Unit-I : Basic Fundamentals

Voltage - The electric potential between one place and another. How much the electricity wants to move from one point to another. Measured in volts. Denoted by "V".

Current - The current flow from one point to another, literally based on how many electrons are moving per second. Measured in amps. Denoted by "I" .

Power - Work that is being done per second. In circuits, this usually means the amount of heat given off by a circuit. Measured in watts, or joules per second. Denoted by "P" .

Energy - Total amount of work done. There is no time component for this, which is the differentiator between power and energy. Measured in joules. These are clarified more later in this tutorial. Denoted by "E".

Variable	Unit	Unit symbol
Electric current (I)	ampere	A
Voltage (V)	volt	V
Resistance (R)	ohm	Ω
Energy	joule	J
Power	watt	W
Charge	coulomb	C
Time	second	s

Relationship (V, I, P&E)

$$I = \frac{Q}{t} \textit{ Amperes,}$$

$$V = \frac{Workdone}{Charge} = \frac{W}{Q} \quad \textit{volts}$$

$$V = I\,R \text{ ………. } \textit{by Ohm's law}$$

$$\textit{Power = Voltage x Current} \quad P = V \times I = \frac{W}{Q} \times \frac{Q}{t} = \frac{W}{t}$$

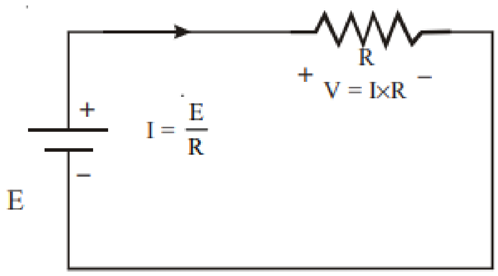
$$P = (I \times R) \times I \textit{ Watts} \qquad P = I^2 \times R \textit{ Watts} \quad P = V \times \frac{V}{R} \textit{ Watts} \quad P = \frac{V^2}{R} \textit{ Watts}$$

$$\textit{Energy } E = P \times t = V \times I \times t \textit{ Watt-sec}, \quad E = I^2 \times R \times t \textit{ Watt-sec}, \quad E = \frac{V^2}{R} \times t \textit{ Watt-sec}$$

Ohm's Law :

The relationship between the current flowing through a conductor and the potential difference across the conductor is given by Ohm's Law.

"***The Ohm's Law states that the potential difference across a conductor is directly proportional to the current flowing through the conductor, the temperature of the conductor remaining constant".***



The constant of proportionality is R, the resistance.

V = I × R Volts or V = R × I Volts

Laws of Resistance

The resistance R offered by a conductor depends on the following factors :

(i) It varies directly as its length, l.
(ii) It varies inversely as the cross-section A of the conductor.
(iii) It depends on the nature of the material.
(iv) It also depends on the temperature of the conductor.

$$\mathbf{R = \rho \frac{l}{A}}$$

Where $\boldsymbol{\rho}$ is a constant depending on the nature of the material of the conductor and is known as its ***Specific resistance or resistivity.***

Sr No.	**Material**	**Resistivity in ohm-metre Temperature coefficient at 20°C**
1	Aluminum, commercial	2.8
2	Brass	6 – 8
3	Carbon	3000 – 7000
4	Copper (annealed)	1.72
5	Gold	2.44
6	Platinum	9 – 15.5
7	Silver	1.64
8	Glass	$10^{10} – 10^{12}$
9	Rubber	10^{16}

1. A coil consists of 2000 turns of copper wire having a cross-sectional area of 0.8 mm2. The mean length per turn is 80cm and the resistivity of copper is 0.02 μΩ–m. Find the resistance of the coil and power absorbed by the coil when connected across 110 V d.c. supply.

Effect of Temperature on Resistance

The effect of rise in temperature is :

(i) To increase the resistance of pure metals. The increase is large and fairly regular for normal ranges of temperature. The temperature/resistance graph is a straight would be presently clarified; metals have a positive temperature co-efficient of resistance.

(ii) To increase the resistance of alloys, though in their case, the increase is relatively small and irregular. For some high-resistance alloys like Eureka (60% Cu and 40% Ni) and manganin, the increase in resistance is (or can be made) negligible over a considerable range of temperature.

(iii) To decrease the resistance of electrolytes, insulators (such as paper, rubber, glass, mica etc.) and partial conductors such as carbon. Hence, insulators are said to possess a negative temperature-coefficient of resistance.

Temperature Coefficient of Resistance

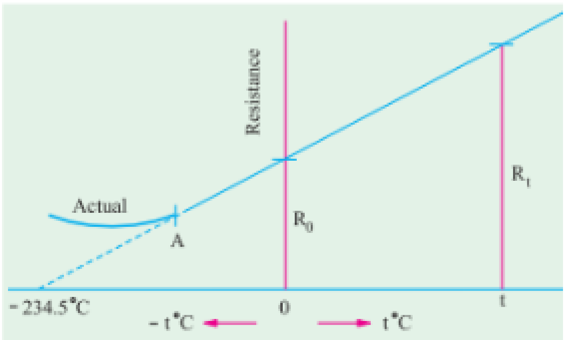
Let a metallic conductor having a resistance of R_0 at 0°C be heated of t°C and let its resistance at this temperature be Rt. Then, considering normal ranges of temperature, it is found that the increase in resistance

$\Delta R = R_t - R_0$ depends

(i) directly on its initial resistance

(ii) directly on the rise in temperature

(iii) on the nature of the material of the conductor.



Or

$$R_t - R_0 \propto R \times t \text{ or } R_t - R_0 = \alpha R_0 t \text{ ...(i)}$$

Where α (alpha) is a constant and is known as the temperature coefficient of resistance of the conductor. Rearranging Eq. (i),

$$\text{We get } \alpha = \frac{Rt - R0}{R0\ t} = \frac{\Delta R}{R0\ t} \text{ ....(ii)}$$

$$\text{If } R0 = 1\ \Omega,\ t = 1°C, \text{ then } \alpha = \Delta R = R_t - R_0$$

Hence, the temperature-coefficient of a material may be defined as :the increase in resistance per ohm original resistance per °C rise in temperature. From Eq. (i), we find that $Rt = R0\ (1 + \alpha\ t)$

Value of α at Different Temperatures

So far we did not make any distinction between values of α at different temperatures. But it is found that value of α itself is not constant but depends on the initial temperature on which the increment in resistance is based. When the increment is based on the resistance measured at 0°C, then α has the value of α_0. At any other initial temperature t°C, value of α is αt and so on. It should be remembered that, for any conductor, α0 has the maximum value.

Suppose a conductor of resistance R_0 at 0°C (point A in Fig. 1.7) is heated to t°C (point B). Its resistance Rt after heating is given by

$$R_t = R_0\ (1 + \alpha_0\ t)\ ...(i)$$

Where α_0 is the temperature-coefficient at 0°C.

Now, suppose that we have a conductor of resistance Rt at temperature t°C. Let this conductor be cooled from t°C to 0°C. Obviously, now the initial point is B and the final point is A. The final resistance R0 is given in terms of the initial resistance by the following equation

$$R_0 = R_t\,[1 + \alpha_t\,(-t)] = R_t(1 - \alpha_t\,.\,t)\ ...(ii)$$

From Eq. (ii) above, we have $\alpha t = \frac{Rt - R0}{Rt\ x\ t}$

Substituting the value of R_t

$$\alpha t = \frac{R0\ (1 + \alpha 0\ t) - R0}{R0\ (1 + \alpha 0\ t)\ \ x\ t} = \frac{\alpha 0}{(1 + \alpha 0\ t)}\ ....(iii)$$

In general, let α1= tempt. coeff. at t_1°C ; α_2 = tempt. coeff. at t_2°C.

Then from Eq. (iii) above, we get

$$\alpha 1 = \frac{\alpha 0}{(1 + \alpha 0\ t1)}\ \text{ or }\ \frac{1}{\alpha 1} = \frac{(1 + \alpha 0\ t1)}{\alpha 0}\quad \text{and}\quad \alpha 2 = \frac{\alpha 0}{(1 + \alpha 0\ t2)}\ \text{ or }\ \frac{1}{\alpha 2} = \frac{(1 + \alpha 0\ t2)}{\alpha 0}$$

$$\frac{1}{\alpha 1} - \frac{1}{\alpha 2} = (t2 - t1) = \frac{1}{\alpha 2} = \frac{1}{\alpha 1} + (t2 - t1)\ \ or\ \ \alpha 2 = \frac{\alpha 1}{(1 + \alpha 1(t2 - t1))}$$

In view of the dependence of α on the initial temperature, we may define the temperature coefficient of resistance at a given temperature as the charge in resistance per ohm per degree centigrade change in temperature from the given temperature. In case R_0 is not given, the relation between the known resistance R_1 at t_1°C and the unknown resistance R_2 at t 2°C can be found as follows:

$$R2 = R0\ (1 + \alpha 0\ t2)\ and\ R1 = R0\ (1 + \alpha 0\ t1)$$

$$\frac{R2}{R1} = \frac{1 + \alpha 0\ t2}{1 + \alpha 0\ t1}$$

The above expression can be simplified by a little approximation as follows :

$$\frac{R2}{R1} = (1 + \alpha 0\ t2)(1 + \alpha 0\ t1)^{-1}$$

$= (1 + \alpha 0\ t2)(1 - \alpha 0\ t1)$ ……. [Using Binomial Theorem for expansion and neglecting squares and higher powers of $\alpha 0\ t1$]

$$= 1 + \alpha 0\ (t2 - t1)$$

$$R2 = R1\ [1 + \alpha 0\ (t2 - t1)]$$

The ratio of m/ρ1 is called the temperature coefficient of resistivity at temperature t1°C. It may be defined as numerically equal to the fractional change in ρ1 per °C change in the temperature from t_1°C. It is almost equal to the temperature-coefficient of resistance α1. Hence, putting

$\alpha_1 = m/\rho 1$,

We get

$$\rho 2 = \rho 1\ [1 + \alpha 1\ (t2 - t1)] \text{ or simply as } \rho t = \rho 0\ (1 + \alpha 0\ t)$$

Numerical practice

Exp 1. A copper conductor has its specific resistance of 1.6 × 10−6 ohm-cm at 0°C and a resistance temperature coefficient of 1/254.5 per °C at 20°C. Find (i) the specific resistance and (ii) the resistance - temperature coefficient at 60°C.

Exp 2. A platinum coil has a resistance of 3.146 Ω at 40°C and 3.767 Ω at 100°C. Find the resistance at 0°C and the temperature-coefficient of resistance at 40°C.

Exp 3. A potential difference of 250 V is applied to a field winding at 15°C and the current is 5 A. What will be the mean temperature of the winding when current has fallen to 3.91 A, applied voltage being constant. Assume α15 = 1/254.5.

Exp 4. Two coils connected in series have resistances of 600 Ω and 300 Ω with tempt. coeff. of 0.1% and 0.4% respectively at 20°C. Find the resistance of the combination at a tempt. Of 50°C. What is the effective tempt. coeff. of combination ?

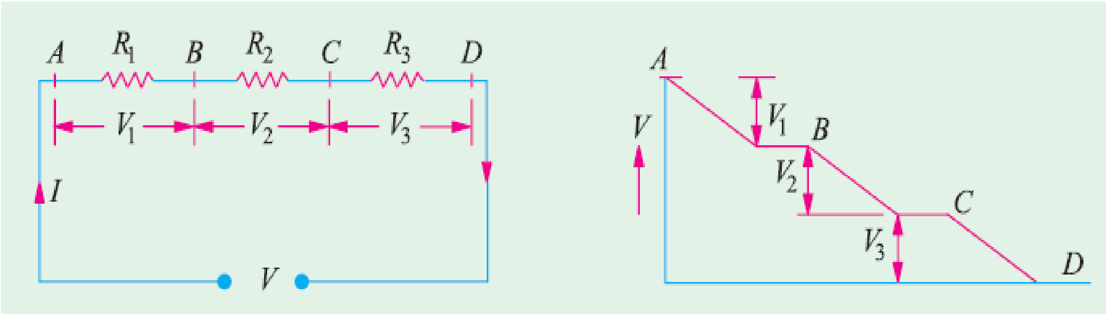
Exp 5. Two wires A and B are connected in series at 0°C and resistance of B is 3.5 times that of A. The resistance temperature coefficient of A is 0.4% and that of the combination is 0.1%. Find the resistance temperature coefficient of B.

Exp 6. Two conductors, one of copper and the other of iron, are connected in parallel and carry equal currents at 25°C. What proportion of current will pass through each if the temperature is raised to 100°C ? The temperature coefficients of resistance at 0°C are 0.0043/°C and 0.0063/°C for copper and iron respectively.

Exp 7. A coil of copper wire has resistance of 90 Ω at 20°C and is connected to a 230- V supply. By how much must the voltage be increased in order to maintain the current consant if the temperature of the coil rises to 60°C ? Take the temperature coefficient of resistance of copper as 0.00428 from 0°C.

Resistance in Series or Series Circuit

When some conductors having resistances R1, R2 and R3 etc. are joined end-on-end as in Fig. they are said to be connected in series. It can be proved that the equivalent resistance or total resistance between points A and D is equal to the sum of the three individual resistances. Being a series circuit, it should be remembered that (i) current is the same through all the three conductors (ii) but voltage drop across each is different due to its different resistance and is given by Ohm's Law and (iii) sum of the three voltage drops is equal to the voltage applied across the three conductors. There is a progressive fall in potential as we go from point A to D as shown in Fig.



$$+ V_2 + V_3 = IR_1 + IR_2 + IR_3 \text{ —Ohm's Law}$$

$$\text{But } V = IR$$

Where R is the equivalent resistance of the series combination.

$$\therefore \quad IR = IR_1 + IR_2 + IR_3 \text{ or } R = R_1 + R_2 + R_3$$

As seen from above, the main characteristics of a series circuit are :

1. Same current flows through all parts of the circuit.

2. Different resistors have their individual voltage drops.

3. Voltage drops are additive.

4. Applied voltage equals the sum of different voltage drops.

5. Resistances are additive.

6. Powers are additive.

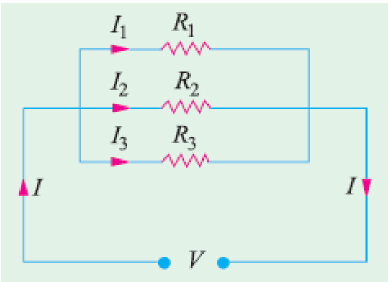
Resistances in Parallel or Parallel Circuit

Three resistances, as joined in Fig. are said to be connected in parallel. In this case

(i) p.d. across all resistances is the same.

(ii) Current in each resistor is different and is given by Ohm's Law.

(iii) The total current is the sum of the three separate currents.



$$\boldsymbol{I = I_1 + I_2 + I_3 = \frac{V}{R1} + \frac{V}{R2} + \frac{V}{R3}}$$

$I = \frac{V}{R}$ where V is the applied voltage.

$$\boldsymbol{\frac{V}{R} = \frac{V}{R1} + \frac{V}{R2} + \frac{V}{R3} \text{ and } \frac{1}{R} = \frac{1}{R1} + \frac{1}{R2} + \frac{1}{R3}}$$

R = equivalent resistance of the parallel combination.

Also $\boldsymbol{G = G_1 + G_2 + G_3}$

The main characteristics of a parallel circuit are :

1. Same voltage acts across all parts of the circuit

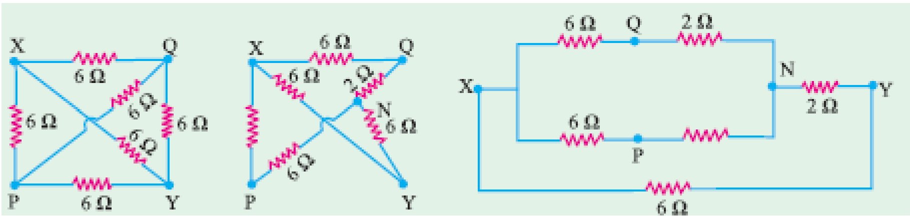
2. different resistors have their individual current.

3. Branch currents are additive.

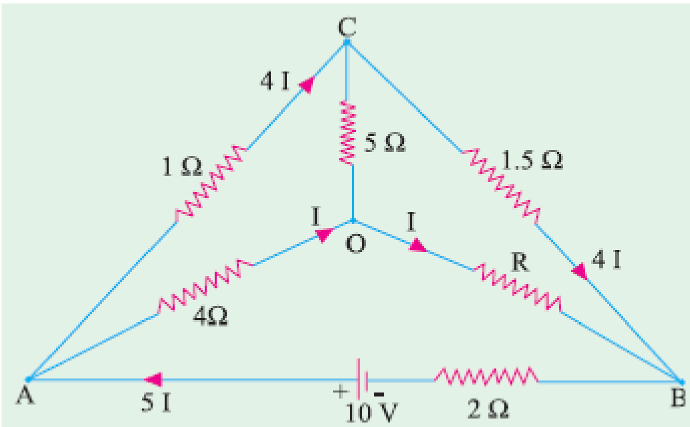
4. Conductance are additive.

5. Powers are additive.

1. In Fig. below, if all the resistances are of 6 ohms, calculate the equivalent resistance between any two diagonal points.



2. In the circuit shown in Fig. below, calculate the value of the unknown resistance R and the current flowing through it when the current in branch OC is zero.



Electric Circuits and Network Theorems

1. **Circuit.** A circuit is a closed conducting path through which an electric current either flows or is intended flow.
2. **Parameters.** The various elements of an electric circuit are called its parameters like resistance, inductance and capacitance. These parameters may be ***lumped or distributed.***

3. **Liner Circuit.** A linear circuit is one whose parameters are constant *i.e.* they do not change with voltage or current.
4. **Non-linear Circuit.** It is that circuit whose parameters change with voltage or current.
5. **Bilateral Circuit.** A bilateral circuit is one whose properties or characteristics are the same in either direction. The usual transmission line is bilateral, because it can be made to perform its function equally well in either direction.
6. **Unilateral Circuit.** It is that circuit whose properties or characteristics change with the direction of its operation. A diode rectifier is a unilateral circuit, because it cannot perform rectification in both directions.
7. **Electric Network.** A combination of various electric elements, connected in any manner whatsoever, is called an electric network.
8. **Passive Network** is one which contains no source of e.m.f. in it.
9. **Active Network** is one which contains one or more than one source of e.m.f.
10. **Node** is a junction in a circuit where two or more circuit elements are connected together.
11. **Branch** is that part of a network which lies between two junctions.
12. **Loop.** It is a close path in a circuit in which no element or node is encountered more than once.
13. **Mesh.** It is a loop that contains no other loop within it.

Kirchhoff's Point Law or Current Law (KCL)

It states as follows :

in any electrical network, the algebraic sum of the currents meeting at a point (or junction) is Zero.

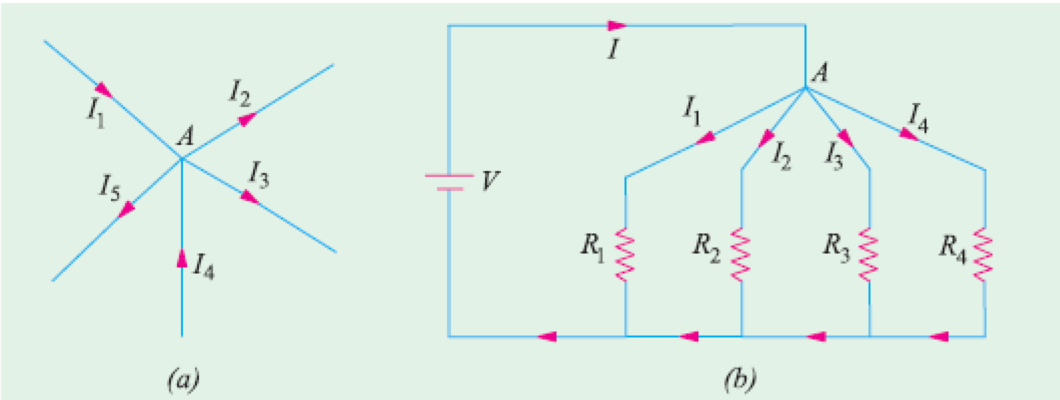
Put in another way, it simply means that the total current *leaving* a junction is equal to the total current ***entering*** that junction. It is obviously true because there is no accumulation of charge at the junction of the network.

Consider the case of a few conductors meeting at a point *A* as in Fig. below. Some conductors have currents leading to point *A*, whereas some have currents leading away from point *A*. assuming the incoming currents to be positive and the outgoing currents negative, we have

$$I_1 + (-I_2) + (-I_3) + (+I_4) + (-I_5) = 0$$

or

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



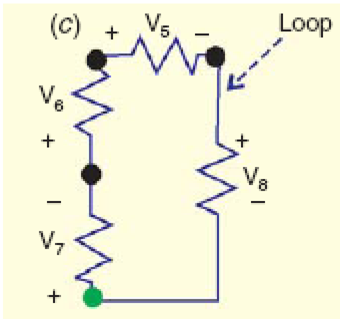
Kirchhoff's Mesh Law or Voltage Law (KVL)

It states as follows :

The algebraic sum of the products of currents and resistances in each of the conductors in any closed path (or mesh) in a network plus the algebraic sum of the e.m.fs. in that path is zero.

In other words, $\Sigma\ IR + \Sigma\ e.m.f. = 0$ ...round a mesh

It should be noted that algebraic sum is the sum which takes into account the polarities of the voltage drops



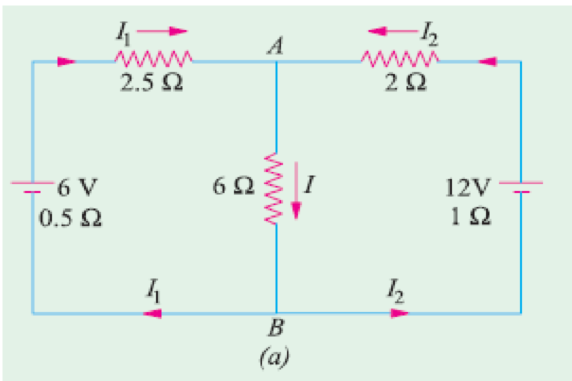
Superposition Theorem

According to this theorem, if there are a number of e.m.fs. acting simultaneously in any linear bilateral network, then each e.m.f. acts independently of the others *i.e.* as if the other e.m.fs. did not exist. The value of current in any conductor is the algebraic sum of the currents due to each e.m.f.

Similarly, voltage across any conductor is the algebraic sum of the voltages which each e.m.f would have produced while acting singly. In other words, current in or voltage across, any conductor of the network is obtained by superimposing the currents and voltages due to each e.m.f. in the network. It is important to keep in mind that this theorem is applicable only to ***linear*** networks where current is ***linearly*** related to voltage as per Ohm's law.

Hence, this theorem may be stated as follows :

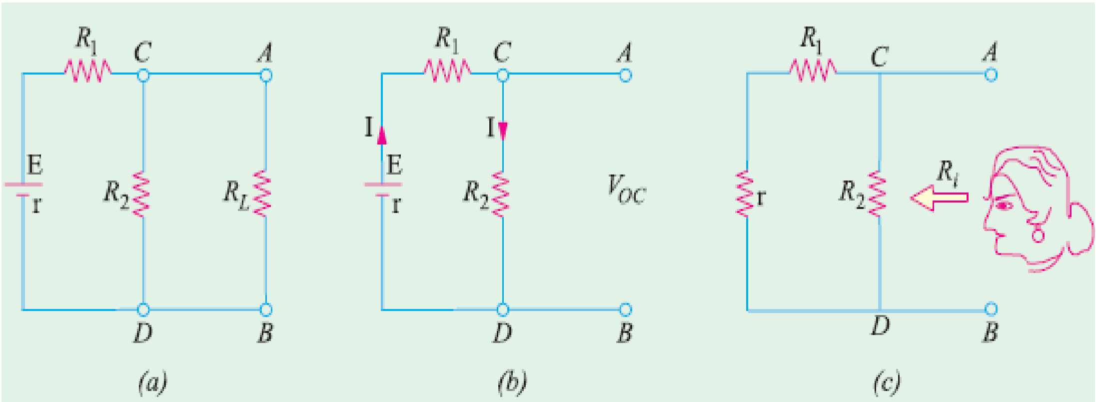
"In a network of linear resistances containing more than one generator (or source of e.m.f.), the current which flows at any point is the sum of all the currents which would flow at that point if each generator where considered separately and all the other generators replaced for the time being by resistances equal to their internal resistances."



Thevenin's Theorem

Thevenin's theorem, as applied to d.c. circuits, may be stated as under :

"The current flowing through a load resistance RL connected across any two terminals A and B of a linear, active bilateral network is given by Voc || (Ri + RL) where Voc is the open-circuit voltage (i.e. voltage across the two terminals when RL is removed) and Ri is the internal resistance of the network as viewed back into the open-circuited network from terminals A and B with all voltage sources replaced by their internal resistance (if any) and current sources by infinite resistance".



Suppose, it is required to find current flowing through load resistance *RL*, as shown in Fig

We will proceed as under

1. Remove RL from the circuit terminals A and B and redraw the circuit as shown in Fig. (b). Obviously, the terminals have become open-circuited.
2. Calculate the open-circuit voltage Voc which appears across terminals A and B when they are open i.e. when RL is removed. As seen, Voc = drop across R_2 = IR_2 where I is the circuit current when A and B are open.

$$I = \frac{E}{R1+R2+r} \qquad Voc = I\,R_2 = \frac{E}{R1+R2+r}R2$$

r is the internal resistance of battery

V_{oc} It is also called 'Thevenin voltage' V_{th}.

3. Now, imagine the battery to be removed from the circuit, leaving its internal resistance r behind and redraw the circuit, as shown in Fig. 2.127 (c). When viewed inwards from terminals A and B, the circuit consists of two parallel paths : one containing R2 and the other containing (R1 + r). The equivalent resistance of the network, as viewed from these terminals is given as

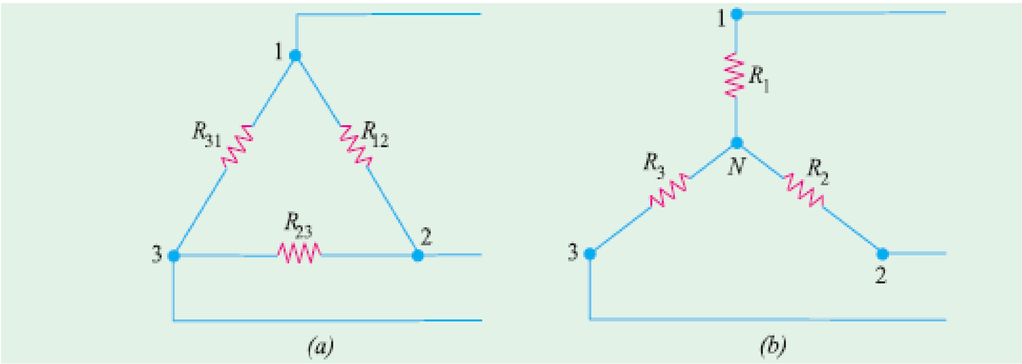
$$R = R2 \,||\, (R1 + r) = \frac{R2 \text{ x } (R1+r)}{R2+ (R1+r)}$$

This resistance is also called,* Thevenin resistance Rsh (though, it is also sometimes written as Ri or R0). Consequently, as viewed from terminals A and B, the whole network (excluding R1) can be reduced to a single source (called Thevenin's source) whose e.m.f. equals V∝ (or Vsh) and whose internal resistance equals Rsh (or Ri) as shown in Fig.

4. RL is now connected back across terminals A and B from where it was temporarily removed earlier. Current flowing through RL is given by

$$I = \frac{Vth}{Rth+RL}$$

1. **Delta –to- Star transformation**



First, take delta connection : Between terminals 1 and 2, there are two parallel paths; one having a resistance of R_{12} and the other having a resistance of (R_{23} + R_{31}).

∴ Resistance between terminals 1 and 2 is = $\frac{R12 \text{ x } (R23+R31)}{R12 + R23 + R31}$ ………(1)

Now, take star connection : The resistance between the same terminals 1 and 2 is ($R_1 + R_2$).
As terminal resistances have to be the same

$$R_1 + R_2 = \frac{R12 \text{ x } (R23+R31)}{R12 + R23 + R31} \text{ ………(2)}$$

Similarly, for terminals 2 and 3 and terminals 3 and 1, we get

$$R_2 + R_3 = \frac{R23\text{x } (R12+R31)}{R12 + R23 + R31} \text{ …….. (3)}$$

$$R_3 + R_1 = \frac{R31 \text{ x } (R12+R23)}{R12 + R23 + R31} \text{ …….. (4)}$$

Now, subtracting **(3)** from **(2)** and adding the result to **(4)**, we get

$$R_1 = \frac{R12 \text{ x } R31}{R12 + R23 + R31} \text{ …… (5)}$$

$$R_2 = \frac{R12 \text{ x } R23}{R12 + R23 + R31} \text{ ……..(6)}$$

$$R_3 = \frac{R23 \text{ x } R31}{R12 + R23 + R31} \text{ …….(7)}$$

2. **Star- to - Delta Transformation**

   This transformation can be easily done by using equations **(2)**, **(3)** and **(4)** given above. Multiplying **(2)** and **(3)**, **(3)** and **(4)**, **(4)** and **(2)** and adding them together and then simplifying them, we get

$$R_{12} = \frac{R1R2+R2R3+R3R1}{R3} = \text{R1 + R2} + \frac{R1R2}{R3}$$

$$R_{23} = \frac{R1R2+R2R3+R3R1}{R1} = \text{R2 + R3} + \frac{R2R3}{R1}$$

$$R_{31} = \frac{R1R2+R2R3+R3R1}{R2} = \text{R1 + R3} + \frac{R1R3}{R2}$$