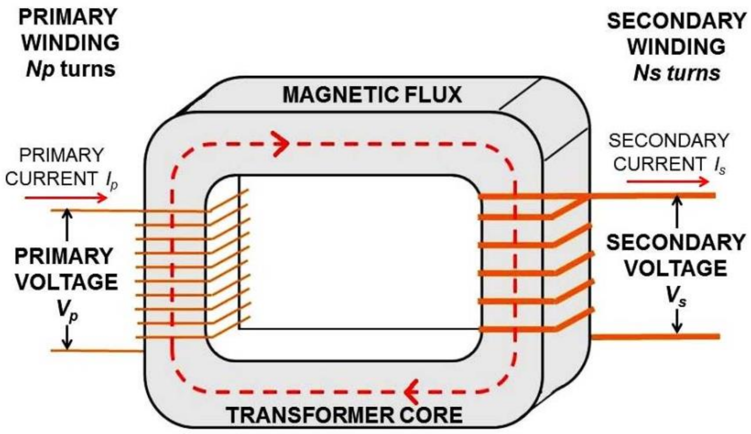
(*d*) Circuit phase angle is $\phi = \pm 45°$.

LO 3.3 – Apply basic concepts of transformer.

A transformer can be defined as a static device which helps in the transformation of electric power in one circuit to electric power of the same frequency in another circuit. The voltage can be raised or lowered in a circuit, but with a proportional increase or decrease in the current ratings. In this article we will be learning about Transformer basics and working principle.

Content/Topic 1: Working principle of a transformer.

The main principle of operation of a transformer is mutual inductance between two circuits which is linked by a common magnetic flux. A basic transformer consists of two coils that are electrically separate and inductive, but are magnetically linked through a path of reluctance. The working principle of the transformer can be understood from the figure below.



As shown above the electrical transformer has primary and secondary windings. The core laminations are joined in the form of strips in between the strips you can see that there are some narrow gaps right through the cross-section of the core. These staggered joints are said to be 'imbricated'. Both the coils have high mutual inductance. A mutual electro-motive force is induced in the transformer from the alternating flux that is set up in the laminated core, due to the coil that is connected to a source of alternating voltage. Most of the alternating flux developed by this coil is linked with the other coil and thus produces the mutual induced electro-motive force. The so produced electro-motive force can be explained with the help of Faraday's laws of Electromagnetic Induction as, **e=M*dI/dt**

If the second coil circuit is closed, a current flow in it and thus electrical energy is transferred magnetically from the first to the second coil. The alternating current supply is given to the first coil and hence it can be called as the primary winding. The energy is drawn out from the second coil and thus can be called as the secondary winding. In short, a transformer carries the operations shown below:

1. Transfer of electric power from one circuit to another.
2. Transfer of electric power without any change in frequency.
3. Transfer with the principle of electromagnetic induction.
4. The two electrical circuits are linked by mutual induction.

Content /Topic 2: Classification of transformer according to:

A. Method of cooling:

1. **Oil Filled Self-Cooled Type:** Oil filled self-cooled type uses small and medium-sized distribution transformers. The assembled windings and core of such transformers are mounted in a welded, oil-tight steel tanks provided with a steel cover. The tank is filled with purified, high quality insulating oil as soon as the core is put back at its proper place. The oil helps in transferring the heat from the core and the windings to the case from where it is radiated out to the surroundings.

For smaller sized transformers the tanks are usually smooth surfaced, but for large size transformers a greater heat radiation area is needed, and that too without disturbing the cubical capacity of the tank. This is achieved by frequently corrugating the cases. Still larger sizes are provided with radiation or pipes.

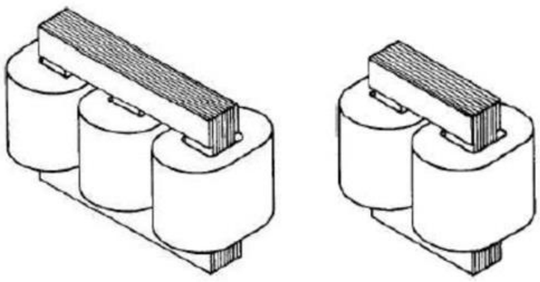
2. **Oil Filled Water Cooled Type:** This type is used for much more economic construction of large transformers, as the above-told self-cooled method is very expensive. The same method is used here as well- the windings and the core are immersed in the oil. The only difference is that a cooling coil is mounted near the surface of the oil, through which cold water keeps circulating. This water carries the heat from the device. This design is usually implemented on transformers that are used in high voltage transmission lines. The biggest advantage of such a design is that such transformers do not require housing other than their own. This reduces the costs by a huge amount. Another advantage is that the maintenance and inspection of this type is only needed once or twice in a year.

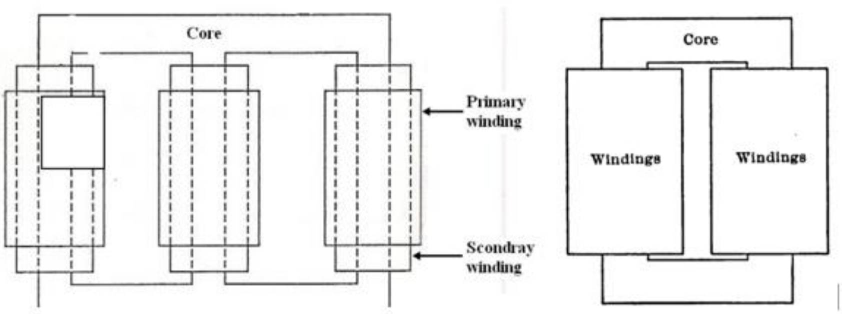
3. **Air Blast Type:** This type is used for transformers that use voltages below 25,000 volts. The transformer is housed in a thin sheet metal box open at both ends through which air is blown from the bottom to the top.

B. Insulation between winding:

Depending upon the manner in which the primary and secondary are wound on the core, transformers are of two types viz.,

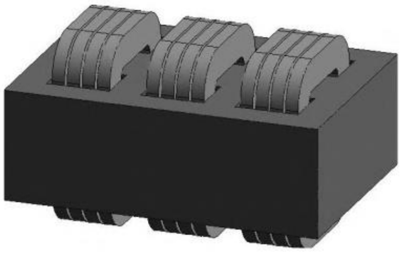
i. **core-type transformer:** In the core form, the windings are wrapped around the core (the windings surrounded the core considerably. Core construction is desirable when compactness is a major requirement. Figure below illustrates core type configurations three-phase transformers.

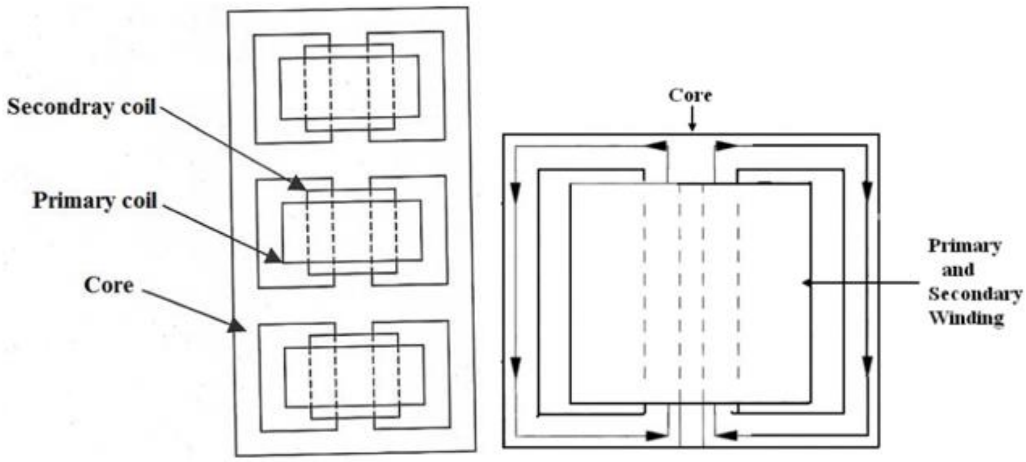




Three-phase core type transformer Single-phase core type transformer

ii. **shell-type transformer:** Shell form transformers completely enclose the windings inside the core assembly (the core surrounds the windings). Shell construction is used for larger transformers, although some core-type units are built for medium and high capacity use. Shell construction is also more flexible, because it allows a wide choice of winding arrangements and coil groupings.





C. Number of phases: According to the supply used, the transformers are mainly classified as;

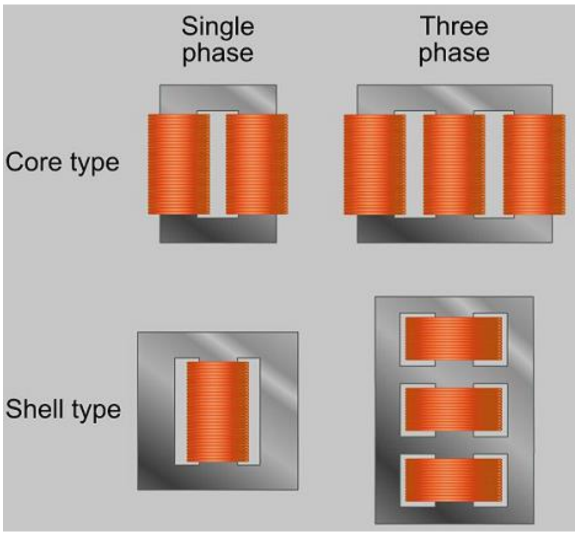
i. **Single phase transformer:** A normal transformer is a single-phase transformer. It has a primary and a secondary winding and it is operated to either decrease or increase the secondary voltage.

ii. **Three phase transformers:** For a three-phase transformer, three primary windings are connected together and three secondary windings are connected together.

A single three phase transformer is preferred to three single phase transformers so as to get good efficiency, where it occupies less space at low cost. But due to the transportation problem of heavy equipment, single phase transformers are used in most cases. Another classification of these transformers is **Core** and **Shell** type.

- In **Shell type**, the windings are positioned on a single leg surrounded by the core.
- In **Core type**, they are wounded on different legs.

The difference is well known by having a look at the following figure.



D. Purpose: According to the application, power transformers can be divided in several subgroups:

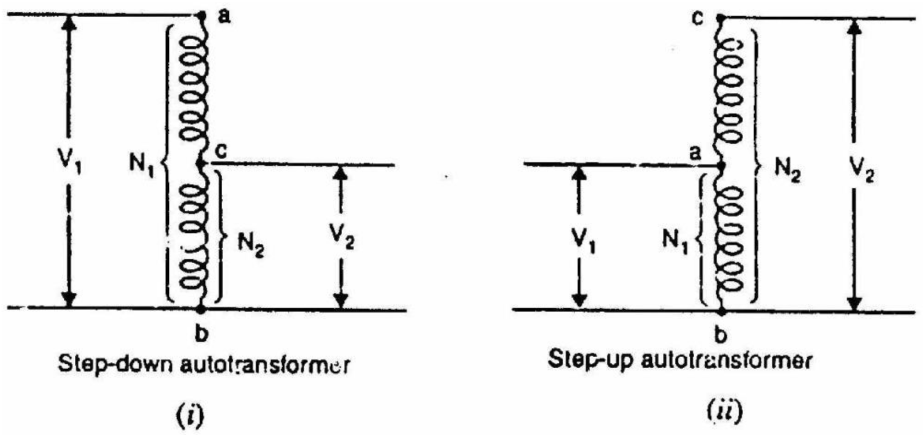
i. **Power transformers:** They are designed to operate with an almost constant load which is equal to their rating. The maximum efficiency is designed to be at full-load. This means that full-load winding copper losses must be equal to the core losses. A power transformer has two or more windings wound on a laminated iron core. The transformer is used to supply stepped up and stepped down values of voltage to the various circuit in electrical equipment.

ii. **Distribution transformers:** These transformers have variable load which is usually considerably less than the full-load rating. Therefore, these are designed to have their maximum efficiency at between 1/2 and 3/4 of full load. A distribution transformer has two windings wound on a laminated iron core. The transformer is used to supply stepped down values of voltage to the various circuit in electrical equipment.

iii. **Autotransformers:** An autotransformer has a single winding on an iron core and a part of winding is common to both the primary and secondary circuits. Fig. below shows the connections of a step-down autotransformer and the connections of a step-up autotransformer. In either case, the winding **ab** having N_1 turns is the primary winding and winding **bc** having N_2 turns is the secondary winding. Note that the primary and secondary windings are connected electrically as well as magnetically. Therefore, power from the primary is transferred to the secondary conductively as well as inductively (transformer action). The voltage transformation ratio **a** of an ideal autotransformer is

$$\mathbf{a} = \frac{V_1}{V_2} = \frac{N_1}{N_2} = \frac{I_2}{I_1}$$

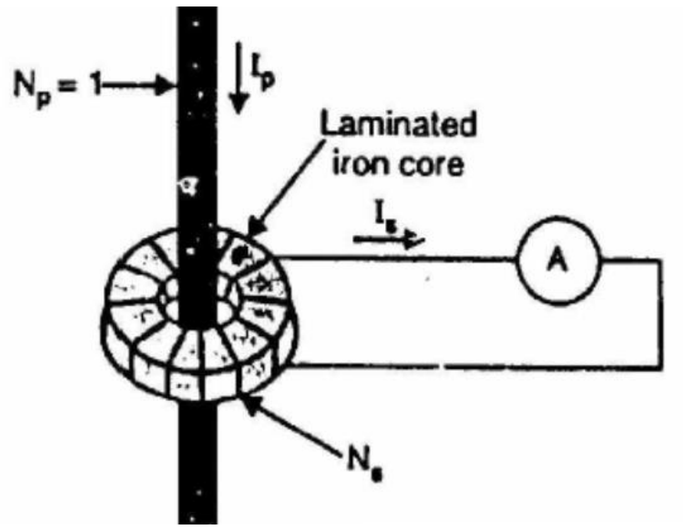
An autotransformer requires less copper than an ordinary 2-winding transformer. Autotransformers are used for starting induction motors (reducing applied voltage during starting) and in boosters for raising the voltage of feeders.



iv. **Instrument transformers:** Current and voltage transformers are used to extend the range of AC instruments.

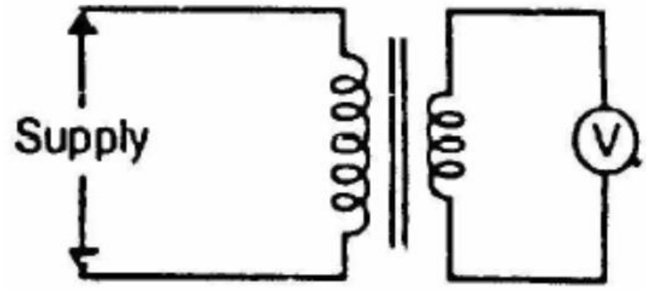
a) **Current transformer:** A current transformer is a device that is used to measure high alternating current in a conductor. Fig. below illustrates the principle of a current transformer. The conductor carrying large current passes through a circular laminated iron core. The conductor constitutes a one-turn primary winding. The secondary winding consists of a large number of turns of much fine wire wrapped around the core as shown. Due to transformer action, the secondary current is transformed to a low value which can be measured by ordinary meters.

$$\text{Secondary current, } I_S = I_P \times \frac{N_P}{N_S}$$



b) **Voltage transformer:** It is a device that is used to measure high alternating voltage. It is essentially a step-down transformer having small number of secondary turns as shown in Fig below. The high alternating voltage to be measured is connected directly across the primary. The low voltage winding (secondary winding) is connected to the voltmeter. The power rating of a potential transformer is small (seldom exceeds 300 W) since voltmeter is the only load on the transformer.

$$V_P = V_S \times \frac{N_P}{N_S}$$

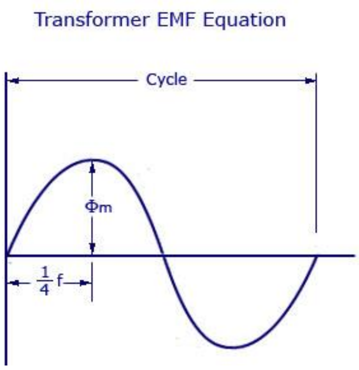


v. **Audio-frequency transformer:** A transformer used in audio frequency circuits to transfer AF signals from one circuit to another.
vi. **Radio-frequency transformer:** A transformer used in radio-frequency circuits to transfer RF signals from one circuit to another.

vii. **Impedance-Matching Transformer:** A transformer used to match the impedance of the source and the impedance of the load. The mathematical relationship of the turns and impedance of the transformer is expressed by equation:

$$\frac{N_P}{N_S} = \sqrt{\frac{Z_P}{Z_S}}$$

Content /Topic 3: E.m.f equation of a transformer.



Let,

N_A = Number of turns in primary

N_B = Number of turns in secondary

$Ø_{max}$ = Maximum flux in the core in webers = B_{max} x A

f = Frequency of alternating current input in hertz (H_Z)
As shown in figure above, the core flux increases from its zero value to maximum value $Ø_{max}$ in one quarter of the cycle, that is in ¼ frequency second.

Therefore, average rate of change of flux = $Ø_{max}$/ ¼ f = 4f $Ø_{max}$Wb/s
Now, rate of change of flux per turn means induced electro motive force in volts.

Therefore, average electro-motive force induced/turn = 4f $Ø_{max}$volt
If flux Ø varies sinusoidally, then r.m.s. value of induced e.m.f is obtained by multiplying the average value with form factor.

Form Factor = r.m.s. value/average value = 1.11
Therefore, r.m.s. value of e.m.f/turn = 1.11 X 4f $Ø_{max}$ = 4.44f $Ø_{max}$
Now, r.m.s. value of induced e.m.f in the whole of primary winding = (induced e.m.f./turn) X Number of primary turns
Therefore,

- $E_A = 4.44f\, N_A Ø_{max} = 4.44fN_A B_m A$
- Similarly, r.m.s. value of induced e.m.f in secondary is
- $E_B = 4.44f\, N_B\, Ø_{max} = 4.44fN_B B_m A$

In an ideal transformer on no load, $V_A = E_A$ and $V_B = E_B$, where V_B is the terminal voltage

i. Voltage Transformation Ratio (K)

From the above equations we get

EB/ EA = VB/ VA = NB/NA = K

This constant K is known as voltage transformation ratio.

1. If NB>NA, that is K>1, then transformer is called step-up transformer.
2. If NB<1, that is K<1, then transformer is known as step-down transformer.

Again, for an ideal transformer, Input V_A = output V_A

$V_A I_A = V_B I_B$

Or, $I_B/I_A = V_A/V_B = 1/K$

Hence, currents are in the inverse ratio of the (voltage) transformation ratio.

Content /Topic 4: Transformer losses.

A. **Core Losses**: Since magnetic lines of force in a transformer are constantly changing in value and direction, heat is developed because of the hysteresis of the magnetic material (friction of the molecules). This heat must be removed; therefore, it represents an energy loss of the transformer. High temperatures in a transformer will drastically shorten the life of insulating materials used in the windings and structures. For every 8 degrees Celsius (°C) temperature rise, life of the transformer is cut by one-half; therefore, maintenance of cooling systems is critical. Losses of energy, which appears as heat due both to hysteresis and to eddy currents in the magnetic path, is known as core losses. Since these losses are due to alternating magnetic fields, they occur in a transformer whenever the primary is energized, even though no load is on the secondary winding.

B. **Copper Losses**: There is some loss of energy in a transformer due to resistance of the primary winding to the magnetizing current, even when no load is connected to the transformer. This loss appears as heat generated in the winding and must also be removed by the cooling system. When a load is connected to a transformer and electrical currents exist in both primary and secondary windings, further losses of electrical energy occur. These losses, due to resistance of the windings, are called copper losses (or the I^2R losses).

Content /Topic 5: Voltage regulation on a transformer.

If the small amount of transformer loss is ignored, the back-voltage (back EMF) of the primary must equal the applied voltage. The magnetic field, which induces the back-voltage in the primary, also cuts the secondary coil. If the secondary coil has the same number of turns as the primary, the voltage induced in the secondary will equal the back-voltage induced in the primary (or the applied voltage). If the secondary coil has twice as many turns as the primary, it will be cut twice as many times by the flux, and twice the applied primary voltage will be induced in the secondary. The total induced voltage in each winding is proportional to the number of turns in that winding. If E_1 is the primary voltage and I_1 the primary current, E_2 the secondary voltage and I_2 the secondary current, N_1 the primary turns and N_2 the secondary turns, then:

$$\frac{E_1}{E_2} = \frac{N_1}{N_2} = \frac{I_2}{I_1}$$

Note that the current is inversely proportional to both voltage and number of turns. This means (as discussed earlier) that if voltage is stepped up, the current must be stepped down and vice versa. The number of turns remains constant unless there is a tap changer (discussed later). The power output or input of a transformer equals volts times amperes (E x I). If the small amount of transformer loss is disregarded, input equals output or:

$$E_1 \times I_1 = E_2 \times I_2$$

If the primary voltage of a transformer is 110 volts (V), the primary winding has 100 turns, and the secondary winding has 400 turns, what will the secondary voltage be?

$$\frac{E_1}{E_2} = \frac{N_1}{N_2} \qquad \frac{110}{E_2} = \frac{100}{400}$$

$$100\ E_2 = 44{,}000 \qquad E_2 = 440 \text{ volts}$$

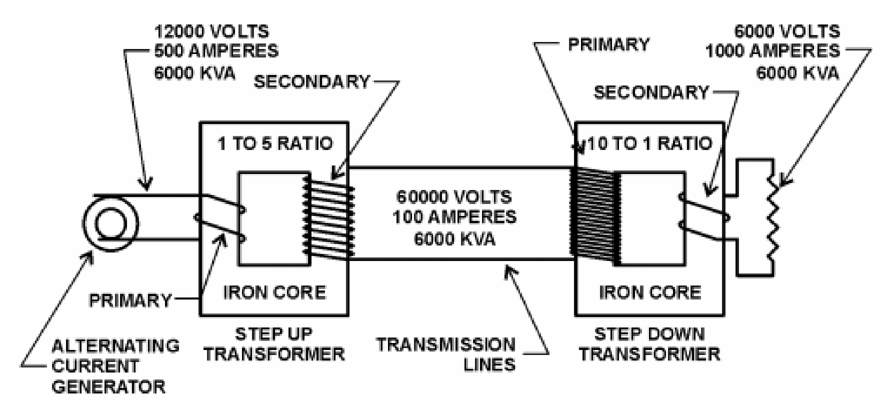
If the primary current is 20 amps, what will the secondary current be?

$$E_2 \times I_2 = E_1 \times I_1$$

$$440 \times I_2 = 110 \times 20 = 2{,}200$$

$$I_2 = 5 \text{ amps}$$

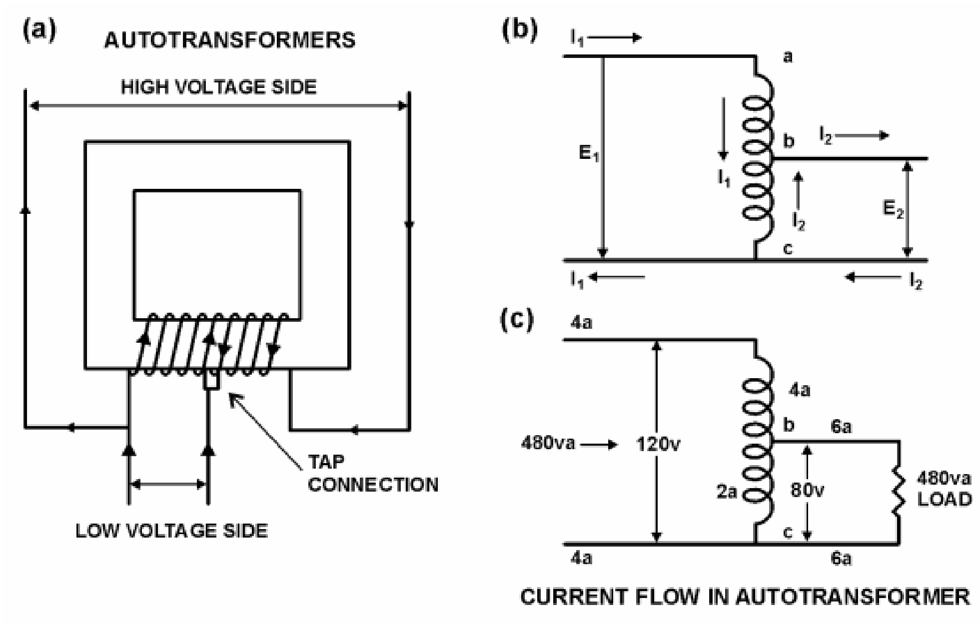
Since there is a ratio of 1 to 4 between the turns in the primary and secondary circuits, there must be a ratio of 1 to 4 between the primary and secondary voltage and a ratio of 4 to 1 between the primary and secondary current. As voltage is stepped up, the current is stepped down, keeping volts multiplied by amps constant. This is referred to as "volt amps." As mentioned earlier and further illustrated in figure 5, when the number of turns or voltage on the secondary of a transformer is greater than that of the primary, it is known as a step-up transformer. When the number of turns or voltage on the secondary is less than that of the primary, it is known as a step-down transformer. A power transformer used to tie two systems together may feed current either way between systems, or act as a step-up or step-down transformer, depending on where power is being generated and where it is consumed. As mentioned above, either winding could be the primary or secondary. To eliminate this confusion, in power generation, windings of transformers are often referred to as high-side and low-side windings, depending on the relative values of the voltages.



Note that kVA (amps times volts) remains constant throughout the above circuit on both sides of each transformer, which is why they are called constant wattage devices. Efficiencies of well-designed power transformers are very high, averaging over 98 percent (%). The only losses are due to core losses, maintaining the alternating magnetic field, resistance losses in the coils, and power used for cooling. The main reason for high efficiencies of power transformers, compared to other equipment, is the absence of moving parts. Transformers are called static AC machines.

Content /Topic 6: Autotransformer.

It is possible to obtain transformer action by means of a single coil, provided that there is a "tap connection" somewhere along the winding. Transformers having only one winding are called autotransformers, shown schematically in figure 9. An autotransformer has the usual magnetic core but only one winding, which is common to both the primary and secondary circuits. The primary is always the portion of the winding connected to the AC power source. This transformer may be used to step voltage up or down. If the primary is the total winding and is connected to a supply, and the secondary circuit is connected across only a portion of the winding (as shown), the secondary voltage is "stepped-down."



Learning Unit 4 – Analyze 3 phases circuits.

LO 4.1 – Analyze AC 3phase connection.

Content/Topic 1: Difference between single phase and three phases in AC.

In electricity, the phase refers to the distribution of a load. What is the difference between single-phase and three-phase power supplies? Single-phase power is a two-wire alternating current (ac) power circuit. Typically, there is one power wire—the phase wire—and one neutral wire, with current flowing between the power wire (through the load) and the neutral wire. Three-phase power is a three-wire AC power circuit with each phase ac signal 120 electrical degrees apart.

Residential homes are usually served by a single-phase power supply, while commercial and industrial facilities usually use a three-phase supply. One key difference between single-phase vs. three-phase is that a three-phase power supply better accommodates higher loads. Single-phase power supplies are most commonly used when typical loads are lighting or heating, rather than large electric motors.

Single-phase systems can be derived from three-phase systems. In the US, this is done via a transformer to get the proper voltage, while in the EU it is done directly. Voltage levels in the EU are such that a three-phase system can also serve as three single-phase systems.

i. **Single-phase vs. three-phase power:** One other important difference between 3-phase power vs. single phase power is the consistency of the delivery of power. Because of the peaks and dips in voltage, a single-phase power supply simply does not offer the same consistency as a three-phase power supply. A three-phase power supply delivers power at a steady, constant rate.
Comparing single-phase vs. three-phase power, three-phase power supplies are more efficient. A three-phase power supply can transmit three times as much power as a single-phase power supply, while only needing one additional wire (that is, three wires instead of two). Thus, three-phase power supplies, whether they have three wires or four, use less conductor material to transmit a set amount of electrical power than do single-phase power supplies.

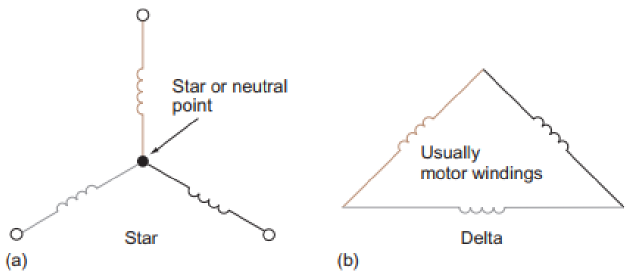
ii. **Difference between 3-phase and single-phase configurations**
Some three-phase power supplies do use a fourth wire, which is a neutral wire. The two most common configurations of three-phase systems are known as wye and delta. A delta configuration has only three wires, while a wye configuration may have a fourth, neutral, wire. Single-phase power supplies have a neutral wire as well.
Both single-phase and three-phase power distribution systems have roles for which they are well-suited. But the two types of systems are quite different from each other.

The key differences between a 1 phase and three phases include the following.

Feature	Single Phase	Three Phase
Definition	Single phase power supply operates using a single conductor	3 phase power supply operates using three conductors
Wave Cycle	It has only one distinct wave cycle	It has three distinct wave cycles
Connection of Circuit	Need just a single wire to connect with the circuit	This power phase requires three wires for connection with the circuit
Output Voltage Levels	Delivers a voltage level of almost 230V	Delivers a voltage level of almost 415V
Phase Name	The phase name of the single phase is split phase	There is no specific name for this phase
The ability of Power Transfer	It has minimum capacity for the power transmission	This phase holds the maximum capacity for transmission of power
Circuit Complexity	1 phase power supply can be constructed simply	The construction of this is complicated
The occurrence of Power Failure	There will be a frequent failure of power	No power failure happens
Loss	The loss in single phase is maximum	The loss in the 3 phase is minimum
Efficiency	It has minimal efficiency	It has maximum efficiency
Cost	It is not expensive than 3 phase power supply	It is a bit costly than single phase
Applications	Used for home applications	Three phase power supply is used in huge industries to run heavy loads.

Content/Topic 2: Connections in AC three phases.

Figure below show the two main ways of connecting three-phase equipment.

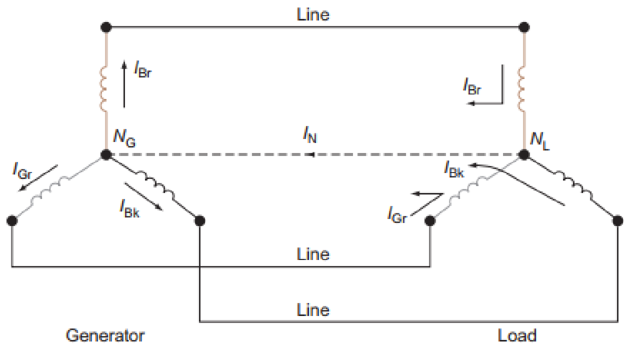


A. **Star:** The Figure below shows the simple system of a star-connected load fed from a star-connected supply. The addition of the conductor between the star points converts the system into what is known as a 'three-phase four-wire system'. We can see that the currents supplied by the generator flow along the lines, through the load and return via the neutral conductor.

However, we have already seen that all line currents in a **balanced** three-phase system are equal, and add up to the neutral current, which is zero:

$$I_{Br} + I_{Bk} + I_{Gr} = I_N = 0$$

Hence the current flowing in the neutral is zero. Also, since no current flows between the star points, they must both be at the same potential, which is also zero. The star point of a transformer is earthed, as earth is also at zero volts. One reason for the connection of the neutral conductor is to provide a path for currents if the system became unbalanced. Another is that it enables single-phase loads to be connected to a three-phase system. The windings of most three-phase.



B. **Delta:** A delta connection is a connection used in a three-phase electrical system in which three elements in series form a triangle, the supply being input and output at the three junctions. The delta connection consists of three-phase windings connected end-to-end which are 120° apart from each other electrically.

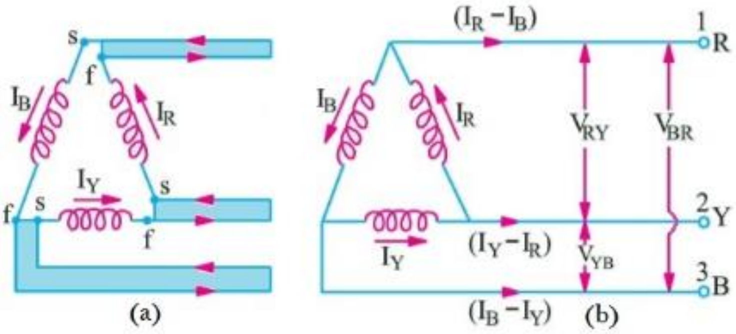
Delta or Mesh Connection (Δ) System is also known as Three Phase Three Wire System (3-Phase 3 Wire) and it is the most preferred system for AC power transmission while for distribution, Star connection is generally used.

In **Delta** (also denoted by **Δ**) system of interconnection, the starting ends of the three phases or coils are connected to the finishing ends of the coil. Or the starting end of the first coil is connected to the finishing end of the second coil and so on (for all three coils) and it looks like a closed mesh or circuit as shown in fig (1).

In more clear words, all three coils are connected in series to form a close mesh or circuit. Three wires are taken out from three junctions and the all outgoing currents from junction assumed to be positive.

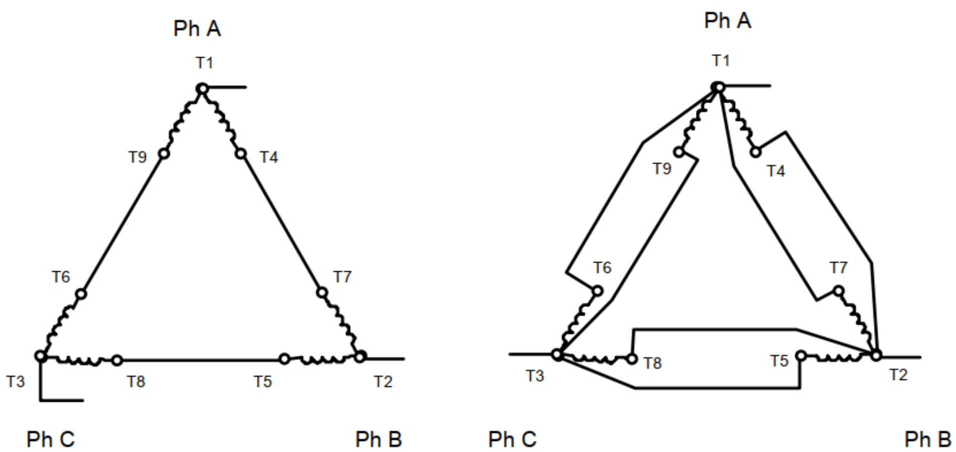
In **Delta connection**, the three windings interconnection looks like a short circuit, but this is not true, **if the system is balanced, then the value of the algebraic sum of all voltages around the mesh is zero** in Delta connection.

Good to Remember: In Delta configuration, at any instant, the EMF value of one phase is equal to the resultant of the other two phases e.m.f values but in the opposite direction.



The diagrams below illustrate the connections and terminal markings for a delta-connected, dual-voltage induction motor. The diagram on the left shows the method of numbering and connecting the nine external leads for high voltage operation. The method of numbering for the delta is much the same as the wye. Starting at the top corner of the delta, number the three corners T_1, T_2, T_3. Then start at the end of the T_1 winding and go clockwise to number for T_4, T_2 toT_5, and T_3 to T_6. For the next terminal, start at the T_4 winding and go clockwise to the next terminal for T_7, then go to clockwise of T_5 and label T_8, and finally label T_9.

Note the diagram on the left, that the two sections of each phase are connected in series for the **high voltage connection**.



Content /Topic 3: Three phase voltage and currents values.

A. Line current: Line current is the current through any one line between a three-phase source and load. ... In balanced "Y" circuits, the line voltage is equal to phase voltage times the square root of 3, while the line current is equal to phase current.

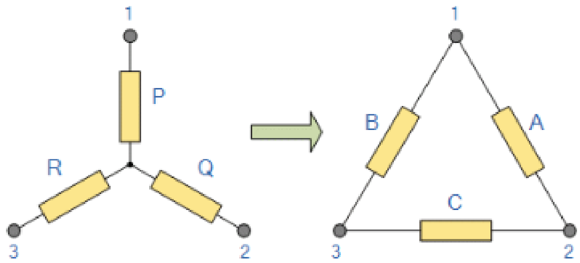
B. Phase current: Phase voltage is the voltage measured across a single component in a three-phase source or load. Line current is the current through any one line between a three-phase source and load. Phase current is the current through any one component comprising a three-phase source or load.

C. **Line voltage:** The conductors between a voltage source and a load are called lines, and the voltage between any two lines is called line voltage. The voltage measured between any line and neutral is called phase voltage. For example, for a 208/120-volt service, the line voltage is 208 Volts, and the phase voltage is 120 Volts.

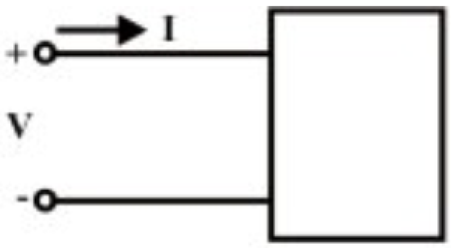
D. **Phase voltage:** A three-phase system may be arranged in delta (Δ) or star (Y) (also denoted as wye in some areas). A wye system allows the use of two different voltages from all three phases, such as a 230/400 V system which provides 230 V between the neutral (center hub) and any one of the phases, and 400 V across any two phases.

Content /Topic 4: Star-delta / delta-star transformations.

Star-Delta Transformations and Delta-Star Transformations allow us to convert impedances connected together in a 3-phase configuration from one type of connection to another.



There are certain circuit configurations that cannot be simplified by series-parallel combination alone. A simple transformation based on mathematical technique is readily simplifies the electrical circuit configuration. A circuit configuration shown below



A. **Delta (Δ) – Wye (Y) conversion**

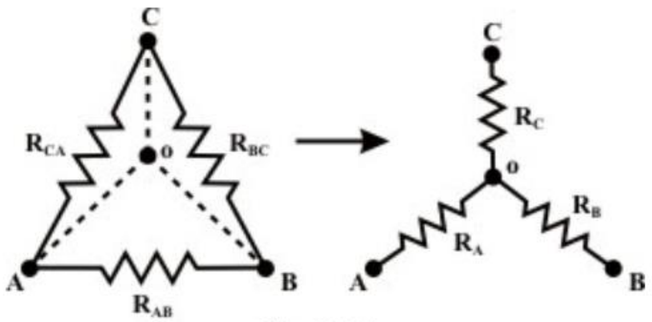


Fig. 6.1 (e)

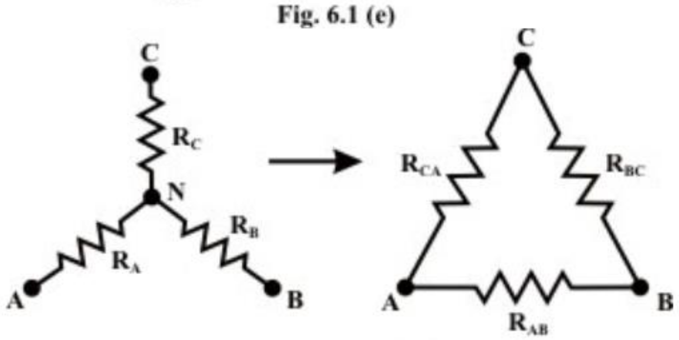


Fig. 6.1 (f)

These configurations may often be handled by the use of a Δ -*Y* or *Y* - Δ transformation. One of the most basic three-terminal network equivalents is that of three resistors connected in "Delta" and in "Wye". These two circuits identified in fig. L6.1(e) and Fig.L.6.1(f) are sometimes part of a larger circuit and obtained their names from their configurations. These three terminal networks can be redrawn as four-terminal networks as shown in fig.L.6.1(c) and fig.L.6.1(d). We can obtain useful expression for direct transformation or conversion from Δ to *Y* or *Y* to Δ by considering that for equivalence the two networks have the same resistance when looked at the similar pairs of terminals.

B. **Conversion from Delta (Δ) to Star or Wye (Y).**

Let us consider the network shown in fig.6.1(e) (or fig in 6.1, C) and assumed the resistances R_{AB} R_{BC} *and* R_{CA}, Δ network are known. Our problem is to find the values R_A, R_B, R_C of in Wye (*Y*) network (see fig.6.1(e)) that will produce the same resistance when measured between similar pairs of terminals. We can write the equivalence resistance between any two terminals in the following form.

Between A & C **terminals:**

$$R_A + R_C = \frac{R_{CA}\left(R_{AB} + R_{BC}\right)}{R_{AB} + R_{BC} + R_{CA}}$$

Between C B & **terminals:**

$$R_C + R_B = \frac{R_{BA}\left(R_{AB} + R_{CA}\right)}{R_{AB} + R_{BC} + R_{CA}}$$

Between *B* & *A* **terminals:**

$$R_B + R_A = \frac{R_{AB}\left(R_{CA} + R_{BC}\right)}{R_{AB} + R_{BC} + R_{CA}}$$

By combining above three equations, one can write an expression as given below.

$$R_A + R_B + R_C = \frac{R_{AB}R_{BC} + R_{BC}R_{CA} + R_{CA}R_{AB}}{R_{AB} + R_{BC} + R_{CA}}$$

Subtracting equations (6.2), (6.1), and (6.3) from (6.4) equations, we can write the express for unknown resistances of Wye (Y) network as

$$R_A = \frac{R_{AB}R_{CA}}{R_{AB} + R_{BC} + R_{CA}}$$

$$R_B = \frac{R_{AB}R_{BC}}{R_{AB} + R_{BC} + R_{CA}}$$

$$R_C = \frac{R_{BC}R_{CA}}{R_{AB} + R_{BC} + R_{CA}}$$

C. Conversion from Star or Wye (Y) to Delta (Δ).

To convert a **Wye (***Y***)** to a **Delta (**Δ**)**, the relationships R_{AB}, R_{BC} *and* R_3 must be obtained in terms of the **Wye (***Y***)** resistances R_A, R_B *and* R_C (referring to fig.6.1 (f)). Considering the ***Y*** connected network, we can write the current expression through, R_A resistor as

$$I_A = \frac{\left(V_A - V_N\right)}{R_A} \quad \text{(for } Y \text{ network)}$$

Content /Topic 5: Applications of Delta Star/Star-Delta connection.

It totally depends on your application, but if you’re talking about star and delta, you Have to be talking about three phase power.

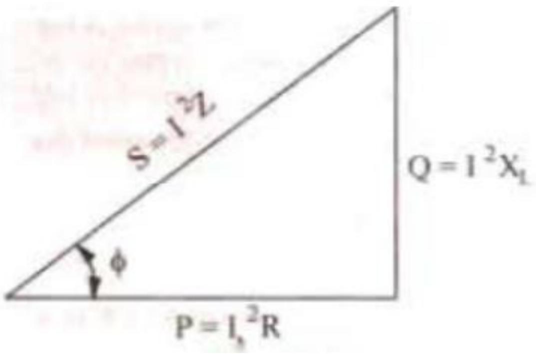
- That said, if you need more current to accompany your voltage, you should use delta.
- If you need to limit current, or of you need two separate voltages (a three phase and a single phase),
- If you want a system neutral (for grounding or other purposes) you want to look at star connection.

LO 4.2 – Identify power in 3 phase AC circuits.

Content/Topic 1: Introduction of power in three phases AC circuits.

A **three-phase ac circuit** is powered by **three** voltage sine waves having the same frequency and magnitude and which are displaced from each other by 120°. The **phase** shift between each voltage waveform of a **three-phase ac power** source is therefore 120° (360°÷ **3 phases**).

Content/Topic 2: Types of power in AC circuits.



$$S^2 = P^2 + Q^2$$

$$S = P + j\,Q$$

A. Active power(P): is the power which actually dissipated in the circuit resistance. It is also known as wattful component of power.

$P = I^2R = I^2Z\cos\Phi = VI\cos\Phi$ watt

B. Apparent power(S): is the product of rms values of the applied voltage and circuit current? It is also known as wattles (idle) component

$\mathbf{S = VI = IZ \times I = I^2Z}$ volt-amp

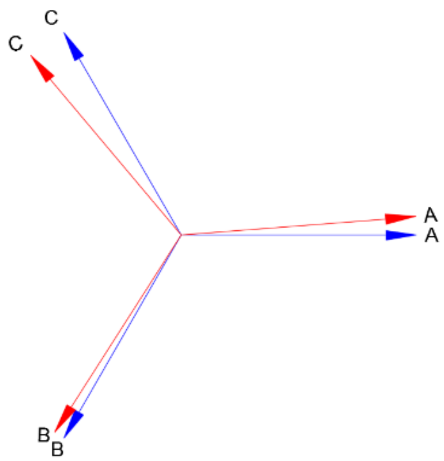
C. Reactive power(Q): is the power developed in the reactance of the circuit.

$Q = I^2X = I^2Z\sin\Phi = VI\sin\Phi$ VAR

Content /Topic3: Phase angle (displacement).

Another situation that usually occurs is when we have two sources with similar phase sequence or phase rotation, but the phase angles are not exactly the same. See the figure below to understand this better. As can be observed both sources have ABC rotation (remember phasors always rotate counter clockwise), but one source angle is not exactly 0, 120, 240 degrees as one would expect. This could be caused due to a variety of reasons some of which are:

- The utility source voltage may not have ideal phase angle displacement.
- There could be upstream transformers that could be causing some phase angle difference due to the construction of the transformer. Remember wye-wye transformers ideally should not introduce any phase angle difference between primary and secondary.
- If one source has a delta-wye transformer upstream, it will cause a 30-degree phase angle difference compared to the source that does not have any upstream transformer.



The question usually is whether I can connect the two systems or not. When connecting two systems with slightly different phase angles, there will be net neutral current that would flow in the ground/neutral that interconnects the two sources. This is illustrated in the simulation below. It can be seen that two sources have similar phase sequence, but source 1 has 0,120,240 degree whereas source 2 has 1, 122, 239-degree phase angle.

Interconnecting two sources with slightly different phase angles will result in neutral/ground current circulating between the two sources.

A. An application where both phase sequence and phase angle are important– Paralleling two transformers in a low voltage substation.

i. Often times it is desired to close the tie breaker and parallel the two medium voltage transformers for meeting the load requirement or some other requirements. Two things need to be performed (in the order) pertaining to phase sequence to make sure things work as intended.

ii. **Check Phase Sequence**: Using phase sequence meter, ascertain that the two sources have similar phase sequence, either both having ABC sequence or both having ACB sequence.

iii. **Check Phase Angle**: Measure the potential difference between the respective phases that is going to be paralleled. The magnitude of the potential difference between the corresponding phase will indicate the phase angle difference between the two sources. Ideally no potential difference should exist between say phase A of source 1 and phase A of source B if both sources have phases that are exactly at 0, 120, 240 degrees apart. Minor phase angle differences can usually be tolerated and it will only result in circulating ground current between the transformers. This test can also be done by using an oscilloscope. If large phase angle difference is noticed additional engineering need to be performed prior to paralleling two transformers.

B. Possible consequences of not checking the phase sequence while connecting devices:

i. Motors could rotate in the opposite direction and depending on the driven load it can damage the driven load.

ii. Electromechanical relays could nuisance trip or worst not function at all.

iii. Electromechanical power meters could give erroneous reading.

iv. Dangerous short circuit current can flow while interconnecting sources with different phase rotation/sequence.

A. Possible consequences of not checking the phase angle while connecting devices:

i. Circulating phase current between the two sources which could result in overheated transformers.

ii. Circulating ground currents between the two sources.

iii. Circulating ground currents causing nuisance trip on ground fault relays.

Content /Topic 4: Power measurement in three phases circuits.

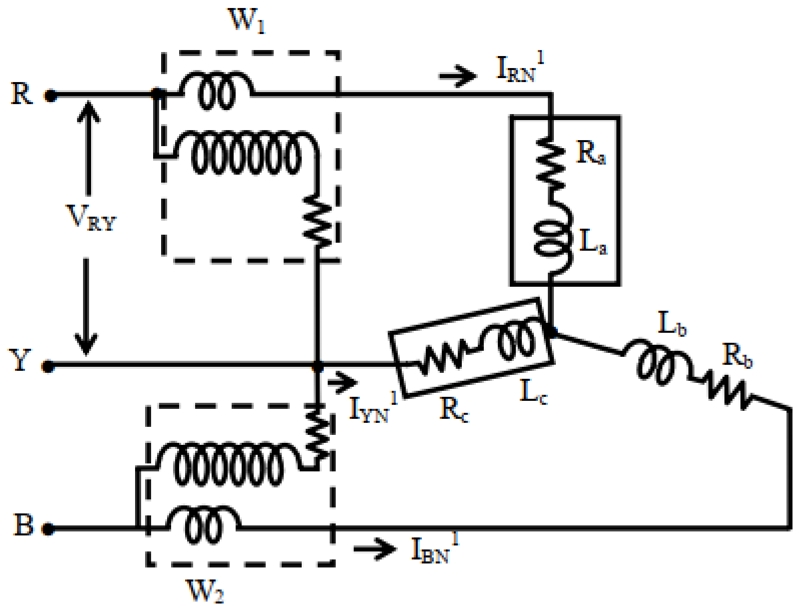
In the previous lesson, the phase and line currents for balanced delta-connected load fed from a three-phase supply, along with the expression for total power, are presented. In this lesson, the measurement of total power in a three-phase circuit, both balanced and unbalanced, is discussed. The connection diagram for two-wattmeter method, along with the relevant phasor diagram for balanced load, is described.

Keywords:

Power measurement, two-wattmeter method, balanced and unbalanced loads, star- and delta-connections. After going through this lesson, the students will be able to answer the following questions:

1. How to connect the two-wattmeter to measure the total power in a three-phase circuit both balanced and unbalanced?
2. Also, how to find the power factor for the case of the above balanced load, from the reading of the two-wattmeter, for the two types of connections – star and delta?

A. Two-wattmeter Method of Power Measurement in a Three-phase Circuit



Connection diagram for two-wattmeter method of power measurement in a three-phase balanced system with star-connected load.

The connection diagram for the measurement of power in a three-phase circuit using two wattmeters, is given in Fig. 20.1. This is irrespective of the circuit connection – star or delta. The circuit may be taken as unbalanced one, balanced type being only a special case. Please note the connection of the two wattmeters. The current coils of the wattmeters, 1 & 2, are in series with the two phases, *R* & *B* , with the pressure or voltage coils being connected across *R* - *Y* and *B* - *Y* respectively. *Y* is the third phase, in which no current coil is connected. If star-connected circuit is taken as an example, the total instantaneous power consumed in the circuit is,

$$W = i_{RN'} \cdot v_{RN'} + i_{YN'} \cdot v_{YN'} + i_{BN'} \cdot v_{BN'}$$

LO 4.3 – Apply power factor improvement techniques.

Content /Topic 1: Overview of power factor.

Power factor (PF) is the ratio of working power, measured in kilowatts (kW), to apparent power, measured in kilovolt amperes (kVA). PF expresses the ratio of true power used in a circuit to the apparent power delivered to the circuit. A 96% power factor demonstrates more efficiency than a 75% power factor.

Power factor is an expression of energy efficiency. It is usually expressed as a percentage—and the lower the percentage, the less efficient power usage is.

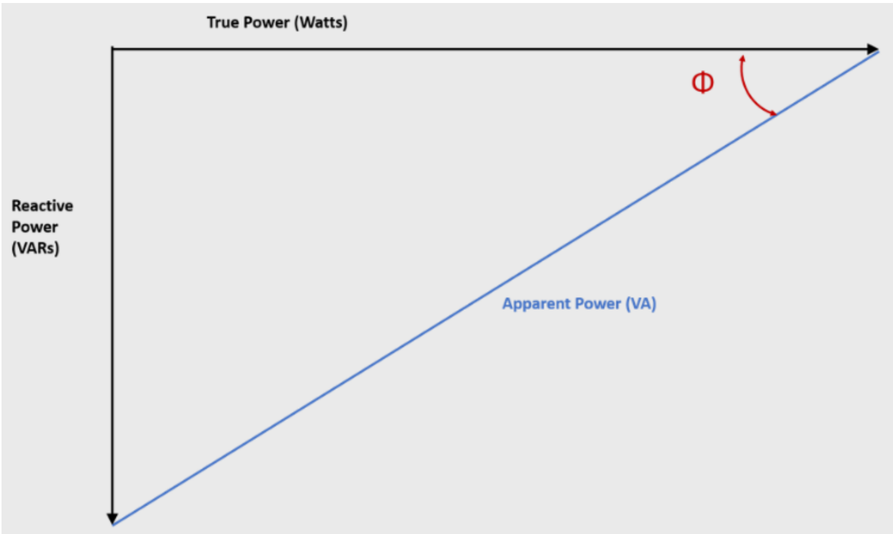
Apparent power, also known as demand, is the measure of the amount of power used to run machinery and equipment during a certain period. It is found by multiplying (kVA = V x A). The result is expressed as kVA units.

How to calculate power factor

To calculate power factor, you need a power quality analyzer or power analyzer that measures both working power (kW) and apparent power (kVA), and to calculate the ratio of kW/kVA. The power factor formula can be expressed in other ways:

PF = (True power)/(Apparent power) or

PF = W/VA ,Where watts measure useful power while VA measures supplied power. The ratio of the two is essentially useful power to supplied power, or:



As this diagram demonstrates, power factor compares the real power being consumed to the apparent power, or demand of the load. The power available to perform work is called real power. You can avoid power factor penalties by correcting for power factor.

Poor power factor means that you're using power inefficiently. This matters to companies because it can result in:

- Heat damage to insulation and other circuit components
- Reduction in the amount of available useful power
- A required increase in conductor and equipment sizes

Finally, power factor increases the overall cost of a power distribution system because the lower power factor requires a higher current to supply the loads.

Content /Topic 2: Methods of improving power factor.

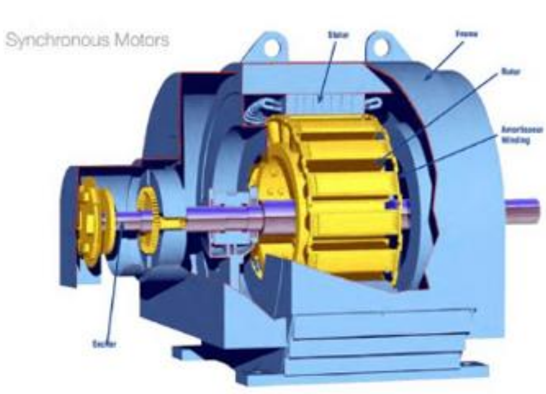
A. **Capacitor banks:** As the name implies, a capacitor bank is merely a grouping of several capacitors of the same rating. Capacitor banks may be connected in series or parallel, depending upon the desired rating. As with an individual capacitor, banks of capacitors are used to store electrical energy and condition the flow of that energy. Increasing the number of capacitors in a bank will increase the capacity of energy that can be stored on a single device.

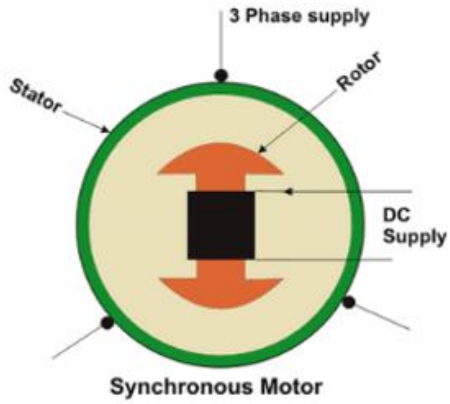
B. **Typical Applications**

Our modern world of electronics requires a lot of energy. To meet this demand, energy must be stored electrically for easy access. Capacitors are ideal for storing large electrical energy charges as well as conditioning the flow of energy as needed. Here are some of the typical uses for capacitor banks:

- **Shunt Capacitor**: A shunt is a mechanism that allows electric current to pass around another point in the circuit by creating a low-resistance path.

C. **Synchronous motor:** A synchronous electric motor is an AC motor in which, at steady state, the rotation of the shaft is synchronized with the frequency of the supply current; the rotation period is exactly equal to an integral number of AC cycles.





Electrical motors are an electro-mechanical device that converts electrical energy to mechanical energy. Based on the type of input we have classified it into single phase and 3 phase motors.
The most common type of 3 phase motors are **synchronous motors** and induction motors. When three-phase electric conductors are placed in certain geometrical positions (i.e. in a certain angle from one another) – an electrical field is generated. The rotating magnetic field rotates at a certain speed known as the **synchronous speed**.

If an electromagnet is present in this rotating magnetic field, the electromagnet is magnetically locked with this rotating magnetic field and rotates with the same speed of rotating field.
This is where the term **synchronous motor** comes from, as the speed of the rotor of the motor is the same as the rotating magnetic field. It is a fixed speed motor because it has only one speed, which is synchronous speed. This speed is synchronized with the supply frequency. The synchronous speed is given by:

i. **Principle of Operation Synchronous Motor**
   Synchronous motors are a doubly excited machine, i.e., two electrical inputs are provided to it. Its stator winding which consists of a We provide three-phase supply to three-phase stator winding, and DC to the rotor winding.
   The 3-phase stator winding carrying 3 phase currents produces 3 phase rotating magnetic flux. The rotor carrying DC supply also produces a constant flux. Considering the 50 Hz power frequency, from the above relation we can see that the 3-phase rotating flux rotates about 3000 revolutions in 1 min or 50 revolutions in 1 sec

ii. **Application of Synchronous Motors**
   1. Synchronous motor having no load connected to its shaft is used for power factor improvement. Owing to its characteristics to behave at any electrical power factor, it is used in power system in situations where static capacitors are expensive.
   2. Synchronous motor finds application where operating speed is less (around 500 rpm) and high power is required. For power requirement from 35 kW to

2500 KW, the size, weight and cost of the corresponding three phase induction motor is very high. Hence these motors are preferably used. Ex- Reciprocating pump, compressor, rolling mills etc.

Content /Topic 3: Benefits of improving power factor.

Electricity transmission and distribution systems are designed to carry a certain amount of current without overloading. Too much current causes excessive resistive losses in electric elements and can result in overheating and excessive voltage drop. If the reactive power of a load with poor power factor is not compensated locally, the reactive power needs to be supplied from the power source. To maximize the capacity of the electric network, transfer of reactive power should be kept at the minimum. Utilities require certain level of DPF from power users and may penalize for excessive reactive power transfer from the power source. The increase in active power transmission capacity with the existing transmission and distribution system by local reactive power compensation is explained in figure 1.

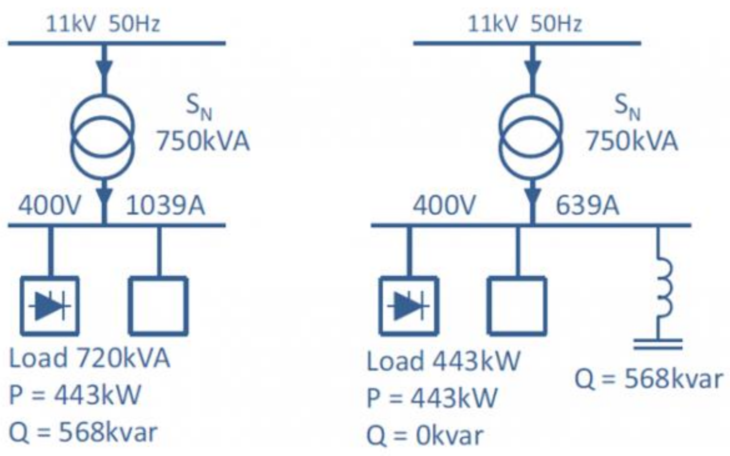


Figure1: Active power supply capacity is increased when reactive power is compensated locally.

Since the nominal capacity of the transformer in figure 1 is 750 kVA, and no reactive power needs to be transmitted from the supplying network when local compensation is used, the whole capacity of the transformer can be used for active power supply. Thus, the increase in active power supply capacity in the case of figure 1 would be 750 kW – 443 kW = 307 kW.

Content /Topic 4: Drawbacks of low power factor.

The undesirable effect of operating a low load at a low power factor is due to the large current required for a low power factor. The important disadvantages of low power factor are

- Higher current is required by the equipment, due to which the economic cost of the equipment is increased.
- At low power factor, the current is high which gives rise to high copper losses in the system and therefore the efficiency of the system is reduced.
- Higher current produced a large voltage drop in the apparatus. This results in the poor voltage regulation.

Since both the capital and running cost are increased, the operation of the system at low power factor (whether it is lagging or leading) is uneconomical from the supplier's point of view.

i. Causes of Low power factor

The usual reason for the low power factor is because of the inductive load. The current in the inductive load lag behind the voltage. The power factor is therefore lagging. The important inductive loads responsible for the low power factor are the three-phase induction motors (which operate at a 0.8 lagging power factor), transformer, lamps and welding equipment operate at low lagging power factors. Power factor improvement methods are used for improving the value of power factor in a power system.

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