Unit # 10
D.C Circuits

Electric Current

A current is motion of any charge moving from one point to another point.

An Electric current is always considered as flow of negative charges (electrons) of the conductor.

The unit of electric current (ampere)

Formula

$$\mathbf{I} = \frac{\mathbf{q}}{\mathbf{t}}$$

I = electric current

q = charge (q = n e)

t = time

Potential Difference

The Potential difference is the difference in the amount of energy that charge carriers have between two points in an electric field.

$$\textbf{Electric Potential} = \frac{Work}{Charge}$$

Potential difference is also called voltage

Potential difference is measured in volt. Volts is denoted by V

Ohms Law

Definition

The current flowing through the conductor is directly proportional to the potential difference (V) across the two ends of a conductor, provided the physical state (Dimension, Temperature, etc) of the conductor remain same

Formula

Mathematically can be written as

$$V \propto I$$

$$V = I\ R$$

Where R is a constant called resistance

Resistance

The electrical resistance measures how much the flow of this electric charge is restricted within the circuit

Definition.

The electrical resistance of a circuit is the ratio between the voltage applied to the current flowing through it

Formula

$$R = \frac{\mathrm{V}}{\mathrm{I}}$$

Unit

Its SI unit is Ohm (Ω).

The resistance of a conductor is one ohm if one ampere current passes through it when potential difference across its eds is one volt

Resistors

Definition.

Resistors are electrical component which are used to provide resistance.

Applications

In electronic circuits resistors usually serve two main purposes to

- Limit the current flow to a specified value
- Provide a desired reduction in voltage, or current

Factor Affecting the Resistance

Resistance of conductor depends upon Dimension of Conductor i.e., Size and shape

Effect of Dimension of Conductor

Electrical resistance is directly proportional to length (L) of the conductor and inversely proportional to the cross-sectional area (A)

$$R \propto L$$

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

Combining

$$R \propto \frac{L}{A}$$

$$R = \rho \frac{L}{A}$$

where ρ is the resistivity of the material measured in Ω m, (ohm-meter

Resistivity and its dependence upon Temperature

Definition.

Resistivity is a qualitative measurement of a material's ability to resist flowing electric current. Resistivity does not depend on the size or shape of the material, but does depend on temperature

Two factors primarily determine the resistivity of a metal:

- The number of conduction electrons per unit volume and
- The rate of collisions between an electron and an ion (nuclei)

The resistivity of the material is measured in Ω m, (ohm-meter)

Affect of Temperature.

It is sensitive to changes in temperature. At a higher temperature, the internal energy is greater; the ions vibrate with larger amplitudes. As a result, the electrons collide more frequently with the ions. With less time to accelerate between collisions, they acquire a smaller drift speed, thus, the current is smaller for a given electric field. Therefore, as the temperature of a metal is raised, its resistivity increases.

Mathematical Relation

Let ρ_o is the initial resistivity of a conductor at 0 °C. If we increase the temperature from O°C to t °C, then resistivity will increase and becomes ρ_t. This increase in resistivity is denoted by $\Delta \rho$. The increment in resistivity depends upon the following two factors.

Initial resistivity (ρ_o)

The increase in resistivity is directly proportional to the original resistivity

$$\Delta\rho \propto \rho_o \dashrightarrow 1$$

Difference in temperature ΔT

The increase in resistivity is directly proportional to the temperature difference.

$$\Delta\rho \propto \Delta T \dashrightarrow 2$$

Combining (1) and (2) we get

$$\Delta\rho \propto \rho_o \Delta T$$

$$\Delta\rho = \alpha \rho_o \Delta T$$

Here α is called temperature coefficient of resistance.

It is defined as

It is the increase in resistance per unit resistance per degree rise in temperature.

Its unit is or $°C^{-1}$ or K^{-1}

Since

$$\Delta\rho = \alpha \rho_o \Delta T$$

$$\rho_t - \rho_o = \alpha \rho_o \Delta T$$

$$\rho_t = \rho_o + \alpha \rho_o \Delta T$$

$$\rho_t = \rho_o (1 + \alpha \Delta T)$$

For Semiconductors.

For semiconductors, $\alpha < 0$. A negative temperature coefficient means that the resistivity decreases with increasing temperature. In semiconductors the number of carriers (conduction electrons or holes) per unit volume increases with increasing temperature, with more carriers, the resistivity is smaller

Conductance

Definition.

The measure of how easily flow of charges (electrical current) can pass through a material"

Conductance is the ability of a material to conduct electricity

Conductance is the reciprocal, or invers of resistance.

The greater the resistance, the less the conductance and vice versa.

It is denoted by symbol "K"

Its unit is the mho

The unit of the mho has been replaced by the unit of *Siemens* (abbreviated by the capital letter "S").

Conductivity

Conductivity and is the reciprocal of the resistivity i.e., 1/ρ

It is denoted by Greek letter sigma (σ).

It is measured in siemens per meter (S/m).

Since electrical conductivity $\sigma = 1/\rho$, the previous expression for electrical resistance,

R can be rewritten as a function of conductivity.

$$R = \frac{L}{\sigma A}$$

The electromotive force ε (e.m.f).

Definition.

The total amount of energy (in joules) per unit charge (in coulombs) supplied to the circuit.

Electro-motive force can be expressed as a voltage

$$\varepsilon = E\ Q$$

E= the energy in joules

Q = the charge in coulombs

ε = the electro-motive force

The e.m.f transfers the energy in the entire circuit,

The electrical energy is gained by the e.m.f in the circuit

The electromotive force can be induced in the magnetic, electric fields

The Potential Difference V.

It is the measure of energy between any two points on the circuit.

The potential difference between the   charges is expressed by the formula shown below.

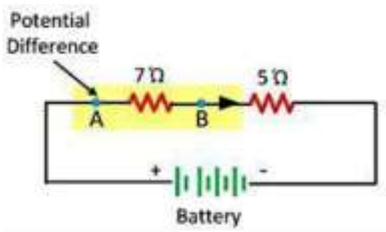
$$\textbf{Potential difference} = \frac{Work}{Charge}$$

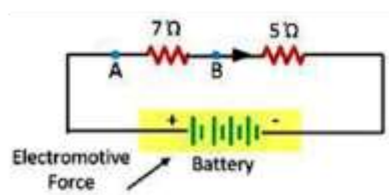
$$V = \frac{E \text{ or } W}{Q}$$

The potential difference is the amount of energy used by the one coulomb of charge

Electrical energy is lost by the potential difference in the circuit.

The potential difference can only be generated in an electric field





Sources of emf:

There must be a source of electromotive force (emf) or voltage for electrons to flow. This emf source can be produced from different primary energy sources. These primary sources supply energy in one form, which is then converted to electric energy. Some Primary sources of electromotive force include:

Light

A solar or photovoltaic cells and solar module or panel converts solar light to electric energy. These are made up of semiconducting, light-sensitive material which makes electrons available when struck by the light energy.

Chemical Reaction

A battery or voltaic cell directly converts chemical energy into electric energy.

It consists of two electrodes and an electrolyte solution. One electrode connects to the (+) or positive terminal (anode), and the other to the (-) or negative terminal (cathode).

Heat

Thermocouple converts heat energy directly into electric energy. When Metal we supplied heat to the hot junction, electrons start moving from one metal to the other. This creates a negative charge on One and a positive charge on the other.

Mechanical Magnetic

An electric generator converts mechanical-magnetic energy into electric energy.

To produce mechanical energy, a generator should be driven by an engine, a turbine or any other machine.

Piezo electric Effect

In this type a substance is used which produces an electric charge when a mechanical pressure is applied. Certain crystals like quartz are piezoelectric in nature.

They generate an electric charge when they are compressed or struck. A common example of piezoelectricity is the piezo gas igniter.

Internal Resistance:

Internal resistance is the opposition to the flow of current within a battery, or other sources of voltage, causing heat generation. Due to this reason a cell becomes hot after a period of time

The effects of Internal resistance of a source of e.m.f on the terminal potential difference:

When a load (external circuit) is connected to the voltage source, current flows through both the load and the internal resistance of the source. The flow of current through the internal resistance causes a voltage drop across it, leading to a reduction in the terminal potential difference compared to the ideal voltage source.

Terminal Potential Difference Vt:

The terminal potential difference Vt is the voltage measured across the terminals of the voltage source when a load is connected.

It is the voltage that is available to the external circuit for doing useful work.

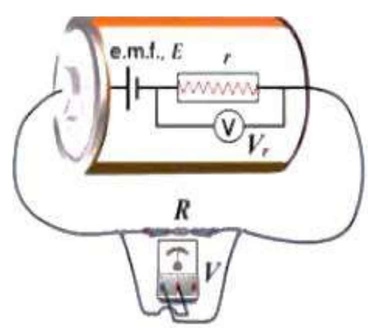
Voltage Drop across Internal Resistance:

As current flows through the internal resistance r of the source, there is a voltage drop across it, given by Ohm's Law:

$$\mathbf{V_{internal} = I\ r}$$

where I is the current flowing through the circuit.

Relationship between emf and terminal potential difference:



Consider a source of EMF connected to a resistance "R" through which a steady current "I" flows as shown in figure

When a battery sends the current in external circuit, some amount of current also flows Internally through battery.

The internal current comes across some internal resistance (r) by the electrolyte.

Thus, battery has to use some its EMF to overcome internal resistance.

Let the

EMF of source = ε	Current in circuit = I	Internal resistance = r
External resistance = R	Total resistance = (R + r)	

Using Ohms Law

$$\mathbf{Current} = \frac{\mathbf{EMF}}{\mathbf{Resistance}}$$

$$\mathbf{I} = \frac{\boldsymbol{\varepsilon}}{\mathbf{R} + \mathbf{r}}$$

$$\mathbf{I}\,(\mathbf{R} + \mathbf{r}) = \boldsymbol{\varepsilon}$$

$$\mathbf{I\,R} + \mathbf{Ir} = \boldsymbol{\varepsilon}$$

$$\mathbf{V} + \mathbf{Ir} = \boldsymbol{\varepsilon}$$

Where V = terminal potential difference

$$\mathbf{V} = \boldsymbol{\varepsilon} - \mathbf{Ir}$$

The terminal potential difference V is reduced from the ideal voltage ε due to the presence of the internal resistance r. The larger the internal resistance, the greater the voltage drop across it, resulting in a more significant reduction in the terminal potential difference.

- If Current Is Supplied from the Source of EMF (E)

  In this condition EMF will be greater than terminal potential difference (E > V)

$$\mathbf{V} = \boldsymbol{\varepsilon} - \mathbf{Ir}$$

- If current Is supplied to the source of EMF (E) i.e. Source Is being charged

  In this condition terminal potential difference will be greater than EMF (V >E)

$$\mathbf{V} = \boldsymbol{\varepsilon} + \mathbf{Ir}$$

- When no current Is drawn from the circuit

  In this condition I = 0 then

$$\mathbf{V} = \boldsymbol{\varepsilon}$$

Consequences internal resistance for external circuits:

Internal resistance affects the performance of emf sources by reducing the potential difference across the external circuit components, which ultimately decreases its ability to supply current and lowers its power output.

- The internal resistance of the battery is difficult to measure directly and can change over time, the analysis of circuits is done with the terminal voltage of the battery,
- The internal resistance of a rechargeable battery increases as the number of times the battery is recharged.
- It increases as a battery is depleted, due to the oxidation of the plates or the reduction of the acidity of the electrolyte
- Internal resistance depends on the magnitude and direction of the current through a voltage source and its temperature

The increased internal resistance may have two effects on the battery.

- The terminal voltage will decrease.
- The battery may overheat due to the increased power dissipated by the internal resistance.

Power Dissipation in Resistors:

Resistors always dissipate power.

"The current flowing through a resistor makes it hot, its power is dissipated by heat".

As the charges Q moves through a resistor, it loses a potential energy

$$W = VQ$$

where V is the potential drop across the resistor.

This energy converted into energy of vibration of the atoms into which the charges (electrons) were bumping and has all been converted into heat. This conversion of potential energy into heat refer to as dissipation.

The power dissipated in a resistor is the energy dissipated per time.

If an amount of charge Δq moves through the resistor in a time Δt, the power loss is

$$\mathbf{Power} = \frac{\mathbf{Work}}{\mathbf{time}}$$

$$\mathbf{P} = \frac{\mathbf{\Delta q\ V}}{\mathbf{\Delta t}}$$

$$\mathbf{P} = \mathbf{V\ I} \qquad \left\{Since\ \ \frac{\Delta q}{\Delta t} = I\right\}$$

Where I is the current through the resistor and Vis the voltage drop across it.

The formula P = I V also gives the power generated by a battery if I is the current coming from the battery and V is its voltage.

From Ohms Law V = I R power may also be shown as,

$$\mathbf{P} = (\mathbf{I\ R})\mathbf{I} = \mathbf{I^2 R}$$

Also, I = V/R

$$\mathbf{P} = \mathbf{V}\left(\frac{\mathbf{V}}{\boldsymbol{R}}\right) = \frac{\mathbf{V^2}}{\mathbf{R}}$$

The SI unit of power is the watt, where 1 watt = 1 joule per second.

Finally, we have 1 watt = 1 ampere x 1 volt

It is a common misconception that Power and Energy/Electricity are same. Interestingly, they have a very different meaning.

- Power is the rate at which electricity is used
- Energy is the actual consumption.

To give an analogy, power is similar to speed but energy is the actual distance travelled.

Power x Time = Energy

The maximum power transfer theorem states that, maximum external power can be obtained from a source, if the resistance of the load is equal to the resistance of the source.

It is called a "matched condition"

Thermoelectricity:

Thermoelectricity is the electricity generated from heat energy.

The conversion of heat energy into electrical energy takes place with the help of a thermocouple.

Thermocouple and its Function

Definition

The thermocouple is used to measure the temperature at one specific point in the form of EMF or an electric current.

Structure

It comprises of two dissimilar metal wires that are connected together at one junction where temperature can be measured.

Principle

The change in temperature of the metal wire stimulates the voltages.

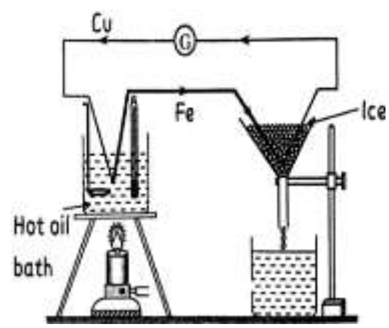
Application

It is useful for signaling electronic systems that control household gas devices, such as water heaters and boilers.

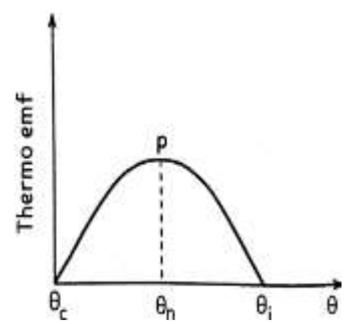
Variation of thermoelectric e.m.f with temperature:

Variation of thermoelectric emf with temperature can be studied using an iron-copper thermocouple as shown in Fig. One junction is dipped in an oil bath and other junction is kept at melting ice (temperature kept constant).

we observe that:



- The galvanometer shows no deflection when the temperature of both junctions is same (0°C), so thermal emf is also zero
- As the temperature of the hot junction is increased gradually, and the cold junction is remains at 0°C, thermo emf also increase till it becomes maximum. Temperature of the hot junction at which the thermo emf becomes maximum is called neutral temperature
- If we increase the temperature of the hot junction beyond neutral temperature, thermo emf starts to decrease and becomes zero and changes its polarity at a temperature called inversion temperature (Ti)
- As the temperature is increased beyond Ti, the direction of thermal emf is reversed. The inversion temperature depends upon the temperature of cold junction and nature of metals used in the thermocouple



The variation of thermal emf with temperature (T) is given by

$$E = \alpha T + \tfrac{1}{2} \beta T^2$$

Where, α and β are constant whose value depends upon material of conductor and the temperature difference of two junctions.

If Tc is the temperature of cold junction, then we can write,

$$T_i - T_n = T_n - T_c \text{ or,}$$

$$2T_n = T_c + T_i$$

Therefore,

$$2T_n = \frac{T_c + T_i}{2}$$

So, the neutral temperature lies between the inversion temperature and temperature of cold junction.

Transistor

Transistor is a miniature semiconductor that regulates or controls current or voltage flow in addition to amplifying and generating these electrical signals and acting as a switch/gate for them

Diode

A diode is a two-terminal electronic component that conducts electricity primarily in one direction

Thermistor:

Thermistor is a resistance whose resistance varies with temperature non linearly it can be used in temperature measurement and control applications.

There are two types of thermistors.

- NTC or Negative Temperature Coefficient:

  Its resistance decreases with temperature rise.
- PTC or Positive Temperature Coefficient:

  It increases its resistance if temperature increases.

Application of thermistor

In Fire Alarm

- Thermistor is a variable resistor whose resistance changes with temperature.
- The resistance of the thermistor decreases with increase in temperature.
- In the fire alarm circuit, the thermistor is connected in series with a variable resistor and a transistor.
- The transistor is connected in such a way that it is turned ON when the resistance of the thermistor decreases.
- When the temperature rises above a certain threshold the resistance of the thermistor decreases, turning ON the transistor.
- This allows current to flow through the buzzer, which produces a beep sound.
- The diode is used to prevent reverse current flow through the transistor.
- The capacitor is used to filter out any noise from the circuit.

Thermostat:

- Thermostat are made up of two Greek words: thermos (heat) and statos (stationary or fixed)
- Thermostats can be used to turn on/off air conditioners, room heaters, and other devices.
- The thermostat circuit consists of a voltage divider circuit and an output “on and off” circuit.
- The voltage divider circuit comprises of a thermistor and a variable resistor.
- The voltage divider circuit output is connected to the base of an NPN transistor through a 1 kΩ resistor.
- The voltage divider circuit makes it possible to sense the variation in voltage caused by variation in resistance of thermistor. ,
- The LED will be switched ON, only if temperature crosses a particular value.

Important Terms

Branch

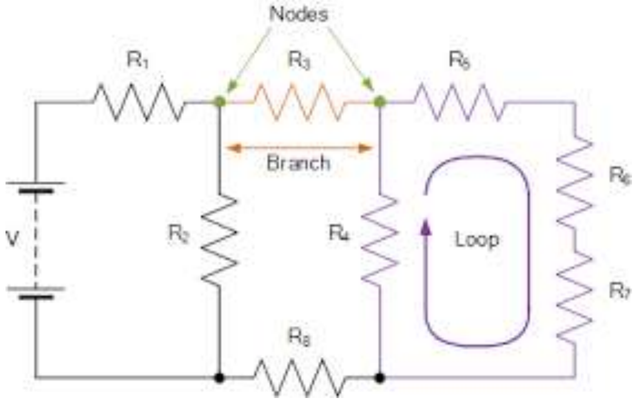
Each of the strength in a circuit is called branch.

Node or Junction

The point at which two branches meet together is called node or junction.

Loop or Mesh

A closed path in a circuit is called loop or mesh.



Kirchhoff's law

Kirchhoff's laws quantify the way in which current flows through a circuit and the voltage varies around a loop in a circuit. These laws help in simplifying the circuits having multiple resistance networks which are usually very time taking to solve through the combination of resistors in series and parallel. Kirchhoff's laws can be applied to solve all types of circuits because they are not limited to specific configurations involving series and parallel connections

Kirchhoff's First Law (Current Law):

Definition

The current that flows into a junction-any electrical connection-must equal the current that flows out of the same junction

Or

The algebraic sum of currents in a network of conductors meeting at a point is zero.

Mathematical Representation

We can write Kirchhoff's first law as an equation:

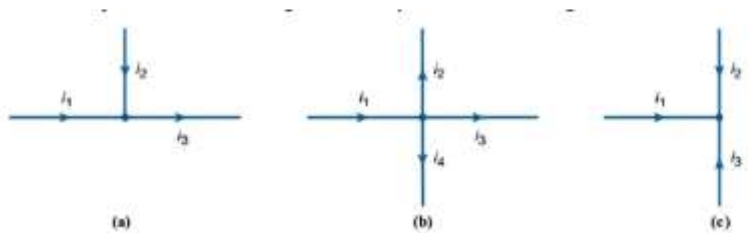
$$\sum I_{In} = \sum I_{out}$$

In figure a, $i_1 + i_2 = i_3$ or $i_1 + i_2 - i_3 = 0$

In figure b, $i_1 + i_2 - i_3 - i_4 = 0$

In figure c, $i_1 + i_2 + i_3 = 0$

Note: The Kirchhoff's Current law is a consequence of the law of conservation of charge



Kirchhoff's Second Law

The second law, known as Kirchhoff's loop rule or Kirchhoff's voltage law (KVL)

Definition

The sum of electromotive forces in a loop equals the sum of potential drops in the loop.

Or

The algebraic sum of Potential difference in a loop in a network is zero.

Equation for Kirchhoff's second law

The Kirchhoff’s second law equation can be written as:

$$\sum E = \sum V$$

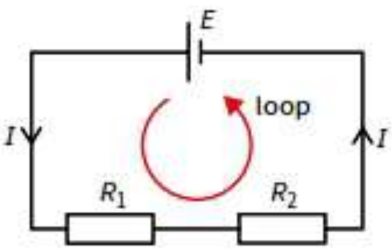
Where $\sum E$ is the sum of the e.m.f. and $\sum V$ is the sum of the potential differences.

We can also write as:

$$\sum V = 0$$

Example

Consider a simple series circuit which contains a cell of emf E and two resistors of resistances R_1 and R_2, the current I must be the same all the way around.



For this circuit, we can write the following equation:

$$E = IR_1 + IR_2$$

e.m.f. of battery= sum of p.d.s across the resistors

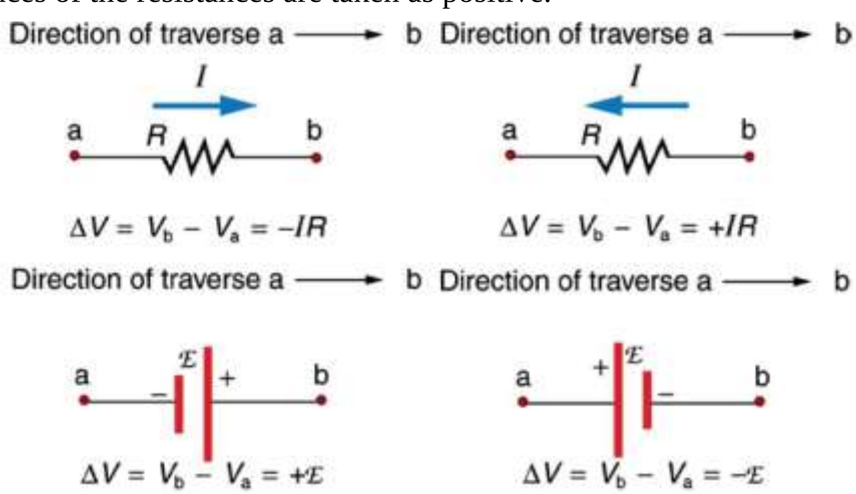
Note: Kirchhoff’s second law is based on the principle of conservation of energy.

When a charge, moves around the circuit, it gains energy as it passes through each source of e.m.f. and loses energy as it moves through each Potential difference (p.d).

Energy gained through sources of e.m.f. = Energy lost through components with p.d.s

Directions and Signs

When the direction of motion is from negative terminal to the positive terminal, the e.m.f of battery is taken as positive. If we move in the opposite direction to the current, then the potential differences of the resistances are taken as positive.

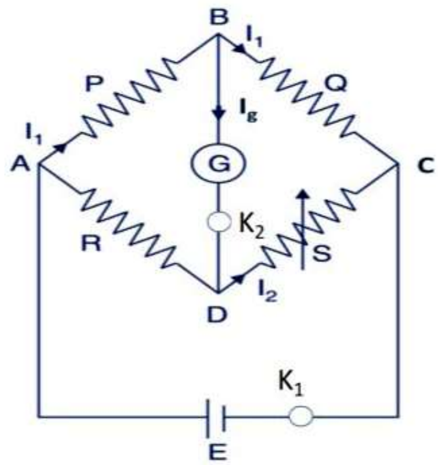


Wheatstone Bridge

Definition

The Wheatstone Bridge also known as the resistance bridge is a diamond shaped circuit which was invented by Samuel Hunter Christie in 1833 and Sir Charles Wheatstone

The Wheatstone bridge circuit gives a very accurate measurement of resistance.



Structure

Wheatstone bridge is a setup with four arms (resistors) connected end to end with each other to form a closed loop ABCDA also called Mesh and a sensitive galvanometer "G" is connected between two opposite junctions B and D through a key. The ratio of two resistances is kept at a fixed value. The two other resistances are balanced, one of which is the unknown resistor whereas the resistance of the other arm can be varied

A wheat-stone bridge consists of four resistances R_1, R_2, R_3 and R_4 K_2, whereas remaining two opposite junctions A and C are connected to voltage source through key K_1 as shown in figure.

Wheatstone Bridge Principle

The Wheatstone bridge works on the principle of null deflection. In normal conditions, current flows through the galvanometer and the bridge is said to be in an unbalanced condition. Adjusting the known resistance and variable resistance a condition is achieved when no current flows through the galvanometer i.e. a balanced condition.

Balanced Wheat-Stone Bridge

A Wheatstone bridge is balanced circuit with zero output voltage.

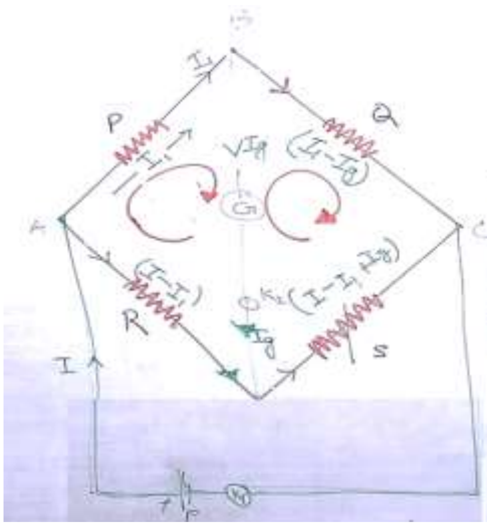
When no current passes through a galvanometer, the bridge circuit is said to be balanced.

Equation of Balanced Wheat-Stone Bridge

$$\frac{\mathbf{P}}{\mathbf{Q}} = \frac{\mathbf{R}}{\boldsymbol{S}}$$

Working of Wheatstone Bridge

Consider four resistance P, Q, R and S are arranged to form a bridge with a cell E and galvanometer of resistance G as shown in figure



One key K_l between the point A and C and tapping key K_2 between the points B and D,

Total current by cell is I, it distributed to P and R as I_1 and I - I_1.

The current through galvanometer is Ig,

Current in Q is I_1- lg and through S current is I - I_1 + Ig,

Closing K_1 first and K_2, if galvanometer shows no deflection, then bridge is balanced i.e. Ig = 0.

According to Kirchhoff's second law (KVL)

The algebraic sum of Potential difference in a loop in a network is zero.

If we apply Kirchhoff's 2nd law in loop ABDA, we get

$$\mathbf{I_1 P} + \mathbf{lg\,G} - (\mathbf{l} - \mathbf{I_1})\,\mathbf{R} = \mathbf{0}$$

If value of R is such that the bridge is balanced Ig = 0

$$\mathbf{I_1 P - (l - I_1)\, R = 0}$$

$$\mathbf{I_1 P = (l - I_1) R \; - - - - (i)}$$

Now apply Kirchhoff's 2nd law in BCDB, we get

$$\mathbf{(I_1 - Ig)\, Q - (l - I_1 + lg\,)\, S - \; IgG \; = 0}$$

Putting Ig = 0

$$\mathbf{I_1\, Q - (l - I_1\,)\, S = 0}$$

$$\mathbf{I_1 Q = (l - I_1\,)\, S \; - - - - (ii)}$$

Dividing (i) by (ii)

$$\frac{\mathbf{I_1 P}}{\mathbf{I_1 Q}} = \frac{\mathbf{(I - \; I_1) R}}{\mathbf{(I - \; I_1) S}}$$

$$\frac{\mathbf{P}}{\mathbf{Q}} = \frac{\mathbf{R}}{\mathbf{S}}$$

Applications of Wheatstone Bridge

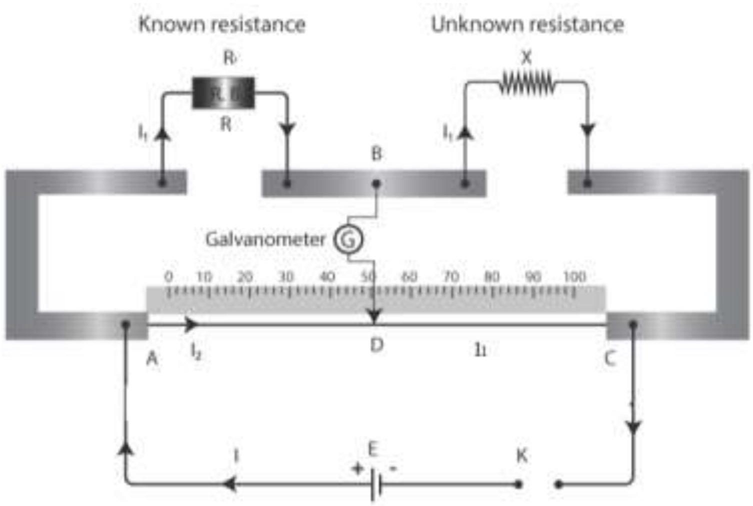
The Wheatstone bridge circuit gives a very accurate measurement of resistance.

Meter bridge, Carey Foster bridge, Wien bridge and many other instruments are based on the Wheatstone bridge principle.

Meter Bridge

A meter bridge is an instrument used to find the unknown resistance of a conductor andt works on the principle of a Wheatstone bridge.

A meter bridge also called a slide wire bridge



It consists of one meter long wire, a known resistance R and unknown resistance X. The length of the wire acts as two resistances. A null point is determined on the wire, which splits the wire into two resistances L_1 an L_2

Equation of Meter Bridge

$$\frac{\mathbf{X}}{\mathbf{R}} = \frac{\mathbf{L_1}}{\mathbf{L_2}}$$

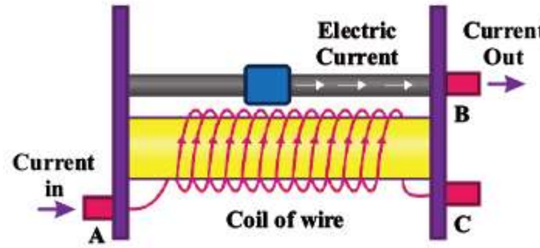
L_1 = length of wire along unknown resistance (X)

L_2 = length of wire along known resistance (R)

Rheostat

Rheostat is a variable resistor, used for controlling the flow of electric current by increasing or decreasing the resistance.

The term rheostat is derived from the Greek word "rheos" and "statis" which means current controlling device.



Working of rheostat as a potential divider

A potential divider is used for getting a variable potential from a fixed potential difference.

A rheostat acts as a potential divider when connected in series with a fixed resistor between a voltage source and ground. By adjusting the position of the rheostat's wiper along its resistive element, the output voltage across the wiper can be varied proportionally to the ratio of the rheostat's resistance to the total resistance in the circuit

Potentiometer

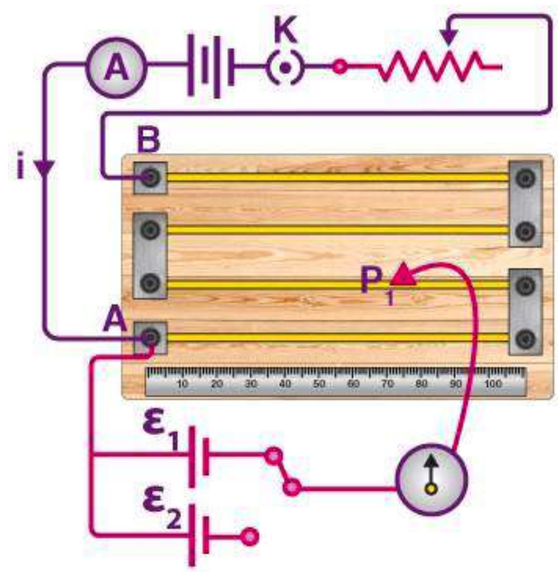
A potential meter is a device used for comparing two potential differences or determining an unknown potential difference.

Principle of Potentiometer:

The potential difference across any two points of a wire is directly proportional to the length of the wire, which has a uniform cross-sectional area and the constant current flowing through it.

Structure.

It consists of a long uniform wire, a sliding contact (wiper), and two fixed terminals. A voltage source is connected between the two ends. the sliding contact allows for precise adjustment of the voltage division ratio for measurement or comparison purposes.



Function of Potentiometer

A potentiometer functions as a voltage measurement and comparison device without drawing any current from the circuit by utilizing a principle of null detection. By adjusting the position of a sliding contact along a resistive element, the potentiometer balances the unknown voltage against a known reference voltage until the null point is reached, indicated by zero current flowing through the circuit, allowing for precise measurement and comparison of potentials

Equation of Potentiometer

$$\frac{E_1}{E_2} = \frac{L_1}{L_2}$$

L_1 = length of wire for E_1

L_2 = length of wire for E_2