# FUNDUMENTALS OF ELECTRICAL ENGINEERING(AEEB01)

**I B. Tech I semester (Autonomous IARE R-18)**

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# MODULE - I
# INTRODUCTION TO ELECTRICAL CIRCUITS

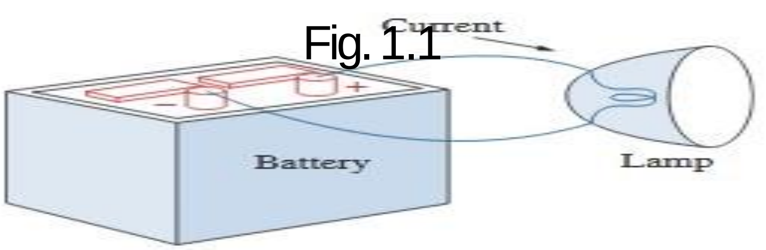
# INTRODUCTION

- Electricity is the flow of electrons from one place to another. Electrons can flow through any material, but does so more easily in some materials than in others. How easily it flows is called resistance. The resistance of a material is measured in Ohms.
- Matter can be broken down into:
- Conductors: electrons flow easily. Low resistance.
- Semi-conductors: electron can be made to flow under certain circumstances. Variable resistance according to formulation and circuit conditions.
- Insulator: electrons flow with great difficulty. High resistance.

# BASICS OF ELECTRICAL ENERGY

- In electrical engineering, we are often interested in communicating or transferring energy from one point to another. To do this requires an interconnection of electrical devices. Such interconnection is referred to as an electric circuit, and each component of the circuit is known as an element.
- A simple electric circuit is shown in Fig. 1.1. It consists of three basic elements: a battery, a lamp, and connecting wires. Such a simple circuit can exist by itself; it has several applications, such as a flash- light, a search light.

Fig. 1.1



# SYSTEMS OF UNITS

Table 1.1 shows the six units and one derived unit that are relevant to this text.

Table 1.2 shows the SI prefixes and their symbols.

**Six basic SI units and one derived unit relevant to this text**

| Quantity | Basic unit | symbol |
|---|---|---|
| Length | Meter | m |
| Mass | Kilogram | kg |
| Time | Second | s |
| Electric current | Ampere | A |
| Thermodynamic temperature | Kelvin | K |
| Luminous intensity | Candela | cd |
| charge | coulomb | C |

**The SI prefixes**

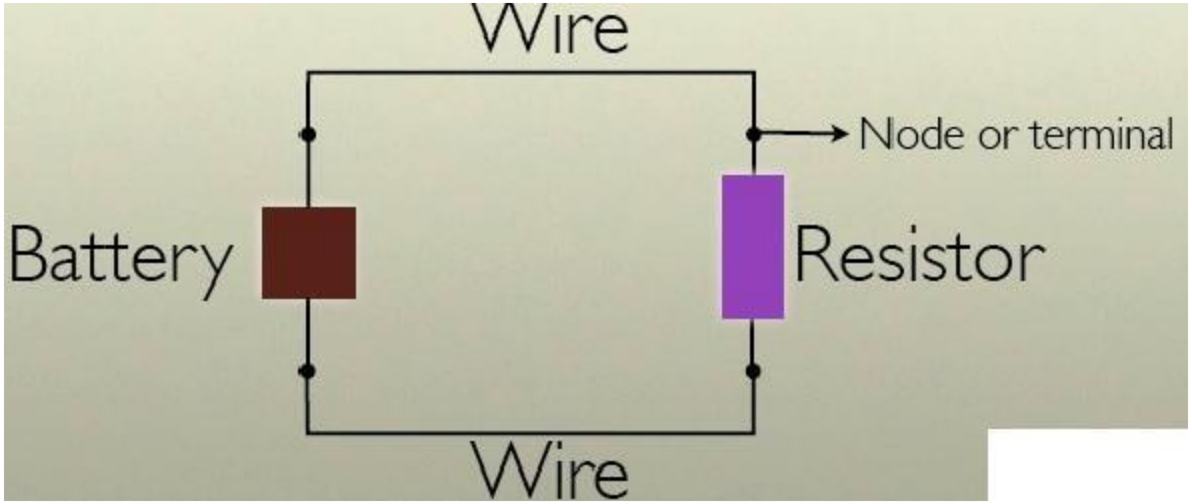
| Multiplier | Prefix | symbol |
|---|---|---|
| $10^{18}$ | exa | E |
| $10^{15}$ | peta | P |
| $10^{12}$ | tera | T |
| $10^{9}$ | giga | G |
| $10^{6}$ | mega | M |
| $10^{3}$ | kilo | k |
| $10^{2}$ | hecto | h |
| 10 | deka | da |
| $10^{-1}$ | deci | d |
| $10^{-2}$ | centi | c |
| $10^{-3}$ | milli | m |
| $10^{-6}$ | micro | μ |
| $10^{-9}$ | nano | n |
| $10^{-12}$ | pico | p |
| $10^{-15}$ | femto | f |
| $10^{-18}$ | atto | a |

# BASIC DEFINITIONS

- Voltage is the difference in charge between two points.
- Current is the rate at which charge is flowing.
- Power the rate at which work is done in an electric circuit is called electric power.
- Energy is defined as the ability to perform work. n electricity, the total work done in an electric circuit is called electrical energy.
- Electric field the region of the charge particle where its force can be experienced by any other charge particle.
- Electric Potential at any point in electric field is defined as work done in bringing a unit positive charge from infinity to that point against electric field. The ability of charged body to do work is called electric potential.

# ELECTRIC CIRCUIT

An electric circuit is an interconnection of electrical elements linked together in a closed path so that electric current may flow continuously



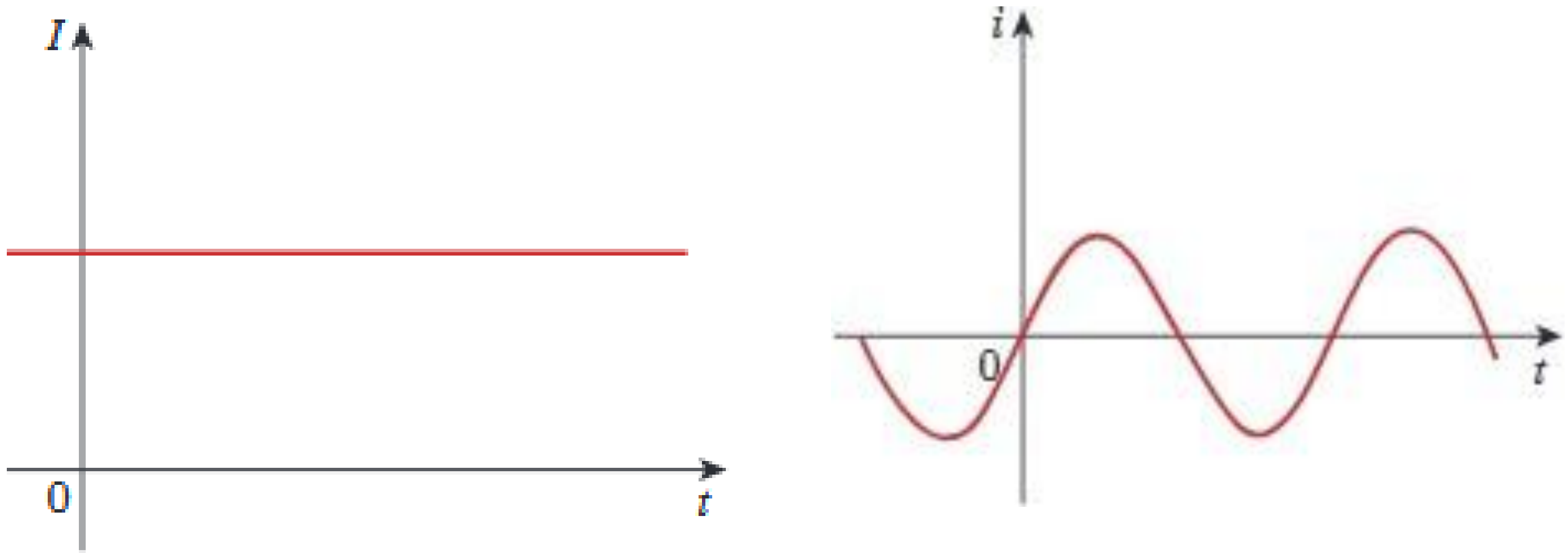
# CHARGE AND CURRENT

- The concept of electric charge is the underlying principle for explaining all electrical phenomena. Also, the most basic quantity in an electric circuit is the electric charge.
- Charge is an electrical property of the atomic particles of which matter consists, measured in coulombs (C).
- Current is the rate of charge flow past a given point in a given direction.

$$i = \frac{dq}{dt}$$

- If the current does not change with time, but remains constant, we call it a direct current(dc).
- A time-varying current is represented by the symbol i. A common form of time-varying current is the sinusoidal current or Alternating current(ac).

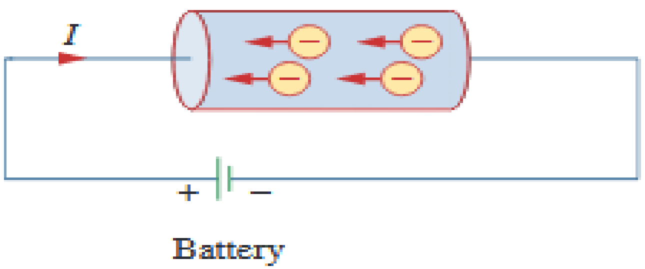
# TYPES OF CURRENT




Two common types of current: (a) direct current (dc), (b) alternating current (ac)

# VOLTAGE

- To Move The Electron In A Conductor In A Particular Direction Requires Some Work Or Energy Transfer.
- This Work Is Performed By An External Electromotive Force (Emf), Typically Represented By The Battery In Fig. 1.3.




- This Emf Is Also Known As Voltage Or Potential Difference.
- The Voltage Between Two Points A And B In An Electric Circuit Is

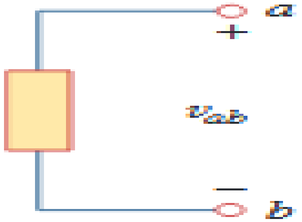
- The Energy (Or Work) Needed To Move A Unit Charge From A To B; Mathematically where ,W Is Energy In Joules (J) And Q Is Charge In Coulombs (C). The Voltage Or Simply V Is Measured In Volts (V)

1 Volt=1 Joule/Coulomb=1 Newton-meter/Coulomb

# VOLTAGE BETWEEN TWO POINTS

- The voltage between two points A and B in an electric circuit is the energy (or work) needed to move a unit charge from a to b; mathematically,

$$v_{ab} = \frac{dw}{dq}$$




- Where ,w is energy in joules (J) and q is charge in coulombs (C). The voltage or simply v is measured in volts (V).

1 volt=1 joule/coulomb=1 newton-meter/coulomb

- Thus, Voltage(or potential difference) is the energy required to move a unit charge through an element, measured in volts (V).

# POWER AND ENERGY

- Power is the time rate of expending or absorbing energy, measured in watts (W).

$$p = \frac{dw}{dt}$$

$$p = \frac{dw}{dt} = \frac{dw}{dq} \cdot \frac{dq}{dt} = vi$$

$$p = vi \ldots\ldots\ldots\ldots\ldots (1.3)$$

The power p in Eq. (1.3) is a time-varying quantity and is called the instantaneous power. Thus, the power absorbed or supplied by an element is the product of the voltage across the element and the current through it. If the power has a sign, power is being delivered to or absorbed by the element. If, on the other hand, the power has a sign, power is being supplied by the element.

# TYPES OF ELEMENTS

- ACTIVE ELEMENTS
- Voltage source
- Current source

- PASSIVE ELEMENTS

- Resistance
- Inductance
- Capacitance

# OHMS LAW

- Georg Ohm found that, at a constant temperature, the electrical current flowing through a fixed linear resistance is directly proportional to the voltage applied across it, and also inversely proportional to the resistance. This relationship between the Voltage, Current and Resistance forms the basis of **Ohms Law** and is shown below.
- **Ohms Law Relationship**

$$\text{CURRENT,(I)} = \frac{\text{VOLTAGE(V)}}{\text{RESISTANCE(R)}}$$

# OHMS LAW

- By knowing any two values of the Voltage, Current or Resistance quantities we can use **Ohms Law** to find the third missing value. **Ohms Law** is used extensively in electronics formulas and calculations so it is "very important to understand and accurately remember these formulas".
- **To find the Voltage, ( V )**

$$[\ V = I \times R\ ] \qquad V\,(\text{volts}) = I\,(\text{amps}) \times R\,(\Omega)$$

- **To find the Current, ( I )**

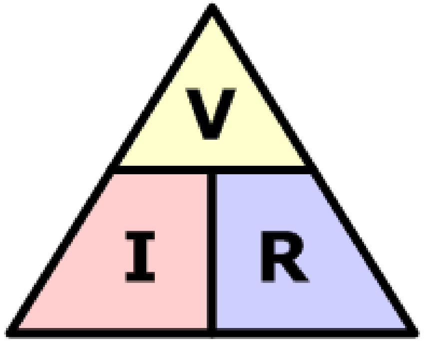
$$[\ I = V \div R] \qquad I\ (\text{amps}) = V\ (\text{volts}) \div R(\Omega)$$

- **To find the Resistance, ( R )**

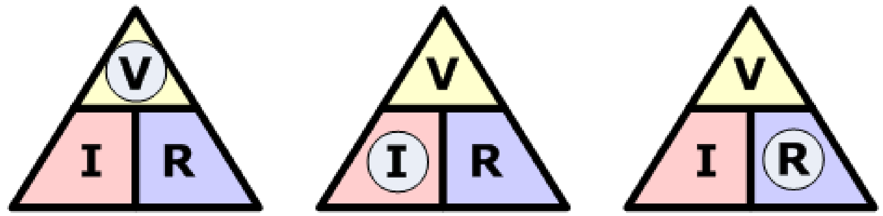
$$[\ R = V \div I\ ] \qquad R(\Omega) = V\ (\text{volts}) \div I\ (\text{amps})$$

# OHMS LAW

- It is sometimes easier to remember this Ohms law relationship by using pictures. Here the three quantities of V, I and R have been superimposed into a triangle (affectionately called the Ohms Law Triangle) giving voltage at the top with current and resistance below. This arrangement represents the actual position of each quantity within the Ohms law formulas.



- Transposing the standard Ohms Law equation above will give us the following combinations of the same equation:




$V = I \times R$ $\quad$ $I = \frac{V}{R}$ $\quad$ $R = \frac{V}{I}$

- Then by using Ohms Law we can see that a voltage of 1V applied to a resistor of 1Ω will cause a current of 1A to flow and the greater the resistance value, the less current that will flow for a given applied voltage.

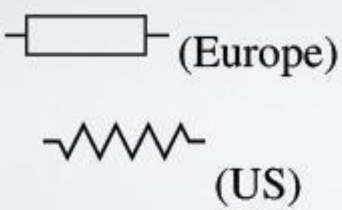
# RESISTORS

**Resistor**

Three resistors

| Type | Passive |
|---|---|

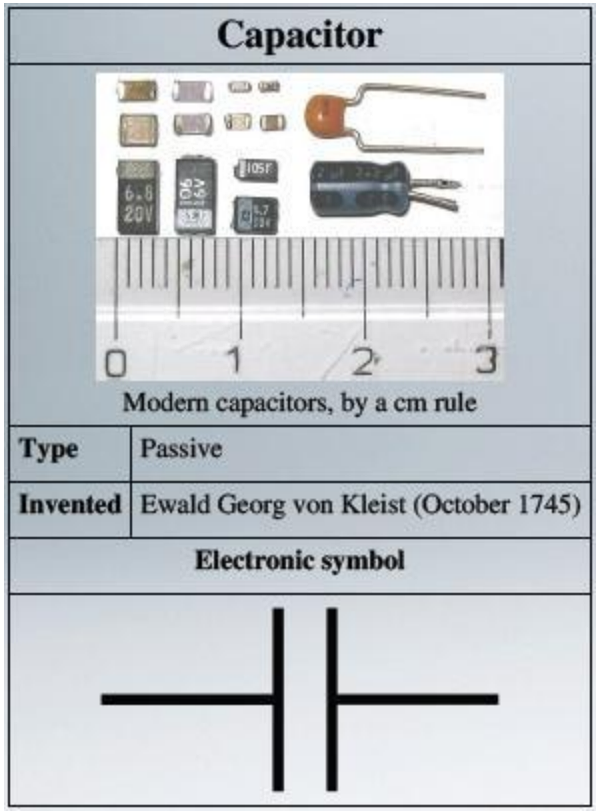
**Electronic symbol**




- Resistance (R) is the physical property of an element that impedes the flow of current . The units of resistance are Ohms (Ω)

- Resistivity (ρ) is the ability of a material to resist current flow. The units of resistivity are Ohm-meters (Ω-m)

# CAPACITORS




- A capacitor consists of a pair of conductors separated by a dielectric (insulator).
- Electric charge is stored in the plates – a capacitor can become “charged”
- Capacitance (C) is the ability of a material to store charge in the form of separated charge or an electric field. It is the ratio of charge stored to voltage difference between two plates.
- Capacitance is measured in Farads (F)

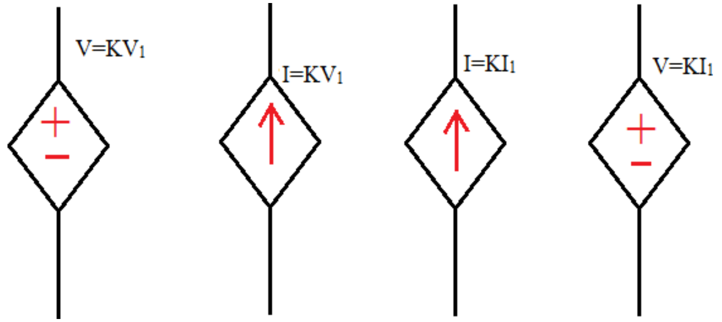
# INDUCTORS

| Inductor | |
|---|---|
|  A selection of low-value inductors | |
| **Type** | Passive |
| **Working principle** | Electromagnetic induction |
| **First production** | Michael Faraday (1831) |
| **Electronic symbol** | |
|  | |

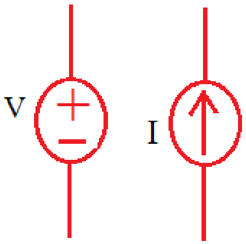
- An inductor is a two terminal element consisting of a winding of N turns capable of storing energy in the form of a magnetic field
- Inductance (L) is a measure of the ability of a device to store energy in the form of a magnetic field. It is measured in Henries (H)

# INDEPENDENT, DEPENDENT SOURCES

- The **dependent sources** depend on the voltage/current in some part of the same circuit.




- The **independent source** does not depend on voltage/current in any part of the circuit.

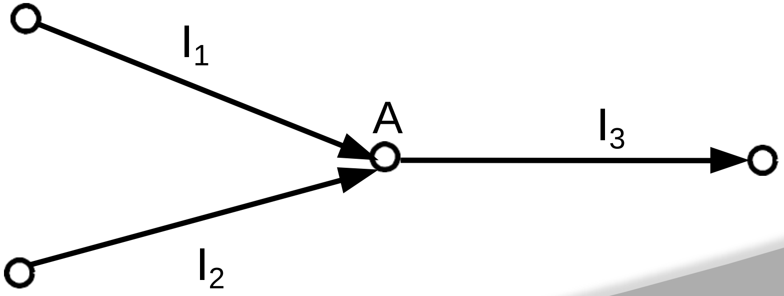


# KIRCHHOFF'S CURRENT LAW

- **KIRCHHOFF'S CURRENT LAW**
- Algebraic sum of all currents entering and leaving a node is zero.
- At node A:

$$I_1 + I_2 - I_3 = 0$$

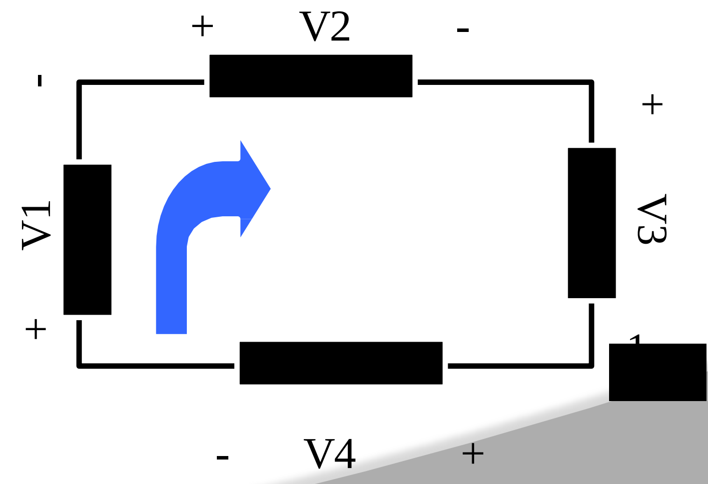
- Current entering a node is assigned positive sign. Current leaving a node is assigned a negative sign.



# KIRCHHOFF'S VOLTAGE LAW

- KIRCHHOFF'S VOLTAGELLAW
- The algebraic sum of voltage around a loop is zero.
- Assumption:
  - Voltage drop across each passive element is in the direction of current flow.

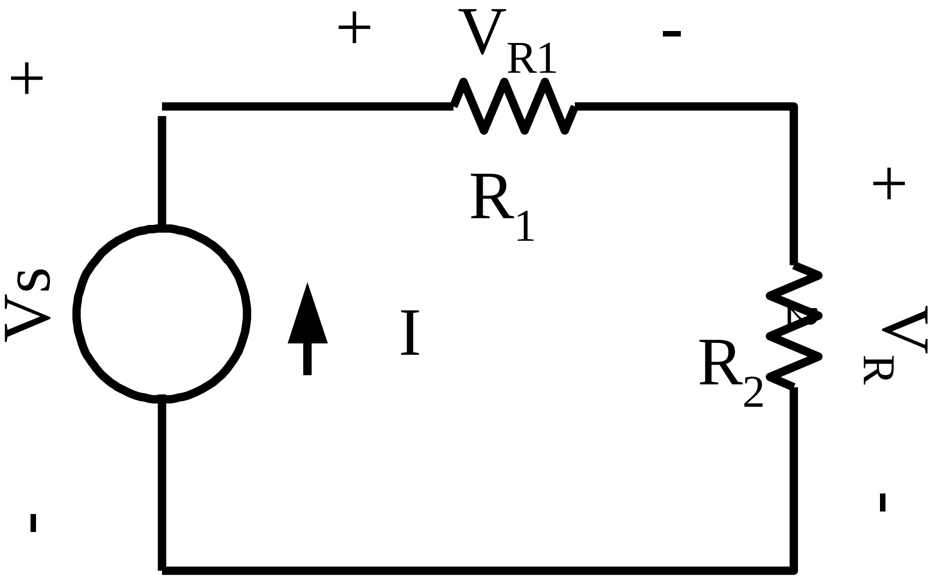
$$V_1 + V_2 + V_3 + V_4 = 0$$



# LAW OF VOLTAGE DIVISION

$$V_{R_1} = \frac{R_1}{R_1 + R_2} V_s$$

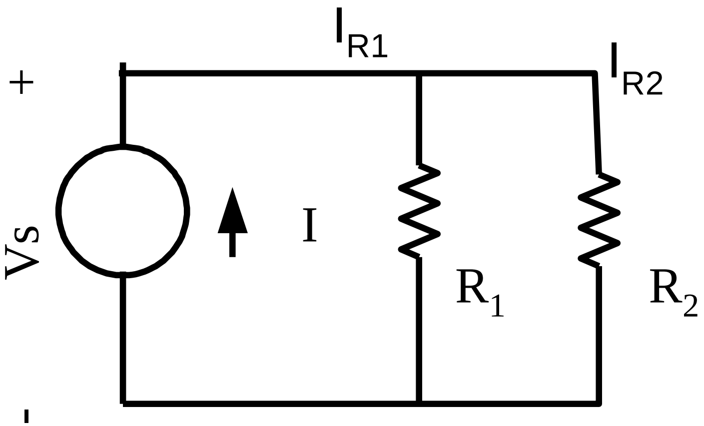
$$V_{R_2} = \frac{R_2}{R_1 + R_2} V_s$$



# LAW OF CURRENT DIVISION

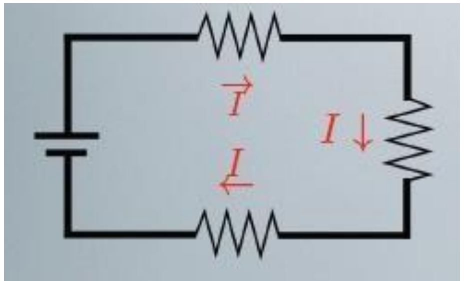
$$I_{R_1} = \frac{R_2}{R_1 + R_2} I$$

$$I_{R_2} = \frac{R_1}{R_1 + R_2} I$$

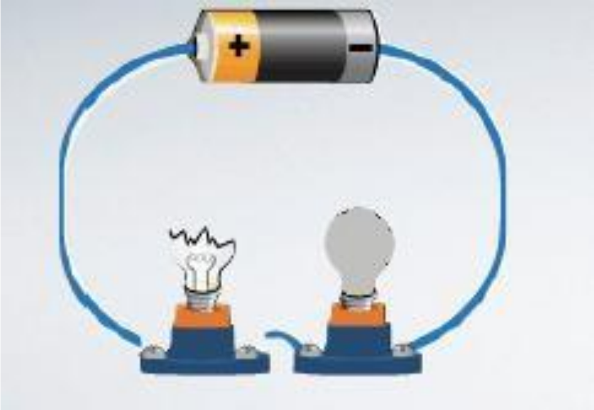


# SERIES CIRCUITS

- A **series circuit** has only **one current path**

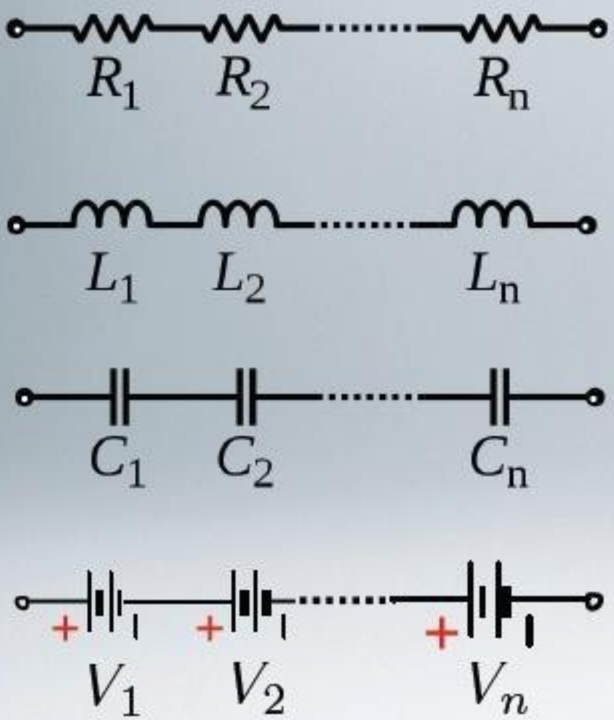


A series circuit with a voltage source (such as a battery) and 3 resistors




- Current through each component is the same
- In a series circuit, all elements must function for the circuit to be complete.

# EQUIVALENT R,L AND C IN SERIES




$$R_{total} = R_1 + R_2 + \ldots + R_n$$

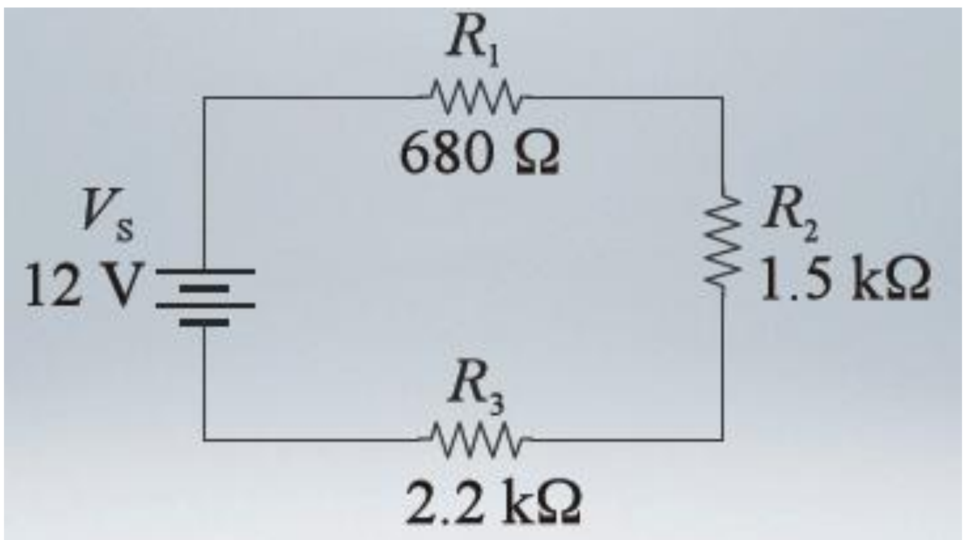
$$L_{total} = L_1 + L_2 + \ldots + L_n$$

$$\frac{1}{C_{total}} = \frac{1}{C_1} + \frac{1}{C_2} + \ldots + \frac{1}{C_n}$$

$$V_{total} = V_1 + V_2 + \ldots + V_n$$

# EXAMPLE: RESISTORS IN SERIES

- The resistors in a series circuit are 680 Ω, 1.5 kΩ, and 2.2 kΩ. What is the total resistance?

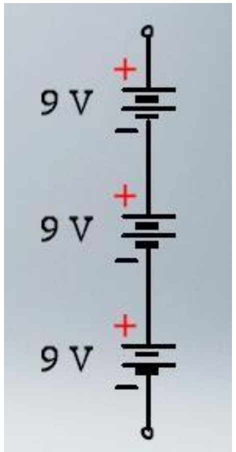



$$
\begin{aligned}
R_{total} &= R_1 + R_2 + R_3 \\
&= 680\Omega + 1500\Omega + 2200\Omega \\
&= 4380\Omega \\
&= 4.38k\Omega
\end{aligned}
$$

# VOLTAGE SOURCES IN SERIES

- Find the total voltage of the sources shown

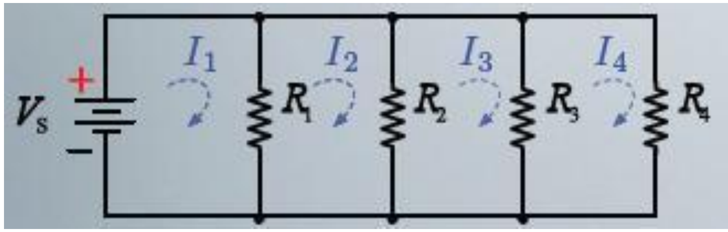
$$V_{total} = V_1 + V_2 + V_3 = 27V$$



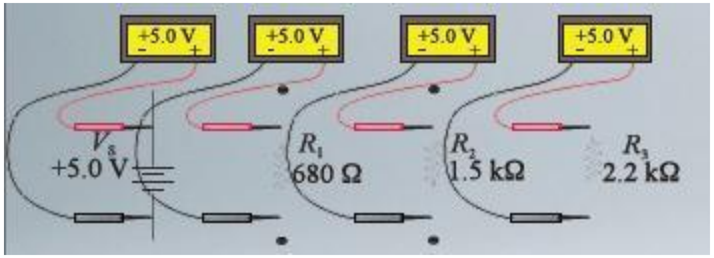

- What happens if you reverse a battery?

# PARALLEL CIRCUITS

- A **parallel circuit** has **more than one current path** branching from the energy source

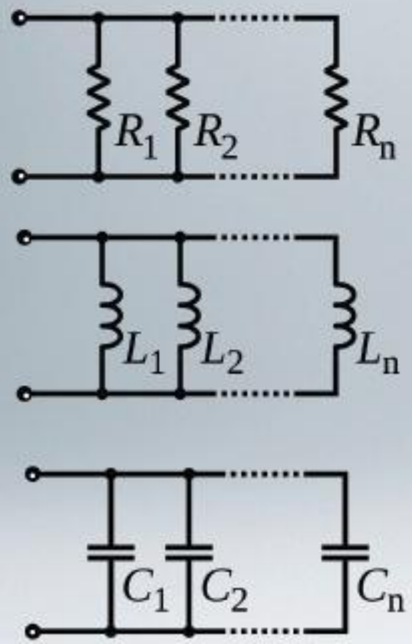



- Voltage across each pathway is the same




- In a parallel circuit, separate current paths function independently of one another

# EQUIVALENT R,L AND C IN PARALLEL



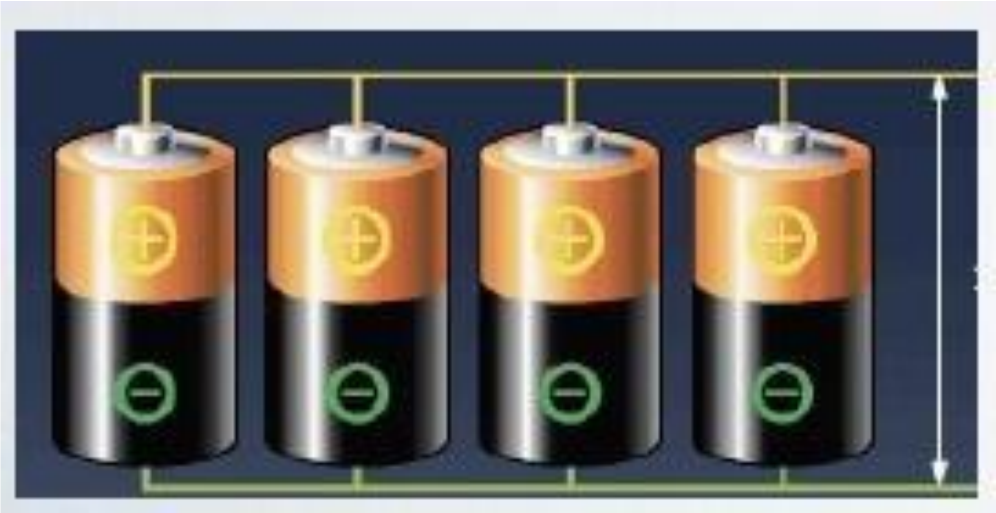

$$\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n}$$

$$\frac{1}{L_{total}} = \frac{1}{L_1} + \frac{1}{L_2} + \ldots + \frac{1}{L_n}$$

$$C_{total} = C_1 + C_2 + \ldots + C_n$$

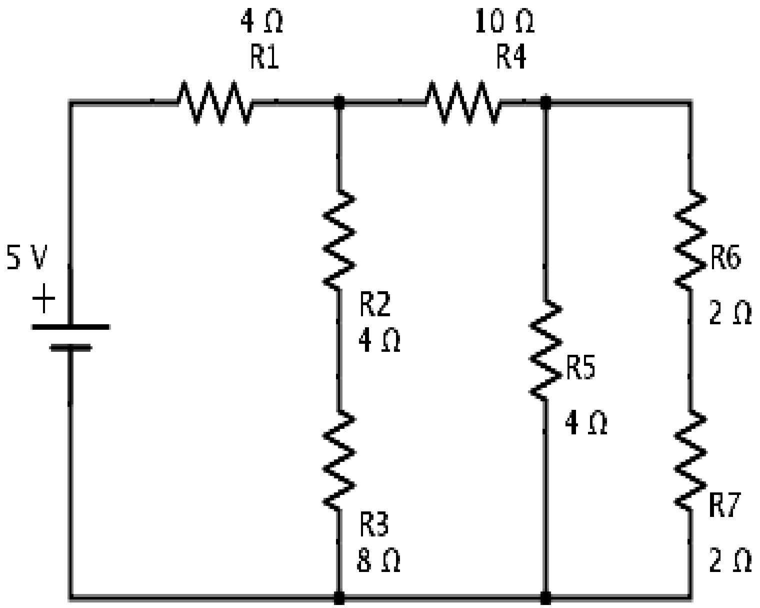
# SIMPLE CIRCUIT IN PARALLEL

- For parallel voltage sources, the voltage is the same across all batteries, but the current supplied by each element is a fraction of the total current



# PROBLEMS ON SERIES AND PARALLELCIRCUITS

- Calculate $R_{eq}$ of the given circuit and also current flowing through $R_4$= 10ohms resistor.



# MODULE-II
# ANALYSIS OF ELECTRICAL CIRCUITS

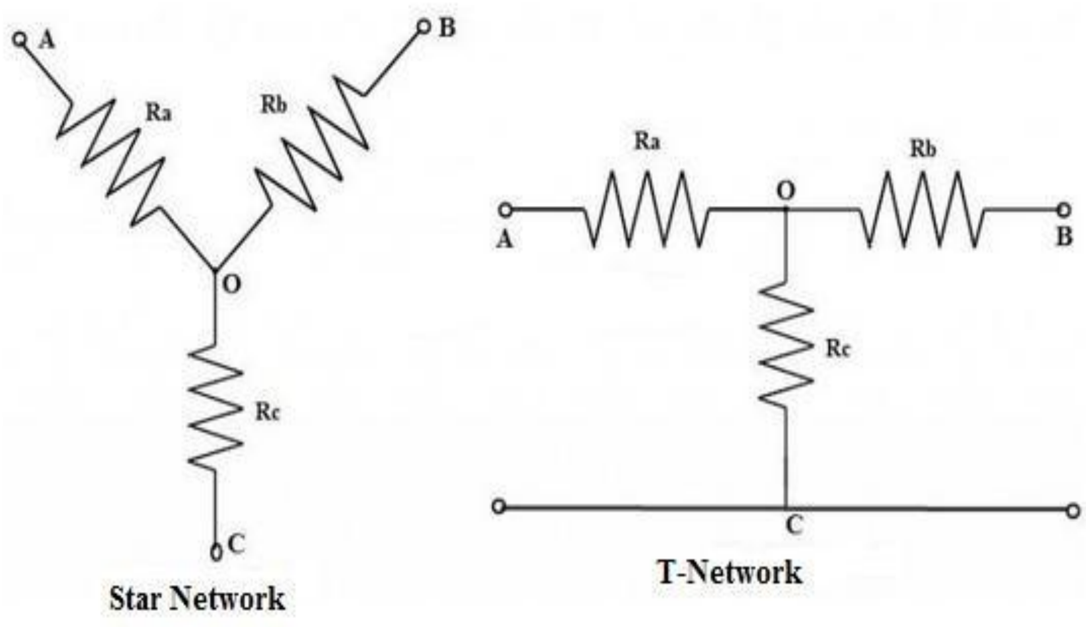
# STAR-DELTA TRANSFORMATION

## STAR- CONNECTION:

- In star connection, components are connected in such a way that one end of all the resistors or components are connected to a common point.
- By the arrangement of three resistors, this star network looks like a alphabet Y hence , this network is also called as Wye or Y network.
- The equivalent of this star connection can be redrawn as T network (as a four terminal network) as shown in below figure. Most of the electrical circuits constitute this T form network.

# STAR- CONNECTION

- Star network and T-network representation:



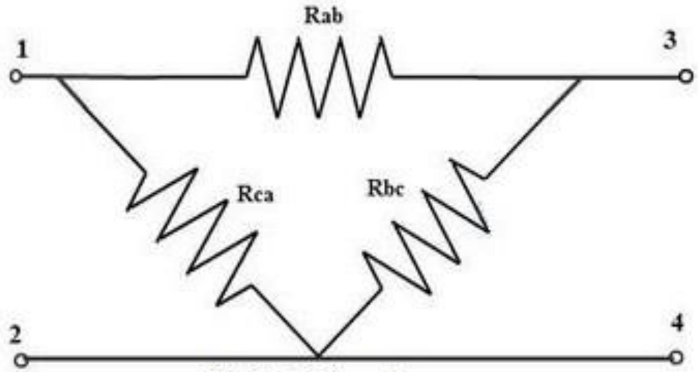
# DELTA CONNECTION

**Delta Connection:**

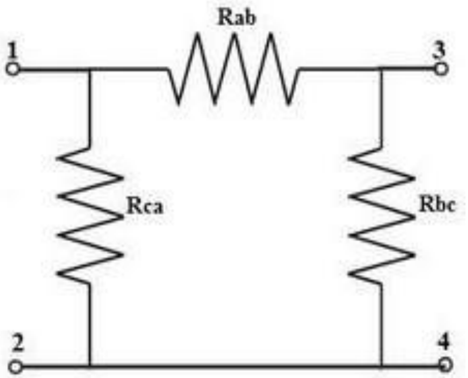
- In a delta connection, end point of each component or coil is connected to the start point of another component or coil.
- It is a series connection of three components that are connected to form a triangle. The name indicates that connection look like an alphabet delta (Δ).
- The equivalent delta network can be redrawn , to look like a symbol Pi (or four terminal network ) as shown in figure. So this network can also be referred as Pi network.

# DELTA CONNECTION

- Delta and PI network representation:



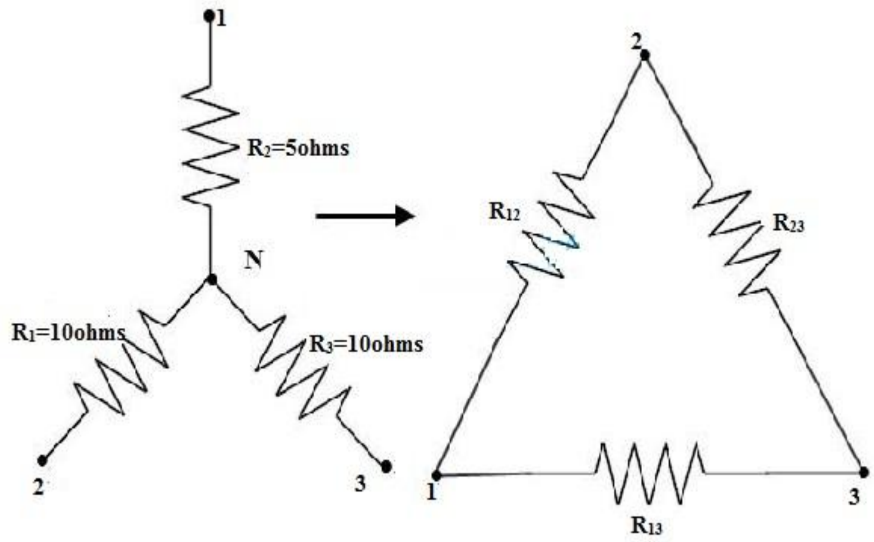
Delta Network



Delta pi Network

# PROBLEMS ON STAR-DELTATRANSFORMATIONS

- Consider the below figure to transform star or Wye to the delta circuit where the resistance values in star network are given as $R_1$= 10 ohms, $R_2$= 5 ohms and $R_3$= 20 ohms.



# PROBLEMS

- For star or wye to delta conversion, the equivalent resistance equations (for this problem) are

$$R_{12} = R_1 + R_2 + ((R_1R_2)/R_3)$$

$$R_{23} = R_2 + R_3 + ((R_2R_3)/R_1)$$

$$R_{31} = R_1 + R_3 + ((R_1R_3)/R_2)$$

- By simplifying the above equations we get the common numerator term as

$$R_1R_2 + R_2R_3 + R_1R_3 = 10 X5 + 10 X20 + 20 X5 = 350 \text{ ohms}$$

Then

$$R_{12} = 350/ R_3 = 350/20 = 17.5 \text{ ohms}$$

$$R_{23} = 350/ R_1 = 350/ 10 = 35 \text{ ohms}$$

$$R_{31} = 350/R_2 = 350 /5 = 70 \text{ ohms}$$

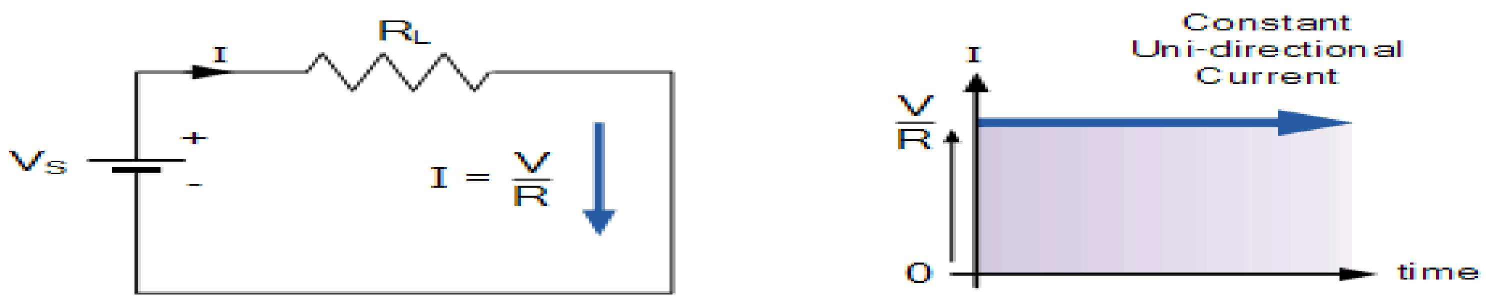
# MODULE-III

# INTRODUCTION TO AC CIRCUITS

# ANALYSIS OF AC CIRCUITS

- **Direct Current** or **D.C.** as it is more commonly called, is a form of electrical current or voltage that flows around an electrical circuit in one direction only, making it a "Uni-directional" supply.
- Generally, both DC currents and voltages are produced by power supplies, batteries, dynamos and solar cells to name a few. A DC voltage or current has a fixed magnitude (amplitude) and a definite direction associated with it. For example, +12V represents 12 volts in the positive direction, or -5V represents 5 volts in the negative direction.
- We also know that DC power supplies do not change their value with regards to time, they are a constant value flowing in a continuous steady state direction.

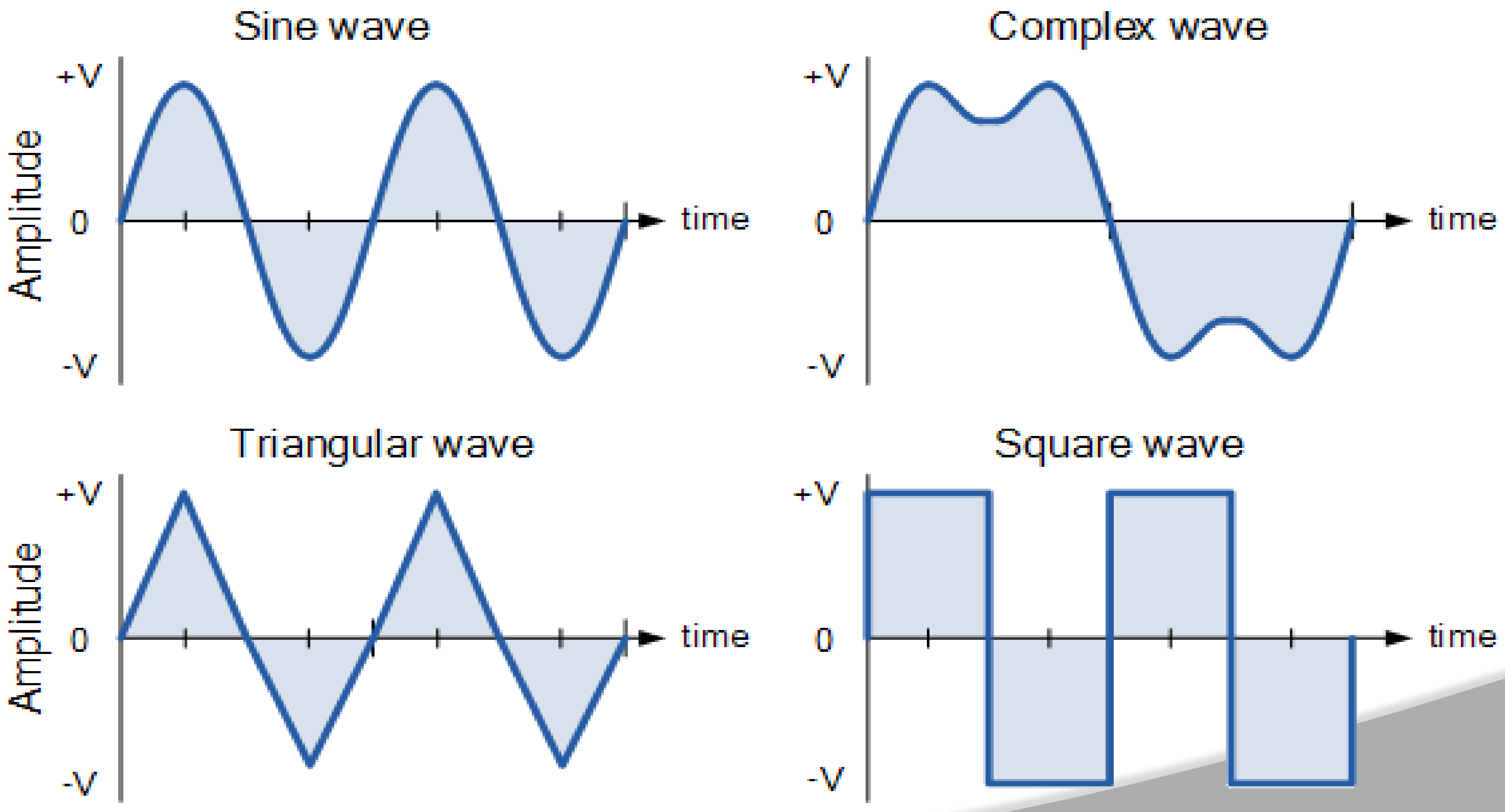
# DC CIRCUIT AND WAVEFORM




- An alternating function or **AC Waveform** on the other hand is defined as one that varies in both magnitude and direction in more or less an even manner with respect to time making it a "Bi-directional" waveform. An AC function can represent either a power source or a signal source with the shape of an *AC waveform* generally following that of a mathematical sinusoid being defined as: $A(t) = A_{max} * \sin(2\pi f t)$.

- The Period, (T) is the length of time in seconds that the waveform takes to repeat itself from start to finish. This can also be called the *Periodic Time* of the waveform for sine waves, or the *Pulse Width* for square waves.
- The Frequency, ($f$) is the number of times the waveform repeats itself within a one second time period. Frequency is the reciprocal of the time period, ( $f = 1/T$ ) with the unit of frequency being the *Hertz*, (Hz).
- The Amplitude (A) is the magnitude or intensity of the signal waveform measured in volts or amps.

# TYPES OF PERIODIC WAVEFORM

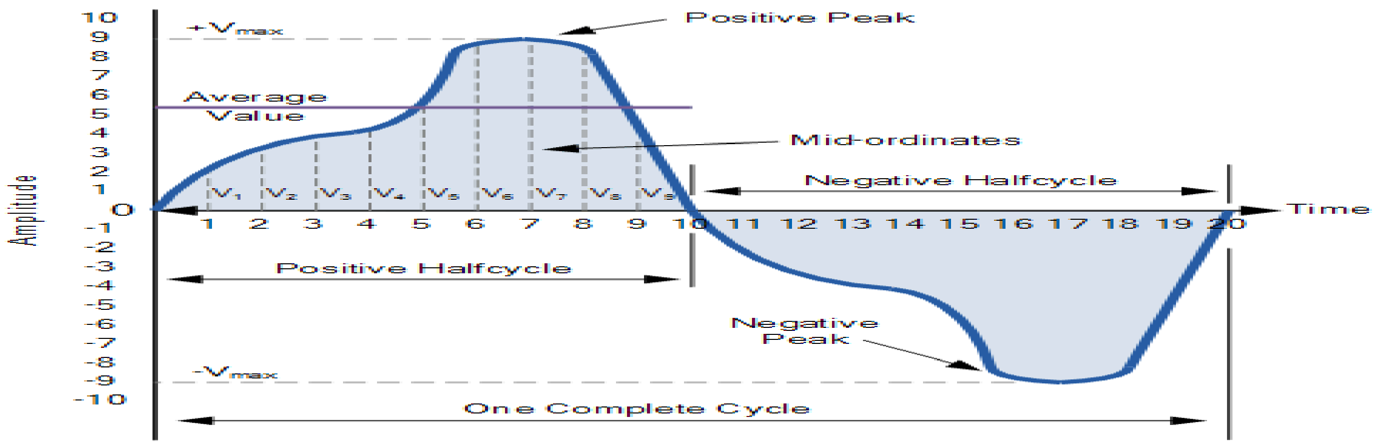


- The time taken for an **AC Waveform** to complete one full pattern from its positive half to its negative half and back to its zero baseline again is called a **Cycle** and one complete cycle contains both a positive half-cycle and a negative half-cycle.
- The time taken by the waveform to complete 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 *f* of the alternating waveform. Frequency is measured in **Hertz**, ( Hz ) named after the German physicist Heinrich Hertz.
- Relationship between frequency and periodic time
- Frequency(f)=1/T Hz
- Time period(T)=1/f Sec

# THE AVERAGE VALUE OF AN AC WAVEFORM

- The average or mean value of a continuous DC voltage will always be equal to its maximum peak value as a DC voltage is constant. This average value will only change if the duty cycle of the DC voltage changes. In a pure sine wave if the average value is calculated over the full cycle, the average value would be equal to zero as the positive and negative halves will cancel each other out. So the average or mean value of an AC waveform is calculated or measured over a half cycle only and this is shown below.

# AVERAGE VALUE OF A NON-SINUSOIDAL WAVEFORM




- To find the average value of the waveform we need to calculate the area underneath the waveform using the mid-ordinate rule, trapezoidal rule or the Simpson's rule found commonly in mathematics. The approximate area under any irregular waveform can easily be found by simply using the mid-ordinate rule.

# AVERAGE VALUE OF AN AC WAVEFORM

$$V_{AVG} = \frac{V_1 + V_2 + V_3 + \ldots\ldots\ldots\ldots + V_n}{n}$$

- Where: n equals the actual number of mid-ordinates used.
- For a pure sinusoidal waveform this average or mean value will always be equal to 0.637*$V_{max}$ and this relationship also holds true for average values of current.

# RMS VALUE OF AN AC WAVEFORM

$$V_{rms} = \sqrt{\frac{V_1^2 + V_2^2 + V_3^2 + \ldots\ldots + V_{n1}^2}{n}}$$

- Where: n equals the number of mid-ordinates.
- For a pure sinusoidal waveform this effective or R.M.S. value will always be equal too: $1/\sqrt{2} * V_{max}$ which is equal to $0.707 * V_{max}$ and this relationship holds true for RMS values of current. The RMS value for a sinusoidal waveform is always greater than the average value except for a rectangular waveform. In this case the heating effect remains constant so the average and the RMS values will be the same.

# FORM FACTOR AND CREST FACTOR

- Although little used these days, both **Form Factor** and **Crest Factor** can be used to give information about the actual shape of the AC waveform. Form Factor is the ratio between the average value and the RMS value and is given as.

$$FormFactor = \frac{\text{R.M.S Value}}{\text{Average Value}} = \frac{0.707 \times V_{max}}{0.637 \times V_{max}}$$

- For a pure sinusoidal waveform the Form Factor will always be equal to 1.11. Crest Factor is the ratio between the R.M.S. value and the Peak value of the waveform and is given as.

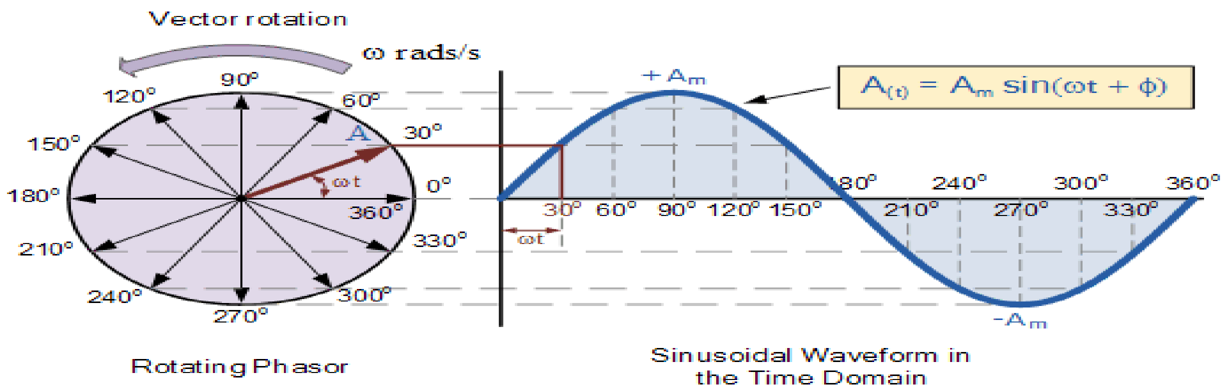
$$CrestFactor = \frac{\text{Peak Value}}{\text{R.M.S Value}} = \frac{V_{max}}{0.707 \times V_{max}}$$

- For a pure sinusoidal waveform the Crest Factor will always be equal to 1.414.

# PHASOR DIAGRAMS AND PHASORALGEBRA

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

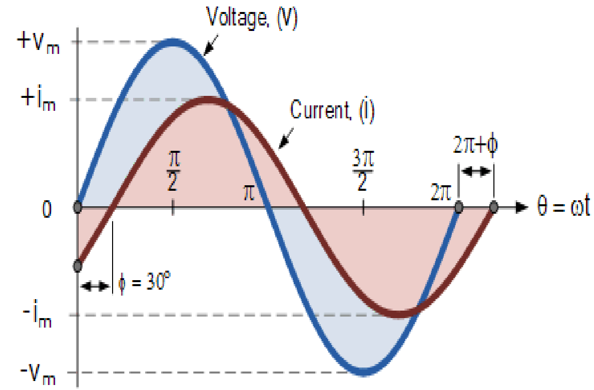
# PHASOR DIAGRAM OF A SINUSOIDAL WAVEFORM




- As the single vector rotates in an anti-clockwise direction, its tip at point A will rotate one complete revolution of $360^o$ or 2π representing one complete cycle. If the length of its moving tip is transferred at different angular intervals in time to a graph as shown above, a sinusoidal waveform would be drawn starting at the left with zero time.
- Each position along the horizontal axis indicates the time that has elapsed since zero time, t = 0. When the vector is horizontal the tip of the vector represents the angles at $0^o$, $180^o$ and at $360^o$.

# PHASE DIFFERENCE OF A SINUSOIDAL WAVEFORM

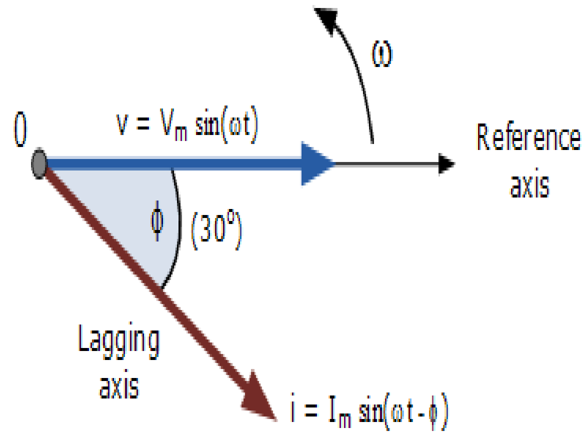
- The generalised mathematical expression to define these two sinusoidal quantities will be written as:
- The current, i is lagging the voltage, v by angle Φ and in our example above this is 30º. So the difference between the two phasors representing the two sinusoidal quantities is angle Φ and the resulting phasor diagram will be.

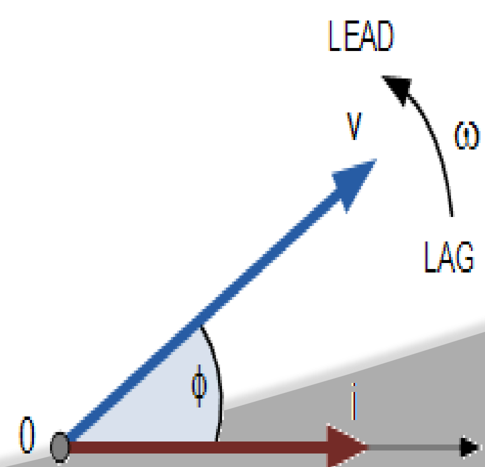



$$v_{(t)} = V_m \sin(\omega t)$$

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

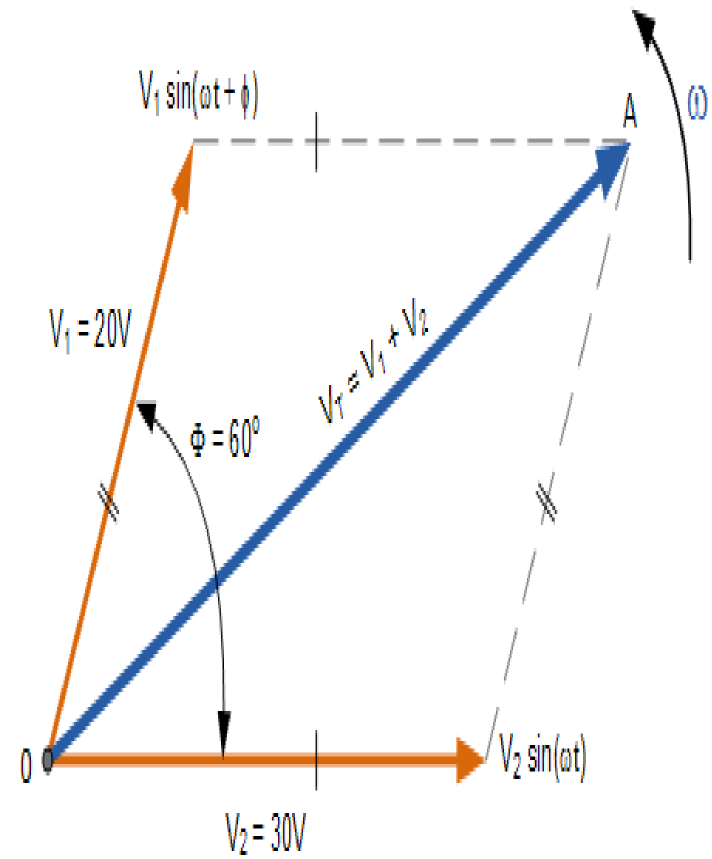
- The phasor diagram is drawn corresponding to time zero ( t = 0 ) on the horizontal axis. The lengths of the phasors are proportional to the values of the voltage, ( V ) and the current, ( I ) at the instant in time that the phasor diagram is drawn. The current phasor lags the voltage phasor by the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



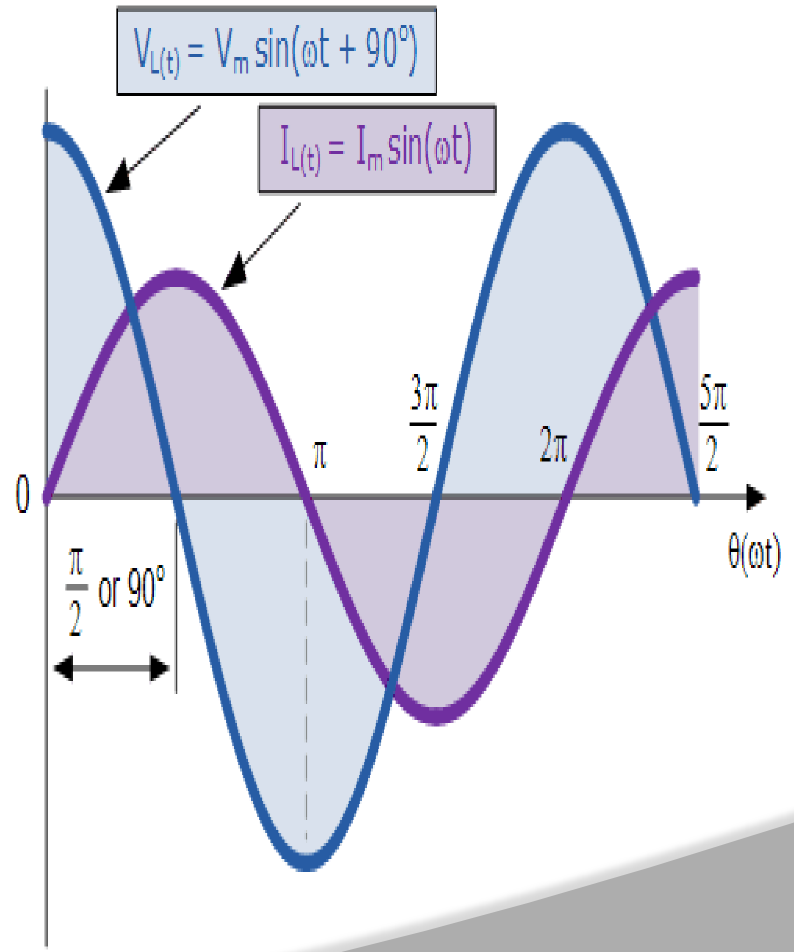
# PHASOR ADDITION OF TWO PHASORS

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



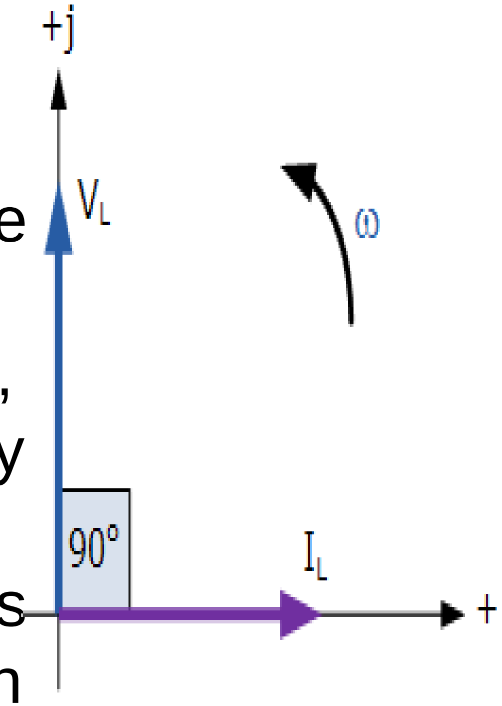
# SINUSOIDAL WAVEFORMS FOR AC INDUCTANCE

- This effect can also be represented by a phasor diagram were in a purely inductive circuit the voltage "LEADS" the current by 90°. But by using the voltage as our reference, we can also say that the current "LAGS" the voltage by one quarter of a cycle or 90° as shown in the vector diagram below.



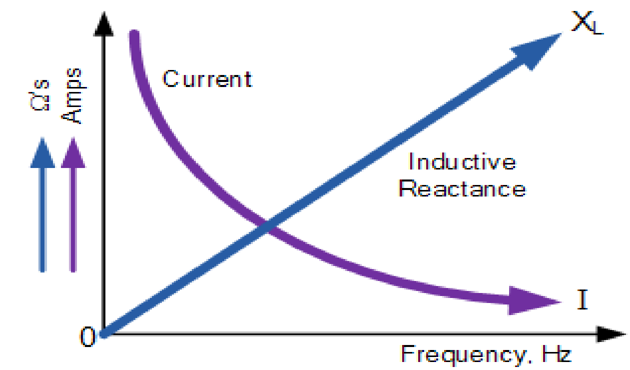
# PHASOR DIAGRAM FOR AC INDUCTANCE

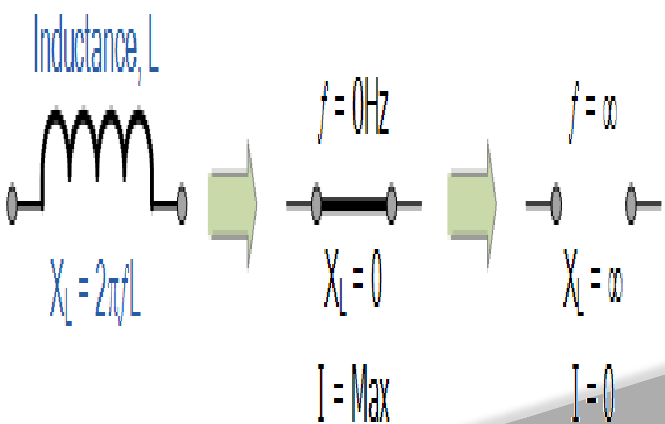
- So for a pure loss less inductor, $V_L$ "leads" $I_L$ by $90^o$, or we can say that $I_L$ "lags" $V_L$ by $90^o$.
- There are many different ways to remember the phase relationship between the voltage and current flowing through a pure inductor circuit, but one very simple and easy to remember way is to use the mnemonic expression "ELI" (pronounced *Ellie* as in the girls name). ELI stands for Electromotive force first in an AC inductance, L before the current I. In other words, voltage before the current in an inductor, E, L, I equals "ELI", and whichever phase angle the voltage starts at, this expression always holds true for a pure inductor circuit.



# INDUCTIVE REACTANCE AGAINST FREQUENCY

- The inductive reactance of an inductor increases as the frequency across it increases therefore inductive reactance is proportional to frequency ( $X_L \alpha f$) as the back emf generated in the inductor is equal to its inductance multiplied by the rate of change of current in the inductor.
- Also as the frequency increases the current flowing through the inductor also reduces in value.



- In an AC circuit containing pure inductance the following formula applies:

$$Current(I) = \frac{\text{Voltage}}{\text{Opposition of current flow}} = \frac{V}{X_L}$$

- So how did we arrive at this equation. Well the self induced emf in the inductor is determined by Faraday's Law that produces the effect of self-induction in the inductor due to the rate of change of the current and the maximum value of the induced emf will correspond to the maximum rate of change. Then the voltage in the inductor coil is given as:

$$V_{L(t)} = L\frac{di_{L(t)}}{dt}$$

$$if,\ i_{L(t)} = I_{\max}\sin(\omega t)$$

$$then: V_{L(t)} = L\frac{d}{dt}I_{\max}\sin(\omega t+\theta) = \omega L I_{\max}\cos(\omega t+\theta) = \omega L I_{\max}\sin(\omega t+90^0)$$

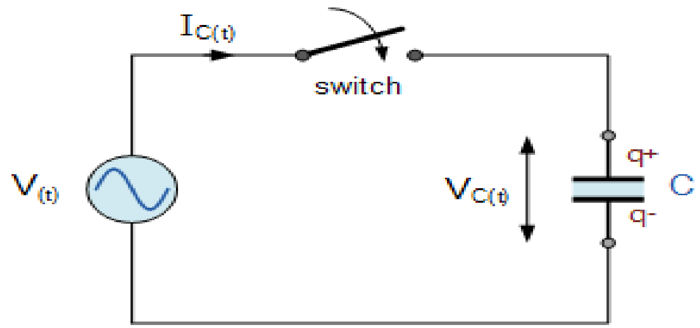
- then the voltage across an AC inductance will be defined as:

# AC CAPACITANCE AND CAPACITIVE REACTANCE

- The opposition to current flow through an AC Capacitor is called Capacitive Reactance and which itself is inversely proportional to the supply frequency
- **Capacitors** store energy on their conductive plates in the form of an electrical charge. When a capacitor is connected across a DC supply voltage it charges up to the value of the applied voltage at a rate determined by its time constant.
- A capacitor will maintain or hold this charge indefinitely as long as the supply voltage is present. During this charging process, a charging current, i flows into the capacitor opposed by any changes to the voltage at a rate which is equal to the rate of change of the electrical charge on the plates. A capacitor therefore has an opposition to current flowing onto its plates.

- A pure capacitor will maintain this charge indefinitely on its plates even if the DC supply voltage is removed. However, in a sinusoidal voltage circuit which contains “AC Capacitance”, the capacitor will alternately charge and discharge at a rate determined by the frequency of the supply. Then capacitors in AC circuits are constantly charging and discharging respectively.
- When an alternating sinusoidal voltage is applied to the plates of an AC capacitor, the capacitor is charged firstly in one direction and then in the opposite direction changing polarity at the same rate as the AC supply voltage. This instantaneous change in voltage across the capacitor is opposed by the fact that it takes a certain amount of time to deposit (or release) this charge onto the plates and is given by $V = Q/C$. Consider the circuit below.

# AC CAPACITANCE WITH A SINUSOIDAL SUPPLY

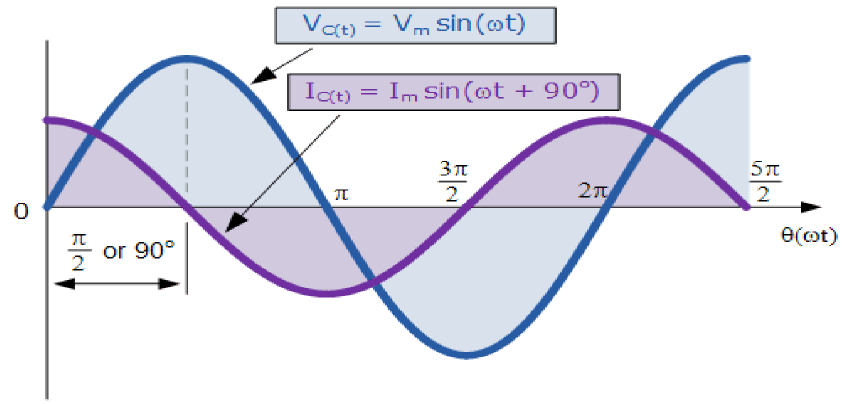



- When the switch is closed in the circuit above, a high current will start to flow into the capacitor as there is no charge on the plates at $t = 0$. The sinusoidal supply voltage, V is increasing in a positive direction at its maximum rate as it crosses the zero reference axis at an instant in time given as $0^o$. Since the rate of change of the potential difference across the plates is now at its maximum value, the flow of current into the capacitor will also be at its maximum rate as the maximum amount of electrons are moving from one plate to the other.

- As the sinusoidal supply voltage reaches its $90^o$ point on the waveform it begins to slow down and for a very brief instant in time the potential difference across the plates is neither increasing nor decreasing therefore the current decreases to zero as there is no rate of voltage change. At this $90^o$ point the potential difference across the capacitor is at its maximum ( $V_{max}$), no current flows into the capacitor as the capacitor is now fully charged and its plates saturated with electrons.

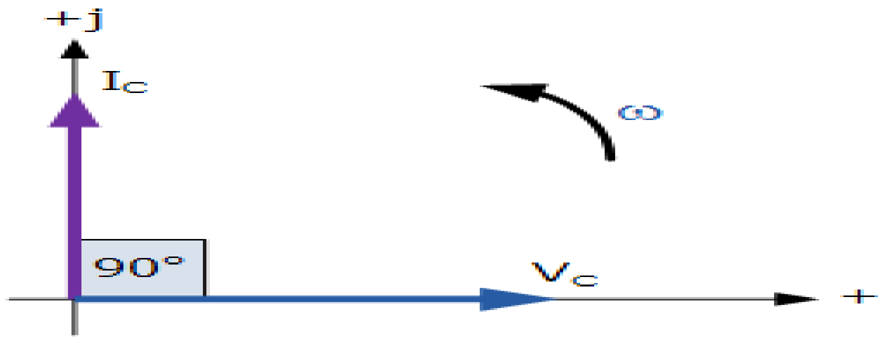
- At the end of this instant in time the supply voltage begins to decrease in a negative direction down towards the zero reference line at 180$^o$. Although the supply voltage is still positive in nature the capacitor starts to discharge some of its excess electrons on its plates in an effort to maintain a constant voltage. This results in the capacitor current flowing in the opposite or negative direction.
- Then during this first half cycle 0$^o$ to 180$^o$ the applied voltage reaches its maximum positive value a quarter ($1/4f$) of a cycle after the current reaches its maximum positive value, in other words, a voltage applied to a purely capacitive circuit "LAGS" the current by a quarter of a cycle or 90$^o$ as shown below.

# SINUSOIDAL WAVEFORMS FOR AC CAPACITANCE




- During the second half cycle 180° to 360°, the supply voltage reverses direction and heads towards its negative peak value at 270°. At this point the potential difference across the plates is neither decreasing nor increasing and the current decreases to zero. The potential difference across the capacitor is at its maximum negative value, no current flows into the capacitor and it becomes fully charged the same as at its 90° point but in the opposite direction.

# PHASOR DIAGRAM FOR AC CAPACITANCE




- So for a pure capacitor, $V_C$ "lags" $I_C$ by 90º, or we can say that $I_C$ "leads" $V_C$ by 90º.
- There are many different ways to remember the phase relationship between the voltage and current flowing in a pure AC capacitance circuit, but one very simple and easy to remember way is to use the mnemonic expression called "ICE". ICE stands for current I first in an AC capacitance, C before Electromotive force. In other words, current before the voltage in a capacitor, I, C, E equals "ICE", and whichever phase angle the voltage starts at, this expression always holds true for a pure AC capacitance circuit

# CAPACITIVE REACTANCE

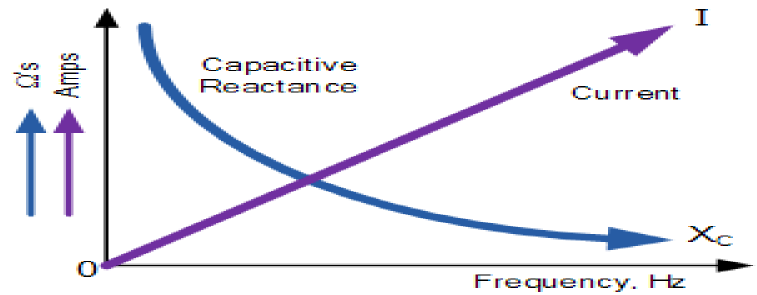
$$X_C = \frac{1}{2\Pi f C}$$

- Where: $X_C$ is the Capacitive Reactance in Ohms, $f$ is the frequency in Hertz and $C$ is the AC capacitance in Farads, symbol F.
- When dealing with AC capacitance, we can also define capacitive reactance in terms of radians, where Omega, ω equals $2\pi f$.

$$X_C = \frac{1}{\omega C}$$

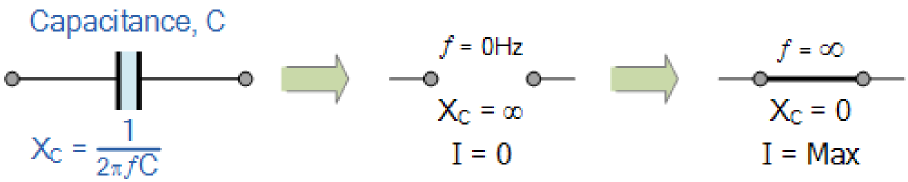
- From the above formula we can see that the value of capacitive reactance and therefore its overall impedance ( in Ohms ) decreases towards zero as the frequency increases acting like a short circuit. Likewise, as the frequency approaches zero or DC, the capacitors reactance increases to infinity, acting like an open circuit which is why capacitors block DC.
- The relationship between capacitive reactance and frequency is the exact opposite to that of inductive reactance, ( $X_L$ ) we saw in the previous tutorial. This means then that capacitive reactance is "inversely proportional to frequency" and has a high value at low frequencies and a low value at higher frequencies as shown.

# CAPACITIVE REACTANCE AGAINST FREQUENCY




- Capacitive reactance of a capacitor decreases as the frequency across its plates increases. Therefore, capacitive reactance is inversely proportional to frequency. Capacitive reactance opposes current flow but the electrostatic charge on the plates (its AC capacitance value) remains constant.
- This means it becomes easier for the capacitor to fully absorb the change in charge on its plates during each half cycle. Also as the frequency increases the current flowing into the capacitor increases in value because the rate of voltage change across its plates increases.

- We can present the effect of very low and very high frequencies on the reactance of a pure AC Capacitance as follows:




- In an AC circuit containing pure capacitance the current (electron flow) flowing into the capacitor is given as

$$I_{C(t)} = \frac{dq}{dt} \quad where: q = CV_C = CV_{max}\sin(\omega t)$$

$$\therefore I_{C(t)} = \frac{d}{dt} CV_{max}\sin(\omega t) = \omega CV_{max}\cos(\omega t)$$

$$if: I_{max} = \frac{V_{max}}{X_C} \quad where: X_C = \frac{1}{2\Pi fC} = \frac{1}{\omega C}$$

$$then: I_{max} = \omega CV_{max}$$

- and therefore, the rms current flowing into an AC capacitance will be defined as:

$$I_{C(t)} = I_{max}\sin(\omega t + 90^0)$$

# MODULE– IV

# COMPLEX POWER ANALYSIS

# COMPLEX POWER

- Previously, we found it convenient to introduce sinusoidal voltage and current in terms of the complex number the **phasor**

- Let the complex power be the complex sum of real power and reactive power

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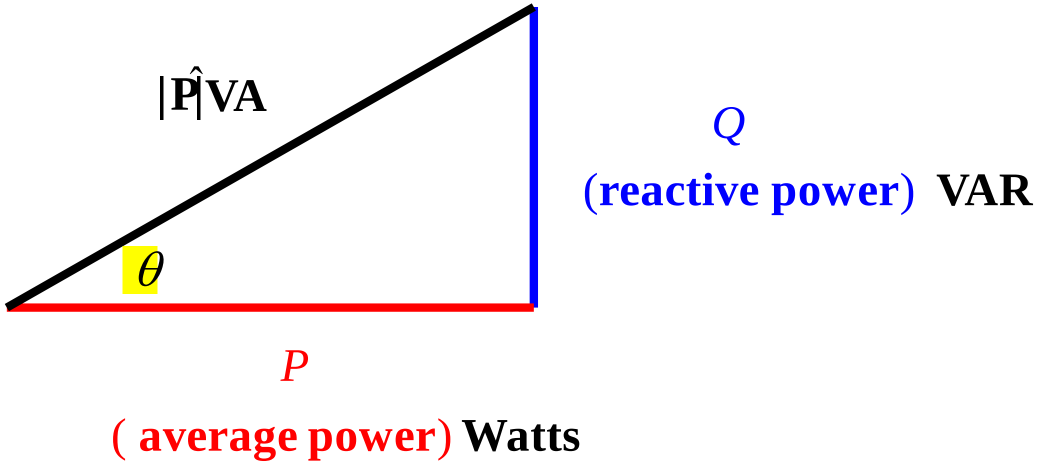
- Let the complex power be the complex sum of real power and reactive power

# REACTIVE POWER

- Apparent Power. The combination of reactive power and true power is called apparent power, and it is the product of a circuit's voltage and current, without reference to phase angle.

- Reactive Power is when the Current flow, caused by AC Voltage applied across a device, results in the Current flow being either ahead or behind the applied AC Voltage.

# POWER TRIANGLE



# POWER FACTOR

- In electrical engineering, the power factor (PF or cosφ) is the ratio between the power that can be used in electric circuit (real power, P) and the power from the result of multiplication between the current and voltage circuit (apparent power, S).
- The power factor is defined as: PF ranges from zero to one.
- There is no particular unit of Power factor (p.f).

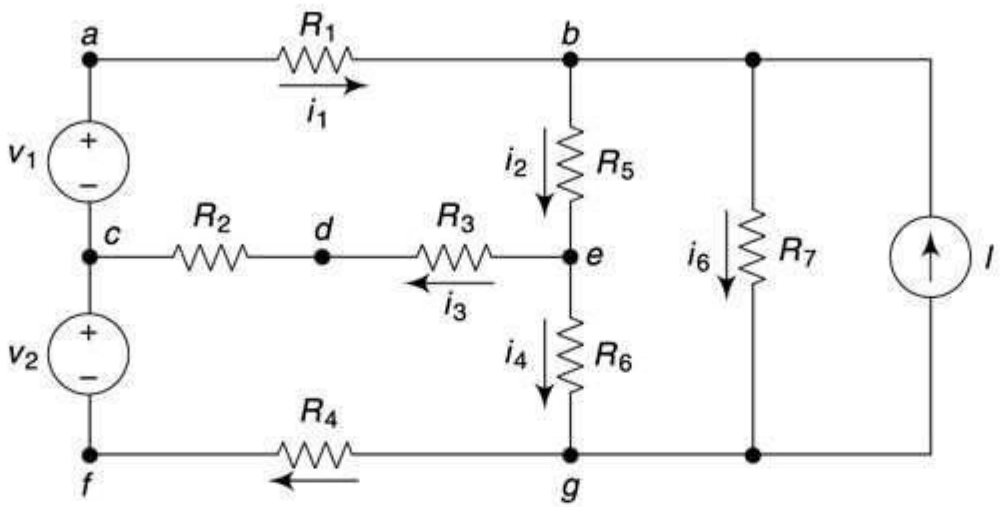
# MODULE-V
# NETWORK TOPOLOGY

## TERMINOLOGY

**Node:** A node is a point in a circuit where two or more circuit.
**Branch:-** A branch is a path that connects two nodes.
**Loop:-** A loop is a complete path, i.e., it starts at a selected node, traces a set of connected basic circuit elements and returns to the original starting node without passing through any intermediate node more than once.
**Mesh:-** A mesh is a special type of loop, i.e., it does not contain any other loops within it.
**Oriented Graph:-** A graph whose branches are oriented is called a directed or oriented graph.

## TERMINOLOGY

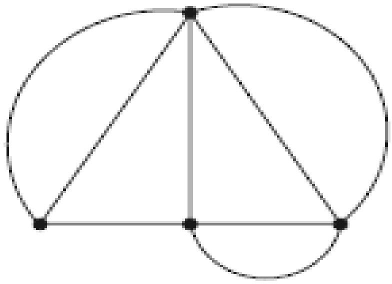
**Node:-** a, b, c, d, e, f and g
**Branch:-** $V_1, R_1, R_2, R_3, V_2, R_4, R_5, R_6, R_7$ and I
**Loop:-** a b e d c a, a b e g f c a, c d e b g f c, etc.
**Mesh:-** b e d c a, c d e g f c, g e b g (through $R_7$ )



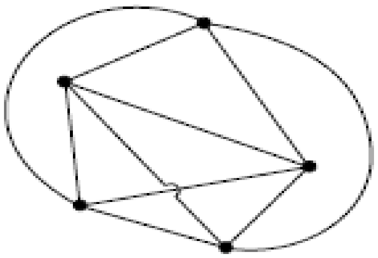

Circuit illustrating terminologies

**Rank of Graph:-** The rank of a graph is (n–1) where n is the number of nodes or vertices of the graph.

**Planar and Non-planar Graph:-** A graph is planar if it can be drawn in a plane such that no two branches intersect at a point which is not a node.



(a) *Planar graph*



(b) *Non-planar graph*

**Subgraph:-** A subgraph is a subset of the branches and nodes of a graph. The subgraph is said to be proper if it consists of strictly less than all the branches and nodes of the graph.

**Path:-** A path is a particular sub graph where only two branches are incident at every node except the internal nodes (i.e., starting and finishing nodes). At the Internal nodes, only one branch is incident.

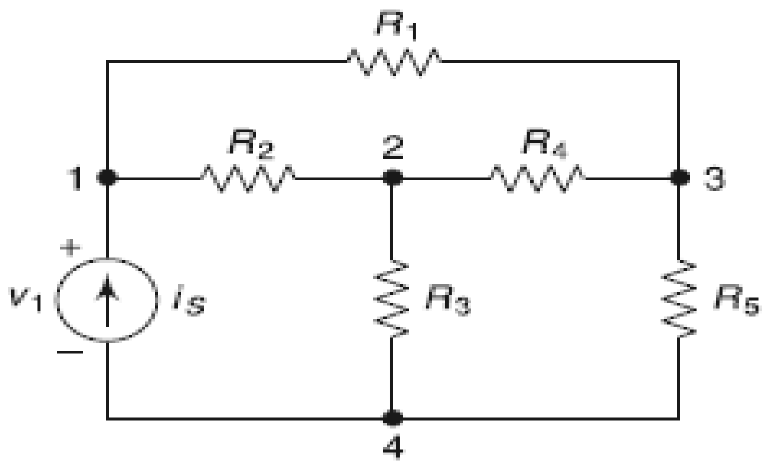
## CONCEPT OF TREE

For a given connected graph of a network, a connected Subgraph is known as a tree of the graph if the Subgraph has all the nodes of the graph without containing any loop.

**Twigs:** The branches of tree are called twigs or tree-branches. The number of branches or twigs, in any selected tree is always one less than the number of nodes, i.e.,
Twigs = (n – 1), where n is the number of nodes of the graph.
For this case, twigs = (4 – 1) = 3 twigs. These are shown by solid lines in Fig. (b).

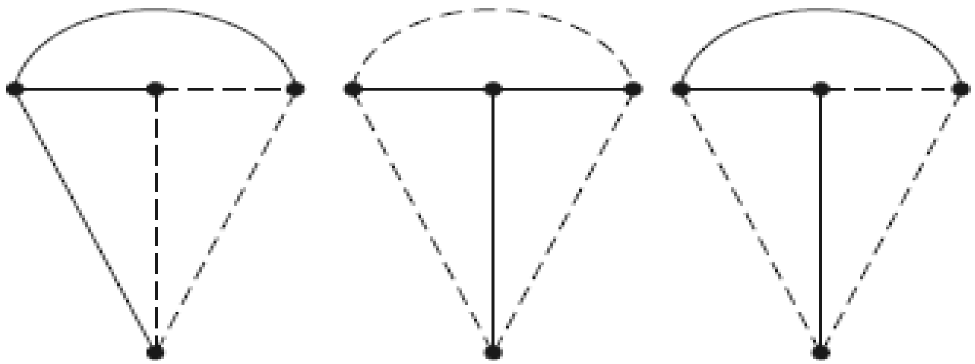
## Links and Co-tree

If a graph for a network is known and a particular tree is specified, the remaining branches are referred to as the links. The collection of links is called a co-tree. So, co-tree is the complement of a tree. These are shown by dotted lines in Fig. (b).




(a) Circuit

# NETWORK TOPOLOGY



(b) Trees and links of circuit of Fig. (a)

The branches of a co-tree may or may not be connected, whereas the branches of a tree are always connected

## Properties of a Tree

1. In a tree, there exists one and only one path between any pair of nodes.

2. Every connected graph has at least one tree.

3. A tree contains all the nodes of the graph.

4. There is no closed path in a tree.

5. The rank of a tree is (n – 1).

## INCIDENCE MATRIX [A]

The incidence matrix symbolically describes a network. It Also facilitates the testing and identification of the independent variables. Incidence matrix is a matrix which represents a graph uniquely.

For a given graph with n nodes and b branches, the complete incidence matrix A is a rectangular matrix of order $n \times b$, whose elements have the following values.

Number of columns in [A] = Number of branches = b

Number of rows in [A] = Number of nodes = n

- Aij = 1, if branch j is associated with node i and oriented away from node i.
- Aij = –1, if branch j is associated with node i and oriented
- towards Node i.
- Aij = 0, if branch j is not associated with node i.

This matrix tells us which branches are incident at which nodes and what are the orientations relative to the nodes.

## Properties of Complete Incidence Matrix

- The sum of the entries in any column is zero.
- The determinant of the incidence matrix of a closed loop is zero
- The rank of incidence matrix of a connected graph is (n-1)

## LOOP MATRIX OR CIRCUIT MATRIX

The incidence matrix gives information regarding the no of nodes, no of branches and their connection orientation of branches to the corresponding nodes . it does not give any idea about the interconnection of branches which constitutes loops.

It is ,however, possible, to obtain this piece of information in a matrix form. For this, we first assign each loop of the graph with an orientation with the help of a curved arrow as show in figure 1. All the loop currents are assumed to be flowing in a clock wise direction. As such orientation is arbitrary

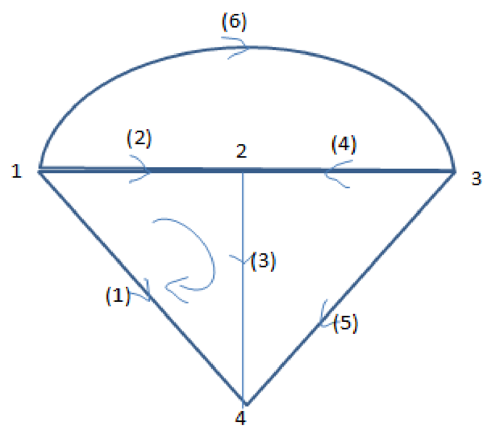
# NETWORK TOPOLOGY

For a graph, having n nodes and b branches the complete loop matrix or circuit matrix. B is a rectangular matrix of order b columns and as many rows as there are loops the graph has. Its elements have the following values.

bij=1 if branch j is in loop I and their orientations coincide.

bij=-1,if branch j is in loop I and their orientations do not coincide.

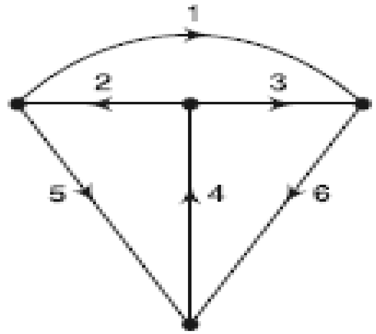
bij=0, if branch j is not in loop i.



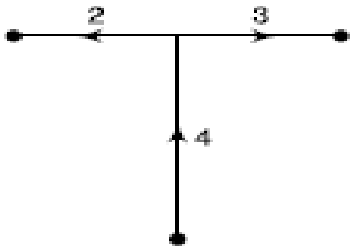
## Tie-Set Matrix and Loop Currents

**Tie-Set:** A tie-set is a set of branches contained in a loop such that each loop contains one link or chord and the remainder are tree branches.

Consider the graph and the tree as shown. This selected tree will result in three fundamental loops as we connect each link, in turn to the tree.




(a) Graph




(b) Tree of the graph

## Cut-Set Matrix

Acut-set is a minimum set of elements thatwhen cut, or removed, separates the graph into two groups of nodes.
Acut-set is a minimum set of branches of a connected graph, such that the removal of these branches from the graph reduces the rank of the graph by one.
In other words, for a given connected graph (G), a set of branches (C) is defined as a cut-set if and only if:
1.the removal of all the branches of Cresults in an unconnected graph.
2.the removal of all but one of the branches of Cleaves the graph still connected.

## Fundamental Cut-Set

A fundamental cut-set (FCS) is a cut-set that cuts or contains one and only one tree branch. Therefore, for a given tree, the number of fundamental cut-sets will be equal to the number of twigs.

## Properties of Cut-Set

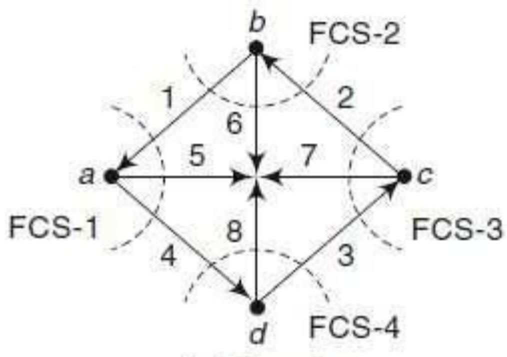
1. A cut-set divides the set of nodes into two subsets.
2. Each fundamental cut-set contains one tree-branch, the remaining elements being links.

3.Each branch of the cut-set has one of its terminals incident at a node in one subset and its other terminal at a node in the other subset.
4.A cut-set is oriented by selecting an orientation from one of the two parts to the other. Generally, the direction of cutset is chosen same as the direction of the tree branch.

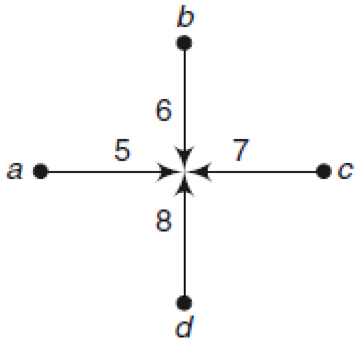
**Cut-Set Matrix (Q)**

For a given graph, a cut-set matrix (Q ) is defined as a rectangular matrix whose rows correspond to cut-sets and columns correspond to the branches of the graph. Its elements have the following values:

Qij = 1, if branch j is in the cut-set i and the orientations coincide.
Qij = –1, if branch j is in the cut-set i and the orientations do Not coincide.
Qij=0, if branch j is not in the cut-set i
By cut-set schedule, the branch voltages can be expressed in terms of the tree-branch voltages.
A cut-set consists of /one and only one/ branch of the tree together with any links which must be cut to divide the network into two parts. A set of fundamental cut-sets includes those cut-sets which are obtained by applying cutset division for each of the branches of the network tree.




(a) Graph




(b) Tree

**To summarize**, KVL and KCL equations in three matrix forms are given below.

| *Matrix* | *KCL* | *KVL* |
|---|---|---|
| Incidence Matrix ($A_a$) | $A_a \times I_b = 0$ | $V_b = A_a^T \times V_n$ |
| Tie-Set Matrix ($B_a$) | $I_b = B_a^T \times I_L$ | $B_a \times V_b = 0$ |
| Cut-Set Matrix ($Q_C$) | $Q_C \times I_b = 0$ | $V_b = Q_C^T \times V_t$ |

## Formulation of Network Equilibrium Equations

The network equilibrium equations are a set of equations that completely and uniquely determine the state of a network at any instant of time. These equations are written in terms of suitably chosen current variables or voltage variables.

These equations will be unique if the number of independent variables be equal to the number of independent equations.

## Generalized Equations in Matrix Forms for Circuits Having Sources

Node Equations: The node equations become

$$\boxed{YV_n = A[Y_b V_s - I_s]}$$

where, $Y = AY_bA^T$ is called the nodal admittance matrix of the order of (n – 1) × (n – 1). The above equation represents a set of (n – 1) number of equations, known as Node equations.

Mesh Equations: The mesh equations become

$$\boxed{ZI_L = B_a[Z_b I_s - V_s]}$$

where, Z is the loop-impedance matrix of the order of (b – n + 1) × (b – n + 1). The above equation represents a set of (b – n + 1) number of equations, known as mesh or loop equations.

Cut-set Equations: The cut-set equations become

$$\boxed{Y_c V_t = Q_c [Y_b V_s - I_s]}$$

where, $Y_c$ is the cut-set admittance matrix of the order of (n – 1) × (n – 1) and the set of (n–1) equations represented by the above equation is known as cut-set equations.

## Solution of Equilibrium Equations

There are two methods of solving equilibrium equations given as follows.

- Elimination method/: by eliminating variables until an equation with a single variable is achieved, and then by the method of substitution.
- Determinant method/: by the method known as Cramer's rule.

# THANK YOU