Unit-I

Electrical Circuits

Introduction

1. Electric charge(Q)

In all atoms there exists number of electrons which are very loosely bounded to its nucleus. Such electrons are free to wander when specific forces are applied. If any of these electrons is removed, the atom becomes positively charged. And if excess electrons are added to the atom it becomes positively charged.

The total deficiency or addition of electrons in an atom is called its charge. A charged atom is called **Ion**. An element containing a number of ionized atoms is said to be charged. And accordingly the element consisting of that atom is said to be positively or negatively charged.

Particle	Electric charge possessed by particle of one number (C)	Atomic charge
Protons	+1.6022X 10^{-19}	+1
Neutrons	0	0
Electrons	1.6022X 10^{-19}	-1

The unit of measurement of charge is **Coulomb** (C). It can be defined as the charge possessed by number of electrons.

Hence if an element has a positive charge of one coulomb then that element has a deficiency of number of electrons.

Conductors:

The atoms of different materials differ in the number of electrons, protons and neutrons, which they contain. They also differ in how tightly the electrons in the outer orbit are bound to the nucleus. The electrons, which are loosely bound to their nuclei, are called **free electrons.** These free electrons may be dislodged from an atom by giving them additional energy. Thus they may be transferred from one atom to another. The electrical properties of materials largely depend upon the number of free electrons available.

A **conductor** is a material in which large number of free electrons is available. Thus current can flow easily through a conductor. All materials with resistivity less than 10^{-3} Ωm come under the category of conductors. Almost all metals are conductors.

Silver, copper Aluminum, carbon is some examples of conductors. Copper and Aluminum conductors are widely used in practice.

Insulators

Insulators are materials in which the outer electrons are tightly bound to the nucleus. It is very difficult to take out the electrons from their orbits. Consequently, current cannot flow through them. All materials with resistivity above 10^5 Ωm fall in the category of insulators.

Examples of insulators are mica, paper, glass, porcelain, rubber, oil and plastics.

Semiconductors

In some materials, the electrons in the outer orbits are normally held by the nucleus, but can be taken out by some means. These materials are called **semiconductors.**

Materials such as germanium and silicon are examples of semiconductors. The addition of slight traces of impurity to silicon or germanium can free the electrons. The semiconductors have resistivity between 10^{-3} and 10^5 Ωm.

Current(I)

An electric current is the movement of electric charges along a definite path. In case of a conductor the moving charges are electrons.

The unit of current in the International system of Units is the ***ampere (A)***.

The ampere is defined as that current which when flowing in two infinitely long parallel conductors of negligible cross-section, situated 1 meter apart in vacuum, produces between the conductors a force of 2×10^{-7} Newton per meter length.

Voltage(V)

Energy is required for the movement of charge from one point to another. Let W joules of energy be required to move positive charge of Q coulombs from *a* point a to *b* in a circuit. We say that a voltage exists between the two points.

The voltage across two terminals is a measure of the work required to move charge through the element. The unit of voltage is the volt, and 1 volt is the same as 1 J/C. Voltage is represented by V or *v*.

The voltage V between two points may be defined in terms of energy that would be required if a charge were transferred from one point to the other. A voltage can exist between the two electrical terminals whether a current is flowing or not.

Voltage between *a* and *b* is given by

$$V = \frac{W}{Q} (J / C)$$

Electromotive Force (EMF)

The emf represents the driving influence that causes a current to flow, and may be interpreted to represent the energy that is used during passing of a unit charge through the source. The term emf is always associated with energy conversion. The emf is usually represented by the symbol E and has the unit **VOLT**

If W = energy imparted by the voltage source in joules (J)
Q = charge transferred through the source in coulombs ©
E = e.m.f. of the source

Then

$$E = \frac{W}{Q} (J / C)$$

Potential Difference:

The potential difference (p.d.) between two points is the energy required to move one coulomb of charge from one to the other.

If : W = energy required to transfer the charge
Q = charge transferred between the points
V = potential difference

Then

$$V = \frac{W}{Q}(J/C)$$

Electric Power

Power is the rate at which work is done. Work is done whenever a force causes motion. If a mechanical force is applied to lift or move a weight, work is done. We know that voltage is an electric force and it forces current to flow in a circuit. When voltage causes current flow (electrons to move), work is done.

The rate at which is work is done is called electric power and is measured in **watts**.

$$P = \frac{W}{t}(J/s)$$

Basic Circuit Components

Resistor, inductor, and capacitor are the three basic components of a network. A resistor is an element that dissipates energy as heat when current passes through it. An inductor stores energy by virtue of a current through it. A capacitor stores energy by virtue of a voltage existing across it.

Resistance

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

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

- Denoted by **R**
- Unit is **Ohms(Ω)**
- Symbol :

Unit of resistance: The practical unit of resistance is ohm and is represented by the symbol Ω. It is defined as under:

A wire is said to have a resistance of **1 ohm** *if a p.d. of 1 volt across its ends causes 1 ampere of current to flow through it.*

Factors upon which Resistance Depends:

The resistance R of a conductor

(i) is directly proportional to its length (l)
(ii) is inversely proportional to its area of cross-section (a)
(iii) Depends upon the nature of material.
(iv) Changes with temperature.

From the first three points (leaving temperature for the time being), we have,

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

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

Material	Resistivity ρ (ohm m)
Copper	$1.68\text{x}10^{-8}$
Aluminum	$2.65\text{x}10^{-8}$
Tungsten	$5.60\text{x}10^{-8}$

Conductance:

Conductance (G) is the reciprocal of resistance.

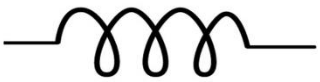
We know $G = \frac{1}{R} = \frac{1}{\rho}\frac{A}{l}$ **or** $G = \sigma \frac{A}{l}$

Where σ (Greek letter 'sigma') is called the conductivity or specific conductance of the material. The unit of conductance is mho.

Inductors

The electrical element that stores energy in association with a flow of current is called *inductor* . The idealized circuit model for the inductor is called an *inductance.* Practical inductors are made of many turns of thin wire wound on a magnetic core or an air core. A unique feature of the inductance is that its presence in a circuit is felt only when there is a changing current. Fig below shows a schematic representation of an inductor.

- Denoted as L.
- Units: Henry (H).
- Symbol



Schematic representation of an inductor

For the ideal circuit model of an inductor, the voltage across it is proportional to the rate of change of current in it. Thus if the rate of change of current is di/dt and *v* is the induced voltage, then

$$v \ \alpha \ \frac{di}{dt} \quad \text{or} \quad v = L\frac{di}{dt} \text{ volt} \qquad \text{(Eq – 1)}$$

In the above equation proportionality constant L is called inductance. The unit of inductance is Henry, named after the American physicist Joseph Henry. Equation may be rewritten as

$$L = \frac{v}{\frac{di}{dt}} = \frac{volt - second}{ampere} \quad \text{or Henrys (H)} \qquad \text{(Eq – 2)}$$

If an inductor induces a voltage of 1 V when the current is uniformly varying at the rate of 1 A/sec, it is said to have an inductance of 1 H. Integrating Eq – 1 with respect to time t,

$$i = \frac{1}{L}\int_0^t v\,dt + i(0) \qquad \text{(Eq –3)}$$

Where $i(0)$ is the current at t = 0. From Eq – 3 it may be inferred that the current in an inductor cannot change suddenly in zero time.

Instantaneous power p entering the inductor at any instant is given by

$$p = vi = Li\frac{di}{dt} \qquad \text{(Eq – 4)}$$

When the current is constant, the derivative is zero and no additional energy is stored in the inductor. When the current increases, the derivative is positive and hence the power is positive; and, in turn, an additional energy is stored in the inductor. The energy stored in the inductor, W_L, is given by

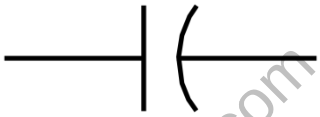
$$W_L = \int_0^t vi\,dt = \int_0^t Li\frac{di}{dt}dt = L\int_0^t i\,di = \frac{1}{2}Li^2 \text{ Joule} \qquad \text{(Eq – 5)}$$

Eq – 5 assumes that the inductor has no previous history, that is, at $t = 0, i = 0$. the energy is stored in the inductor in a magnetic field. When the current increases, the stored energy is the magnetic field also increases. When the current reduces to zero, the energy stored in the inductor is returned to the source from which it receives the energy.

Capacitors:

A *capacitor* is a device that can store energy in the form of a charge separation when it is suitably polarized by an electric field by applying a voltage across it. In the simplest form, a capacitor consists of two parallel conducting plates separated by air or any insulating material, such as mica. It has the characteristic of storing electric energy (charge), which can be fully retrieved, in an electric field. A significant feature of the capacitor is that its presence is felt in an electric circuit when a changing potential difference exists across the capacitor. The presence of an insulating material between the conducting plates does not allow the flow of dc current; thus a capacitor acts as an open circuit in the presence of dc current.

- Denoted as C
- Unit is Farad (F).
- Symbol



(Schematic representation of a capacitor.)

The ability of the capacitor is store charge is measured in terms of capacitance C. *Capacitance* of a capacitor is defined as charge stored per volt applied and its unit is farad (F). However, for practical purposes the unit of farad is too large. Hence, microfarad (μ F) is used to specify the capacitance of the components and circuits.

If the charge on the capacitor at any time t after the switch S is closed in q coulombs and the voltage across it is v volts. Then by definition

$$\boxed{C = \frac{q}{v}} \text{ coulomb} \qquad \text{(Eq – 6)}$$

Current i flowing through the capacitor can be obtained as

$$\boxed{i = \frac{dq}{dt} = C\frac{dv}{dt}} \text{ Ampere} \qquad \text{(Eq – 7)}$$

Eq – 7 is integrated with respect to time to get the voltage across the capacitor as

$$\boxed{v = \frac{1}{C}\int_0^t idt + v(0)} \qquad \text{(Eq – 8)}$$

Where $v(0)$ denotes the initial voltage across the capacitor at t = 0.

Power p in the capacitor is given as

$$p = vi = Cv\frac{dv}{dt} \text{ Watts} \qquad \text{(Eq – 9)}$$

Energy stored in capacitor, W_C, is given by

$$W_C = \int p\ dt = C\int v\ dv = \frac{1}{2}Cv^2 \text{ joule} \qquad \text{(Eq – 10)}$$

Capacitance of a capacitor depends on its dimensions :

A capacitor consists of two electrodes (plates) separated by a insulating material (dielectric). If the area of the plate in A m^2 and the distance between them is d m, it is observed that

$$C \ \alpha \ A \quad \text{and} \quad C \ \alpha \ \frac{1}{d}$$

$$\therefore \quad C = \frac{\varepsilon A}{d} \qquad \text{(Eq – 11)}$$

Where ε is the absolute permittivity constant. The absolute permittivity constant depends on the type of dielectric employed in the capacitor. The ratio of the absolute permittivity constant of the dielectric ε to the permittivity constant of vacuum ε_0 is called relative permittivity ε_r, that is,

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

Hence,

$$\varepsilon = \varepsilon_0 \varepsilon_r$$

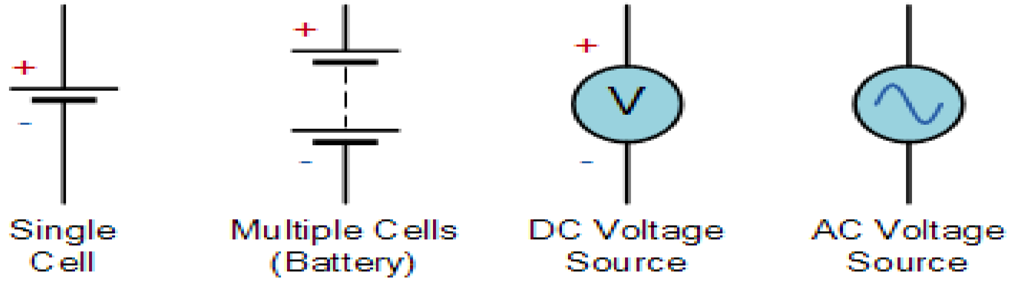
The units for absolute permittivity ε can be established from Eq.11 as under:

$$\varepsilon = \frac{C(farads) \times d(meters)}{A(meters)^2} = \frac{C \times d}{A} \ (farads/metre(F/m))$$

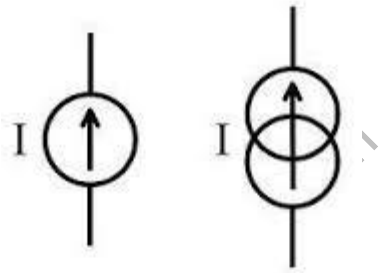
Based on experimental results, the value of the permittivity constant of vacuum has been found to be equal to 8.85 × 10^{-12} F/m. Therefore, the value of ε_r for vacuum is 1.0 and for air is 1.0006. For practical purposes, the value of ε_r for air is also taken as 1.

VOLTAGE SOURCE

It is a two terminal device which can maintain a fixed voltage. An ideal voltage source can maintain the fixed voltage independent of the load resistance or the output current. However, a real-world voltage source cannot supply unlimited current. A voltage source is the dual of a current source. Real-world sources of electrical energy, such as batteries, generators, and power systems, can be modeled for analysis purposes as a combination of an ideal voltage source.



CURRENT SOURCE -is an electronic circuit that delivers or absorbs an electric current which is independent of the voltage across it. A current source is the dual of a voltage source.The term constant-current 'sink' is sometimes used for sources fed from a negative voltage supply. Figure 1 shows the schematic symbol for an ideal current source, driving a resistor load There are two types - an independent current source (or sink) delivers a constant current. A dependent current source delivers a current which is proportional to some other voltage or current in the circuit.



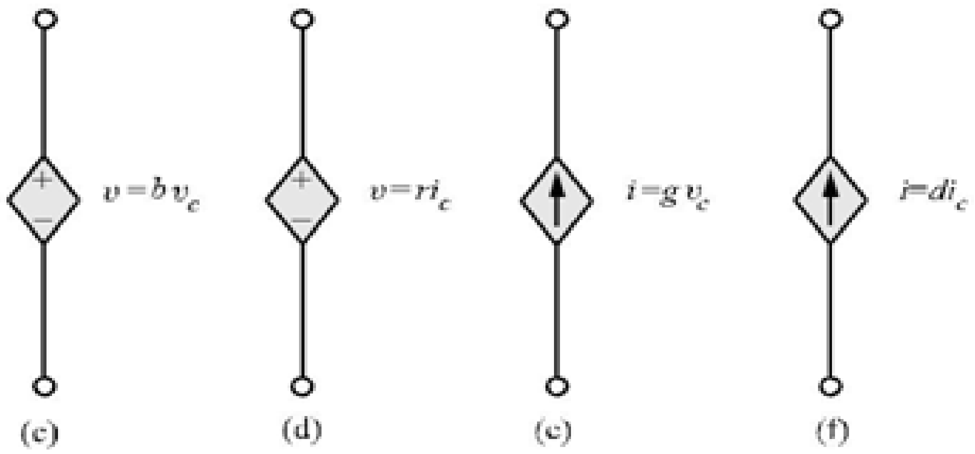
Independent Sources -The ideal voltage source and ideal current source discussed here come under the category of *independent sources*. The independent source is one which does not depend on any other quantity in the circuit. It has a constant value i.e., the strength of voltage or current is not changed by any variation in the connected circuit. Thus, the voltage or current is fixed and is not adjustable.

Dependent Sources: The source whose output voltage or current is not fixed but depends on the voltage or current in another part of the circuit is called as dependent or controlled source.

The dependent source is basically a three terminal device. The three terminals are paired with one common terminal. One pair is referred as input while the other pair as output. For example, in a transistor, the output voltage depends upon the input voltage. The dependent sources are represented by diamond shaped box as shown in Fig.

The dependent sources can be categorized as:

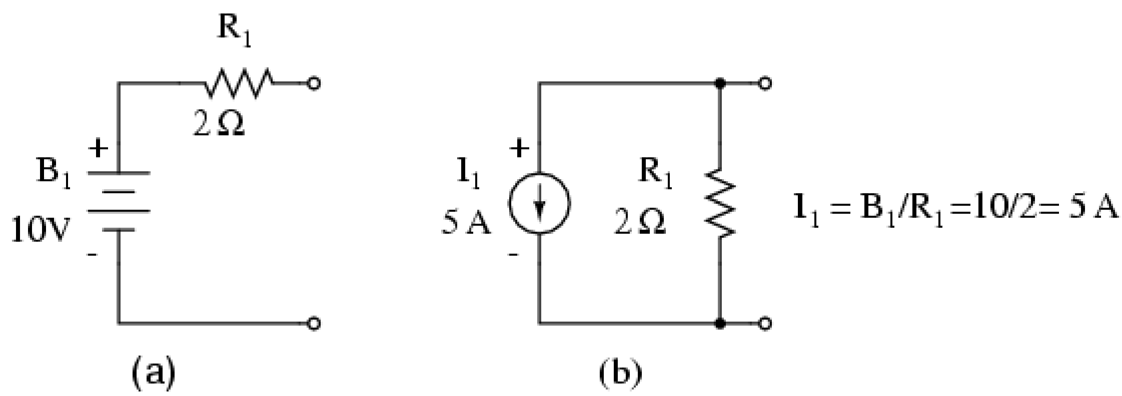
c. Voltage dependent voltage source
d. Current dependent voltage source
e. Voltage dependent current source
f. Current dependent current source



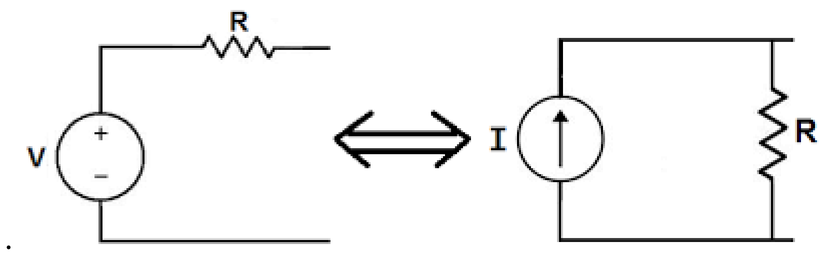
SOURCE CONVERSION

It is most important part of the circuit analysis. To simplify the circuit, certain rules have been framed which are given below:

(a) A voltage source having some resistance can be replaced by the current source in parallel with the resistance as shown in Fig.



(b) A current source in parallel with some resistance can be replaced by a voltage source in series with the same resistance as shown in fig.



<u>Ohms Law</u>

The relationship between Voltage, Current and Resistance in any DC electrical circuit was firstly discovered by the German physicist **Georg Ohm**.**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.

Ohms Law Relationship

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

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 x R](volts) = I (amps) x R (Ω)

To find the Current, (I)

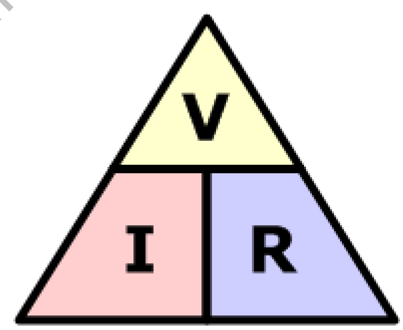
[$I = \frac{V}{R}$] I (amps) = V (volts) ÷ R (Ω)

To find the Resistance, (R)

[$R = \frac{V}{I}$] R (Ω) = V (volts) ÷ I (amps)

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.

Ohms Law Triangle



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

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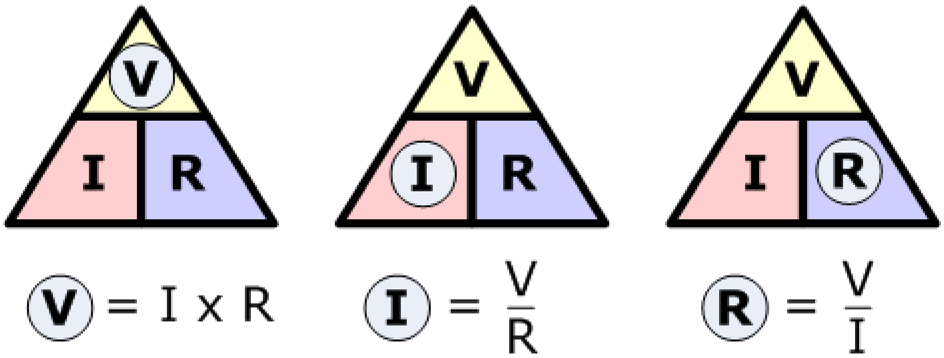
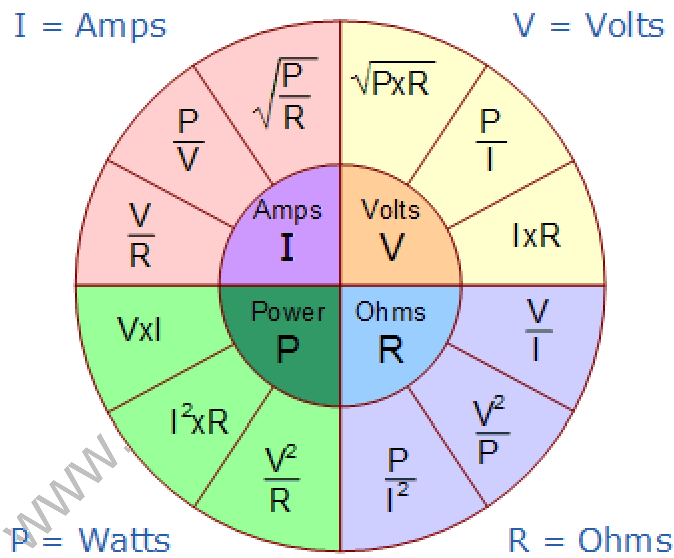


Then by using Ohms Law we can see that a voltage of 1V applied to a resistor of 1Ω will cause a current of 1A to flow and the greater the resistance value, the less current that will flow for a given applied voltage. Any Electrical device or component that obeys "Ohms Law" that is, the current flowing through it is proportional to the voltage across it (I α V), such as resistors or cables, are said to be**"Ohmic"** in nature, and devices that do not, such as transistors or diodes, are said to be **"Non-ohmic"** devices.

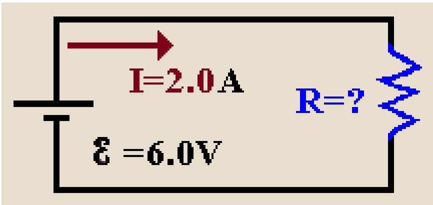
Ohms Law Pie Chart



Ohms Law Matrix Table

Ohms Law Formulas				
Known Values	Resistance (R)	Current (I)	Voltage (V)	Power (P)
Current & Resistance	---	---	$V = I \times R$	$P = I^2 \times R$
Voltage & Current	$R = \frac{V}{I}$	---	---	$P = V \times I$
Power & Current	$R = \frac{P}{I^2}$	---	$V = \frac{P}{I}$	---
Voltage & Resistance	---	$I = \frac{V}{R}$	---	$P = \frac{V^2}{R}$
Power & Resistance	---	$I = \sqrt{\frac{P}{R}}$	$V = \sqrt{P \times R}$	---
Voltage & Power	$R = \frac{V^2}{P}$	$I = \frac{P}{V}$	---	---

Question 1:
An emf source of 6.0V is connected to a purely resistive lamp and a current of 2.0 amperes flows. All the wires are resistance-free. What is the resistance of the lamp?



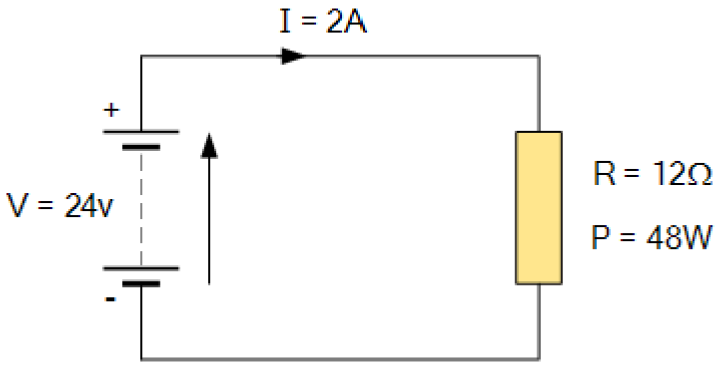
Solution: The gain of potential energy occurs as a charge passes through the battery, that is, it gains a potential of E =6.0V. No energy is lost to the wires, since they are assumed to be resistance-free. By conservation of energy, the potential that was gained (i.e. =V=6.0V) must be lost in the resistor. So, by Ohm's Law:

$$V = I R$$

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

$$R = 3.0\ \Omega$$

Problem 2: For the circuit shown below find the Voltage (V), the Current (I), the Resistance (R) and the Power (P).



Voltage [V = I x R] = 2 x 12Ω = 24V

Current [I = V ÷ R] = 24 ÷ 12Ω = 2A

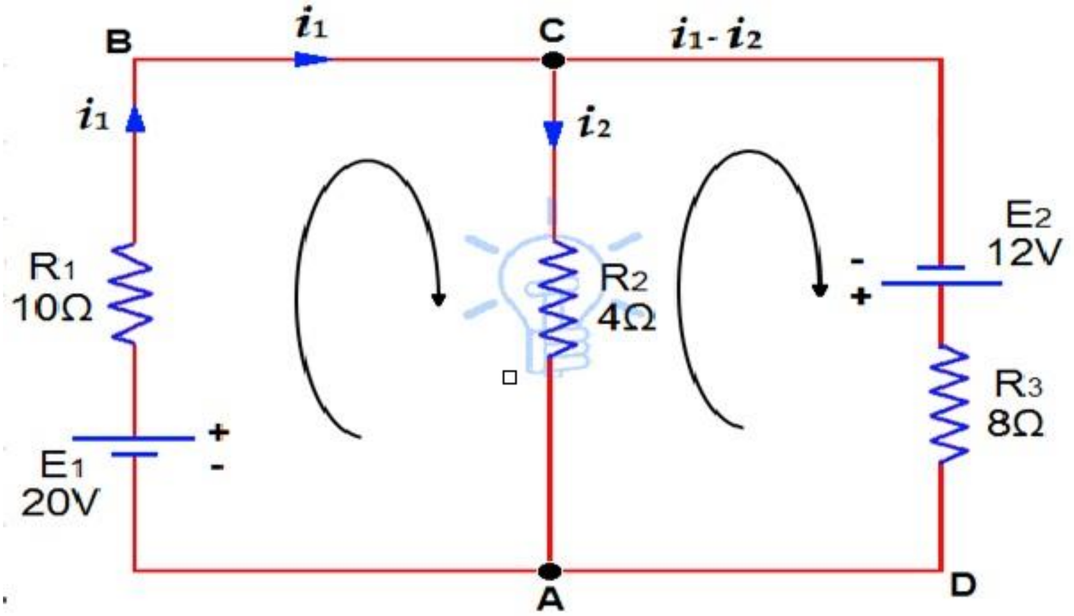
Resistance [R = V ÷ I] = 24 ÷ 2 = 12 Ω

Power [P = V x I] = 24 x 2 = 48W

Power within an electrical circuit is only present when **BOTH** voltage and current are present. For example, in an open-circuit condition, voltage is present but there is no current flow I = 0 (zero), therefore V x 0 is 0 so the power dissipated within the circuit must also be 0. Likewise, if we have a short-circuit condition, current flow is present but there is no voltage V = 0, therefore 0 x I = 0 so again the power dissipated within the circuit is 0.

As electrical power is the product of V x I, the power dissipated in a circuit is the same whether the circuit contains high voltage and low current or low voltage and high current flow. Generally, electrical power is dissipated in the form of **Heat** (heaters), **Mechanical Work** such as motors, **Energy**in the form of radiated (Lamps) or as stored energy (Batteries).

Problem 1: Resistors of R_1= 10Ω, R_2 = 4Ω and R_3 = 8Ω are connected up to two batteries (of negligible resistance) as shown. Find the current through each resistor.



Solution:

Assume currents to flow in directions indicated by arrows.

Apply KCL on Junctions C and A.

Therefore, current in mesh ABC $= i_1$

Current in Mesh CA $= i_2$

Then current in Mesh CDA $= i_1 - i_2$

Now, Apply KVL on Mesh ABC, 20V are acting in clockwise direction. Equating the sum of IR products, we get;

$10i_1 + 4i_2 = 20$ …………… (1)

In mesh ACD, 12 volts are acting in clockwise direction, then:

$8(i_1 - i_2) - 4i_2 = 12$

$8i_1 - 8i_2 - 4i_2 = 12$

$8i_1 - 12i_2 = 12$ …………… (2)

Multiplying equation (1) by 3;

$30i_1 + 12i_2 = 60$

Solving for i_1

$30i_1 + 12i_2 = 60$

$8i_1 - 12i_2 = 12$

$38i_1 = 72$

The above equation can be also simplified by Elimination or Cramer's Rule.

$i_1 = 72/38 =$ **1.895 Amperes** = Current in 10 Ohms resistor

Substituting this value in (1), we get:

$10(1.895) + 4i_2 = 20$

$4i_2 = 20 - 18.95$

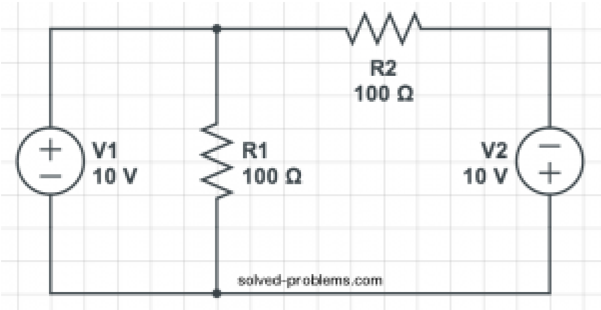
$i_2 =$ **0.263 Amperes** = Current in 4 Ohms Resistors.

Now,

$$i_1 - i_2 = 1.895 - 0.263 = \mathbf{1.632\ Amperes}$$

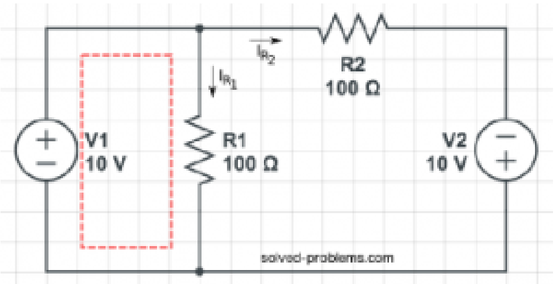
Problem: 2

Find resistor currents using KVL.



Solution:

R_1 and V_1 are parallel. So the voltage across R_1 is equal to V_1 . This can be also calculated using KVL in the left hand side loop:

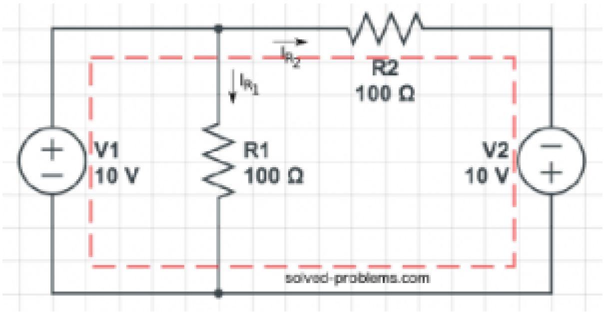


$-V_1 + V_{R_1} = 0 \rightarrow V_{R_1} = V_1 = 10V$.

Now, use Ohm's law to find I_{R_1} :

$V_{R_1} = R_1 \times I_{R_1} \rightarrow I_{R_1} = \frac{V_{R_1}}{R_1} = 0.1A$.

To find I_{R_2} , write KVL around the outer loop:



$-V_1 + V_{R_2} - V_2 = 0 \rightarrow V_{R_2} = V_1 + V_2 = 20V$.

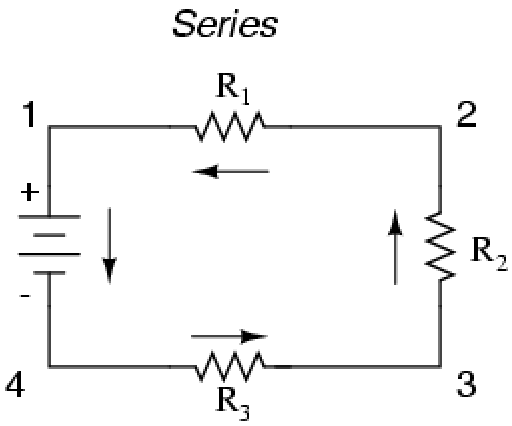
Again, use Ohm's law to determine I_{R_2} :

$$V_{R_2} = R_2 \times I_{R_2} \rightarrow I_{R_2} = \frac{V_{R_2}}{R_2} = 0.2A \, .$$

Series and Parallel Circuits

Circuits consisting of just one battery and one load resistance are very simple to analyze, but they are not often found in practical applications. Usually, we find circuits where more than two components are connected together.

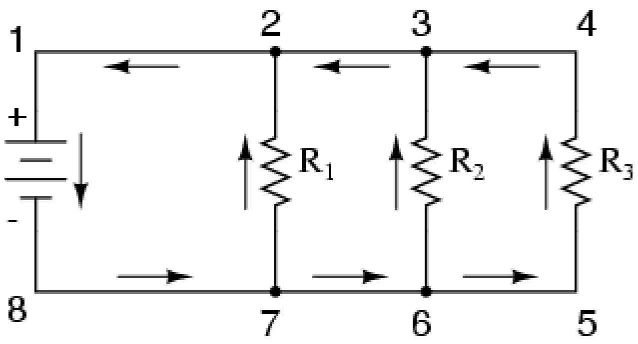
There are two basic ways in which to connect more than two circuit components: *series* and *parallel*. First, an example of a series circuit:



Here, we have three resistors (labeled R_1, R_2, and R_3), connected in a long chain from one terminal of the battery to the other. (It should be noted that the subscript labeling—those little numbers to the lower-right of the letter "R"—are unrelated to the resistor values in ohms. They serve only to identify one resistor from another.) The defining characteristic of a series circuit is that there is only one path for electrons to flow. In this circuit the electrons flow in a counter-clockwise direction, from point 4 to point 3 to point 2 to point 1 and back around to 4.

Now, let's look at the other type of circuit, a parallel configuration:

Parallel

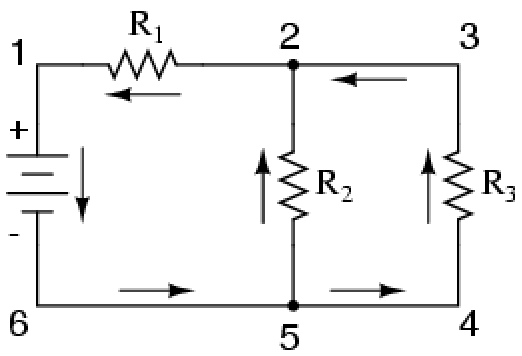


Again, we have three resistors, but this time they form more than one continuous path for electrons to flow. There's one path from 8 to 7 to 2 to 1 and back to 8 again. There's another from 8 to 7 to 6 to 3 to 2 to 1 and back to 8 again. And then there's a third path from 8 to 7 to 6 to 5 to 4 to 3 to 2 to 1 and back to 8 again. Each individual path (through R_1, R_2, and R_3) is called a *branch*.

The defining characteristic of a parallel circuit is that all components are connected between the same set of electrically common points. Looking at the schematic diagram, we see that points 1, 2, 3, and 4 are all electrically common. So are points 8, 7, 6, and 5. Note that all resistors as well as the battery are connected between these two sets of points.

And, of course, the complexity doesn't stop at simple series and parallel either! We can have circuits that are a combination of series and parallel, too:

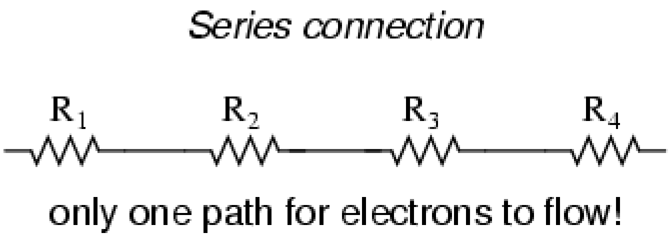
Series-parallel



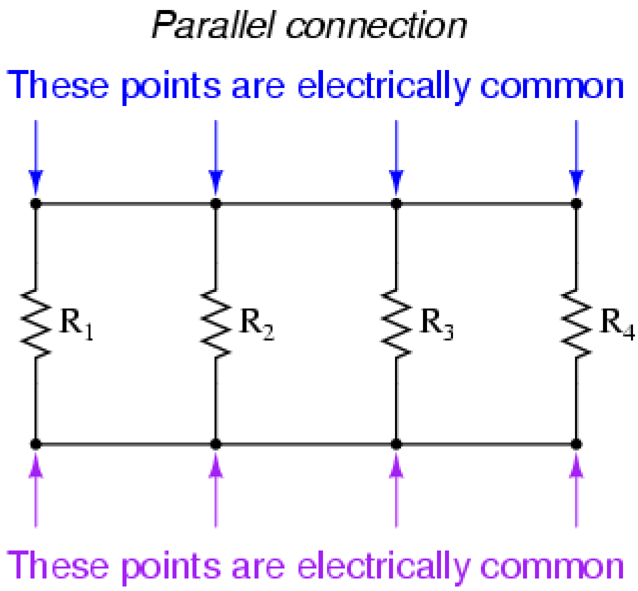
In this circuit, we have two loops for electrons to flow through: one from 6 to 5 to 2 to 1 and back to 6 again, and another from 6 to 5 to 4 to 3 to 2 to 1 and back to 6 again. Notice how both current paths go through R_1 (from point 2 to point 1). In this configuration, we'd say that R_2 and R_3 are in parallel with each other, while R_1 is in series with the parallel combination of R_2 and R_3.

This is just a preview of things to come. Don't worry! We'll explore all these circuit configurations in detail, one at a time!

The basic idea of a "series" connection is that components are connected end-to-end in a line to form a single path for electrons to flow:



The basic idea of a "parallel" connection, on the other hand, is that all components are connected across each other's leads. In a purely parallel circuit, there are never more than two sets of electrically common points, no matter how many components are connected. There are many paths for electrons to flow, but only one voltage across all components:

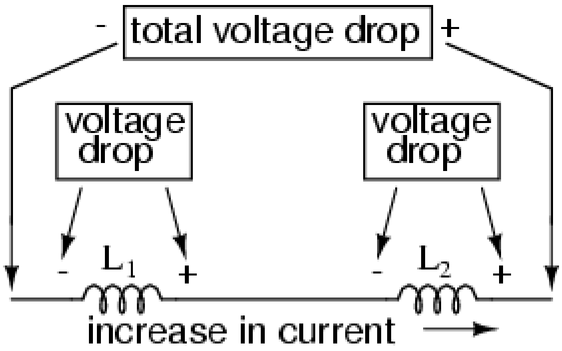


Series and parallel resistor configurations have very different electrical properties. We'll explore the properties of each configuration in the sections to come.

- **REVIEW:**
- In a series circuit, all components are connected end-to-end, forming a single path for electrons to flow.
- In a parallel circuit, all components are connected across each other, forming exactly two sets of electrically common points.
- A "branch" in a parallel circuit is a path for electric current formed by one of the load components (such as a resistor).

Inductors in Series and Parallel:

When inductors are connected in series, the total inductance is the sum of the individual inductors' inductances. To understand why this is so, consider the following: the definitive measure of inductance is the amount of voltage dropped across an inductor for a given rate of current change through it. If inductors are connected together in series (thus sharing the same current, and seeing the same rate of change in current), then the total voltage dropped as the result of a change in current will be additive with each inductor, creating a greater total voltage than either of the individual inductors alone. Greater voltage for the same rate of change in current means greater inductance.

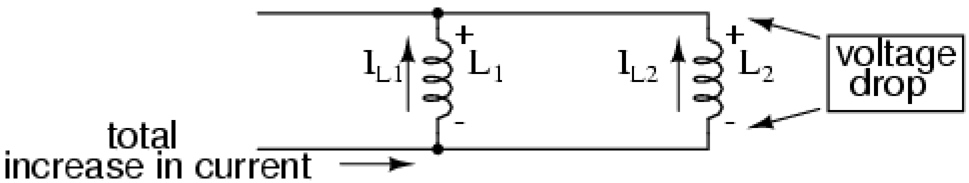


Thus, the total inductance for series inductors is more than any one of the individual inductors' inductances. The formula for calculating the series total inductance is the same form as for calculating series resistances:

Series Inductances

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

When inductors are connected in parallel, the total inductance is less than any one of the parallel inductors' inductances. Again, remember that the definitive measure of inductance is the amount of voltage dropped across an inductor for a given rate of current change through it. Since the current through each parallel inductor will be a fraction of the total current, and the voltage across each parallel inductor will be equal, a change in total current will result in less voltage dropped across the parallel array than for any one of the inductors considered separately. In other words, there will be less voltage dropped across parallel inductors for a given rate of change in current than for any of those inductors considered separately, because total current divides among parallel branches. Less voltage for the same rate of change in current means less inductance.



Thus, the total inductance is less than any one of the individual inductors' inductances. The formula for calculating the parallel total inductance is the same form as for calculating parallel resistances:

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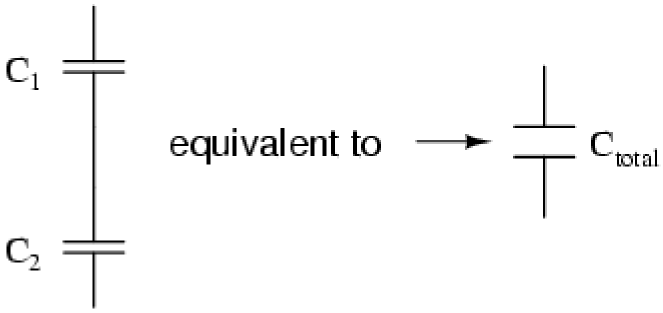
Parallel Inductances

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

Capacitors in series and parallel:

When capacitors are connected in series, the total capacitance is less than any one of the series capacitors' individual capacitances. If two or more capacitors are connected in series, the overall effect is that of a single (equivalent) capacitor having the sum total of the plate spacings of the individual capacitors. As we've just seen, an increase in plate spacing, with all other factors unchanged, results in decreased capacitance.

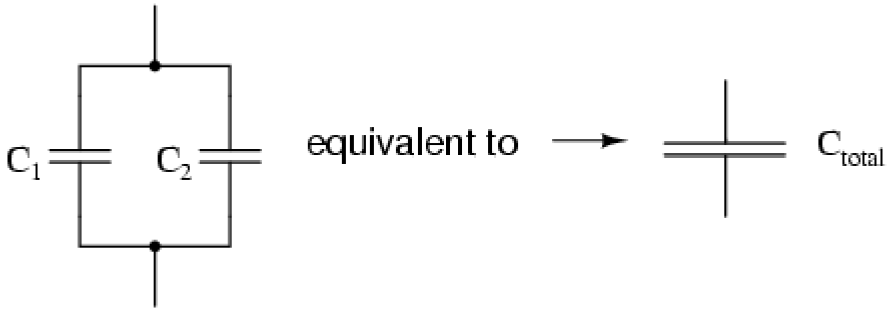


Thus, the total capacitance is less than any one of the individual capacitors' capacitances. The formula for calculating the series total capacitance is the same form as for calculating parallel resistances:

Series Capacitances

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

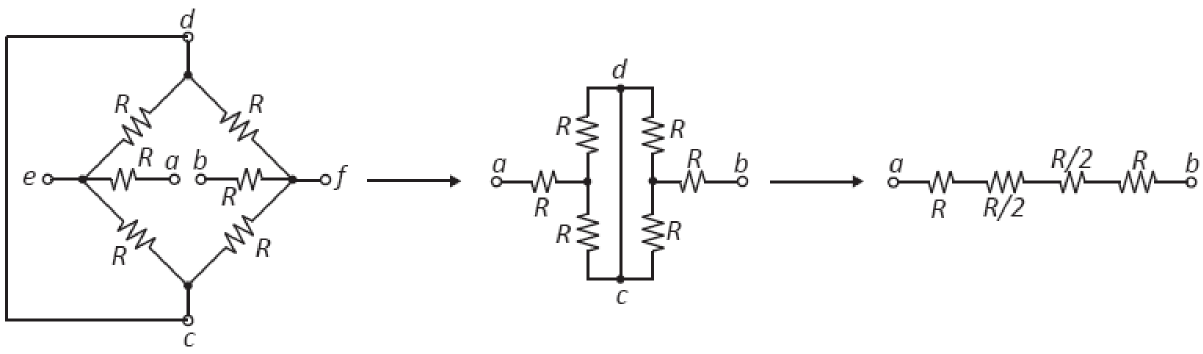
When capacitors are connected in parallel, the total capacitance is the sum of the individual capacitors' capacitances. If two or more capacitors are connected in parallel, the overall effect is that of a single equivalent capacitor having the sum total of the plate areas of the individual capacitors. As we've just seen, an increase in plate area, with all other factors unchanged, results in increased capacitance.

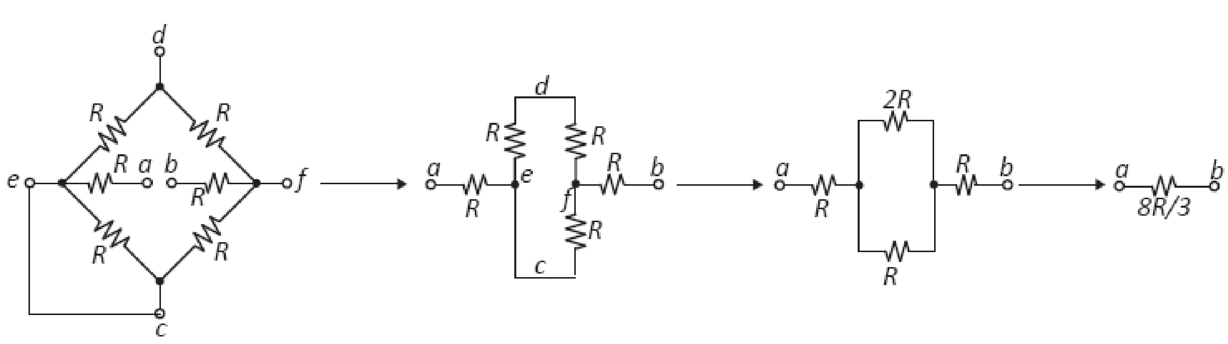


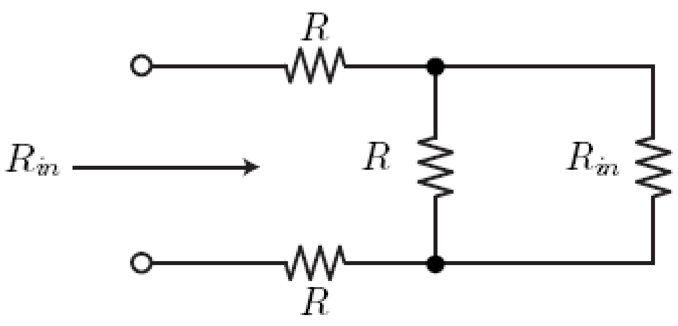
Thus, the total capacitance is more than any one of the individual capacitors' capacitances. The formula for calculating the parallel total capacitance is the same form as for calculating series resistances:

Parallel Capacitances

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







<u>Introduction to PORT NETWORKS</u>

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

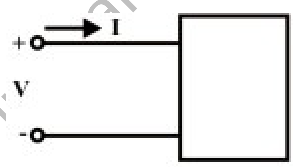


Fig. 6.1(a) One port network

is a general **one-port circuit.** When any voltage source is connected across the terminals, the current entering through any one of the two terminals, equals the current leaving the other terminal. For example, resistance, inductance and capacitance acts as a **one-port.** On the other hand, a **two-port** is a circuit having two pairs of terminals. Each pair behaves as a one-port; current entering in one terminal must be equal to the current living the other terminal.

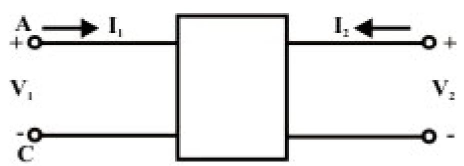


Fig. 6.1(b) Two port network

Fig.6.1.(b) can be described as a four terminal network, for convenience subscript 1 to refer to the variables at the input port (at the left) and the subscript 2 to refer to the variables at the output

port (at the right). The most important subclass of two-port networks is the one in which the minus reference terminals of the input and output ports are at the same. This circuit configuration is readily possible to consider the ‘π’ or ‘Δ’ – network also as a three-terminal network in fig.6.1(c). Another frequently encountered circuit configuration that shown in fig.6.1(d) is approximately referred to as a three-terminal *Y* connected circuit as well as two-port circuit.

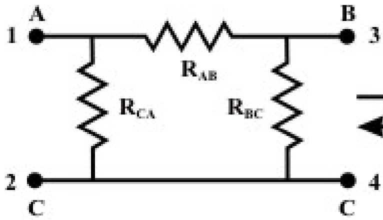


Fig. 6.1 (c)

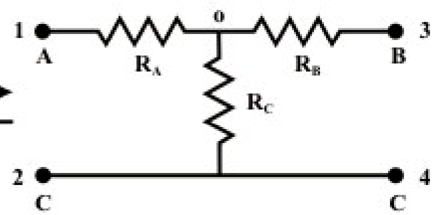


Fig. 6.1 (d)

The name derives from the shape or configuration of the circuit diagrams, which look respectively like the letter Y and the Greek capital letter Δ.

Delta – Wye conversion (Δ) (Y)

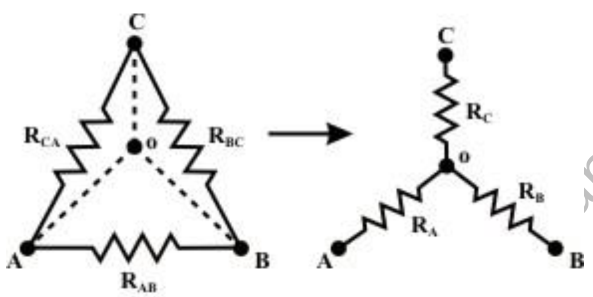


Fig. 6.1 (e)

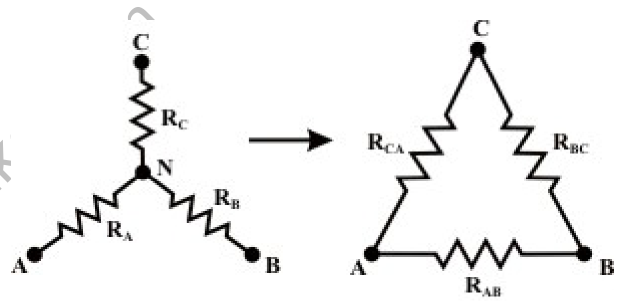


Fig. 6.1 (f)

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

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

Let us consider the network shown in fig.6.1(e) and assumed the resistances (*RAB,RBC and RCA*) in Δ network are known. Our problem is to find the values of in Wye (*Y*) network (see fig.6.1(e)) that will produce the same resistance when measured between similar pairs of terminals. We can write the equivalence resistance between any two terminals in the following form.

Between A & C **terminals:**

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

Between C & B **terminals:**

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

Between B & A terminals:

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

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

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

we can write the express for unknown resistances of Wye (Y) network as

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

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

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

When we need to transform a Delta (Δ) network to an equivalent Wye (Y) network, the equations (6.5) to (6.7) are the useful expressions. On the other hand, the equations (6.12) – (6.14) are used for Wye (Y) to Delta (Δ) conversion.

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

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

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

Appling KCL at ‘’ for Y connected network (assume N,,ABC terminals having higher potential than the terminal) we have,

$$\frac{(V_A - V_N)}{R_A} + \frac{(V_B - V_N)}{R_B} + \frac{(V_C - V_N)}{R_C} = 0 \quad \Rightarrow V_N\left(\frac{1}{R_A} + \frac{1}{R_B} + \frac{1}{R_C}\right) = \left(\frac{V_A}{R_A} + \frac{V_B}{R_B} + \frac{V_C}{R_C}\right)$$

or, $$\Rightarrow V_N = \frac{\left(\frac{V_A}{R_A} + \frac{V_B}{R_B} + \frac{V_C}{R_C}\right)}{\left(\frac{1}{R_A} + \frac{1}{R_B} + \frac{1}{R_C}\right)}$$

For Δ-network (see fig.6.1.(f)),
Current entering at terminal A = Current leaving the terminal ‘ A ’

$$I_A = \frac{V_{AB}}{R_{AB}} + \frac{V_{AC}}{R_{AC}} \text{ (for } \Delta \text{ network)} \qquad (6.10)$$

From equations (6.8) and (6.10),

$$\frac{(V_A - V_N)}{R_A} = \frac{V_{AB}}{R_{AB}} + \frac{V_{AC}}{R_{AC}}$$

Using the V_N expression in the above equation, we get

$$\frac{\left(V_A - \frac{\left(\frac{V_A}{R_A} + \frac{V_B}{R_B} + \frac{V_C}{R_C}\right)}{\left(\frac{1}{R_A} + \frac{1}{R_B} + \frac{1}{R_C}\right)}\right)}{R_A} = \frac{V_{AB}}{R_{AB}} + \frac{V_{AC}}{R_{AC}} \quad \Rightarrow \quad \frac{\left(\frac{\left(\frac{V_A - V_B}{R_B} + \frac{V_A - V_C}{R_C}\right)}{\left(\frac{1}{R_A} + \frac{1}{R_B} + \frac{1}{R_C}\right)}\right)}{R_A} = \frac{V_{AB}}{R_{AB}} + \frac{V_{AC}}{R_{AC}}$$

or $$\frac{\left(\frac{\left(\frac{V_{AB}}{R_B} + \frac{V_{AC}}{R_C}\right)}{\left(\frac{1}{R_A} + \frac{1}{R_B} + \frac{1}{R_C}\right)}\right)}{R_A} = \frac{V_{AB}}{R_{AB}} + \frac{V_{AC}}{R_{AC}} \qquad (6.11)$$

Equating the coefficients of V_{AB} and V_{AC} in both sides of eq.(6.11), we obtained the following relationship.

$$\frac{1}{R_{AB}} = \frac{1}{R_A R_B\left(\frac{1}{R_A}+\frac{1}{R_B}+\frac{1}{R_C}\right)} \Rightarrow R_{AB} = R_A + R_B + \frac{R_A R_B}{R_C}$$

$$\frac{1}{R_{AC}} = \frac{1}{R_A R_C\left(\frac{1}{R_A}+\frac{1}{R_B}+\frac{1}{R_C}\right)} \Rightarrow R_{AC} = R_A + R_C + \frac{R_A R_C}{R_B}$$

Similarly, I_B for both the networks (see fig.61(f)) are given by

$$I_B = \frac{(V_B - V_N)}{R_B} \quad \text{(for } Y \text{ network)}$$

$$I_B = \frac{V_{BC}}{R_{BC}} + \frac{V_{BA}}{R_{BA}} \quad \text{(for } \Delta \text{ network)}$$

Equating the above two equations and using the value of V_N (see eq.(6.9), we get the final expression as

$$\frac{\left(\frac{\left(\frac{V_{BC}}{R_C}+\frac{V_{BA}}{R_A}\right)}{\left(\frac{1}{R_A}+\frac{1}{R_B}+\frac{1}{R_C}\right)}\right)}{R_B} = \frac{V_{BC}}{R_{BC}} + \frac{V_{BA}}{R_{BA}}$$

Equating the coefficient of V_{BC} in both sides of the above equations we obtain the following relation

$$\frac{1}{R_{BC}} = \frac{1}{R_B R_C\left(\frac{1}{R_A}+\frac{1}{R_B}+\frac{1}{R_C}\right)} \Rightarrow R_{BC} = R_B + R_C + \frac{R_B R_C}{R_A} \qquad (6.14)$$

When we need to transform a Delta (Δ) network to an equivalent Wye (*Y*) network, the equations (6.5) to (6.7) are the useful expressions. On the other hand, the equations (6.12) – (6.14) are used for Wye (*Y*) to Delta (Δ) conversion.

2. D.C. GENERATORS

Introduction

Although a far greater percentage of the electrical machines in service are a.c. machines, the d.c. machines are of considerable industrial importance. The principal advantage of the d.c. machine, particularly the d.c. motor, is that it provides a fine control of speed. Such an advantage is not claimed by any a.c. motor. However, d.c. generators are not as common as they used to be, because direct current, when required, is mainly obtained from an a.c. supply by the use of rectifiers. Nevertheless, an understanding of d.c. generator is important because it represents a logical introduction to the behavior of d.c. motors. Indeed many d.c. motors in industry actually operate as d.c. generators for a brief period.

Generator Principle

An electric generator is a machine that converts mechanical energy into electrical energy. An electric generator is based on the principle that whenever flux is cut by a conductor, an e.m.f. is induced which will cause a current to flow if the conductor circuit is closed. The direction of induced e.m.f. (and hence current) is given by Fleming's right hand rule. Therefore, the essential components of a generator are:

(a) a magnetic field
(b) conductor or a group of conductors
(c) motion of conductor w.r.t. magnetic field.

Simple Loop Generator

Consider a single turn loop ABCD rotating clockwise in a uniform magnetic field with a constant speed as shown in Fig.(1.1). As the loop rotates, the flux linking the coil sides AB and CD changes continuously. Hence the e.m.f. induced in these coil sides also changes but the e.m.f. induced in one coil side adds to that induced in the other.

(i) When the loop is in position no. 1 [See Fig. 1.1], the generated e.m.f. is zero because the coil sides (AB and CD) are cutting no flux but are moving parallel to it

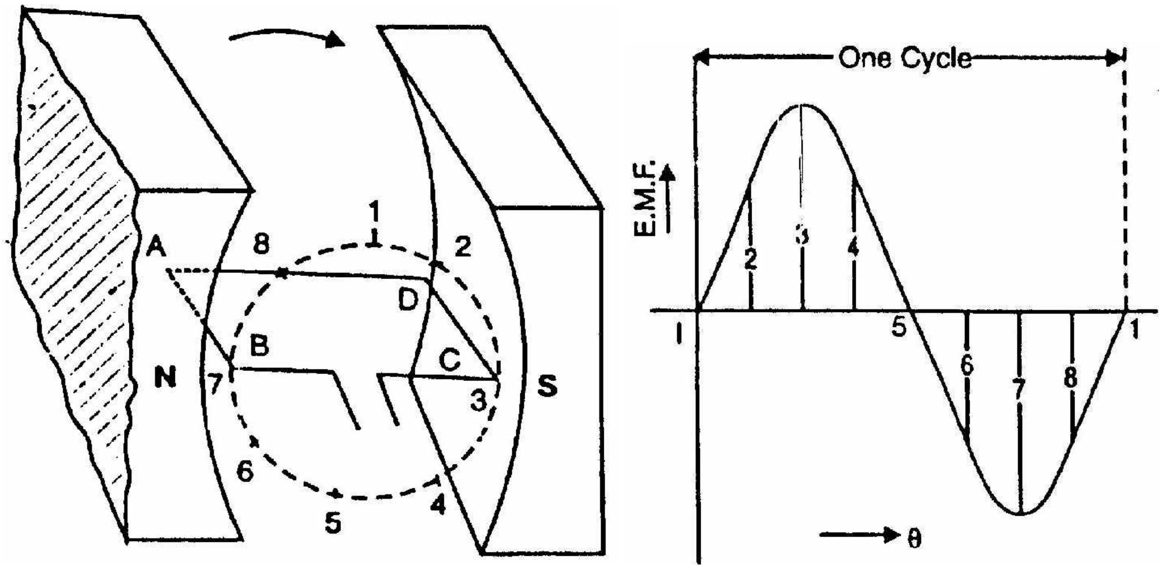
(ii) When the loop is in position no. 2, the coil sides are moving at an angle to the flux and, therefore, a low e.m.f. is generated as indicated by point 2 in Fig. (1.2).

(iii) When the loop is in position no. 3, the coil sides (AB and CD) are at right angle to the flux and are, therefore, cutting the flux at a maximum rate. Hence at this instant, the generated e.m.f. is maximum as indicated by point 3 in Fig. (1.2).

(iv) At position 4, the generated e.m.f. is less because the coil sides are cutting the flux at an angle.

(v) At position 5, no magnetic lines are cut and hence induced e.m.f. is zero as indicated by point 5 in Fig. (1.2).

(vi) At position 6, the coil sides move under a pole of opposite polarity and hence the direction of generated e.m.f. is reversed. The maximum e.m.f. in this direction (i.e., reverse direction, See Fig. 1.2) will be when the loop is at position 7 and zero when at position 1. This cycle repeats with each revolution of the coil.



Note that e.m.f. generated in the loop is alternating one. It is because any coilside, say AB has e.m.f. in one direction when under the influence of N-pole and in the other direction when under the influence of S-pole. If a load is connected across the ends of the loop, then alternating current will flow through the load.The alternating voltage generated in the loop can be converted into direct voltage by a device called commutator. We then have the d.c. generator. In fact, a commutator is a mechanical rectifier.

E.M.F. Equation of a D.C. Generator

Let ϕ = flux/pole in Wb
Z = total number of armature conductors
P = number of poles
A = number of parallel paths = 2 ... for wave winding
= P ... for lap winding
N = speed of armature in r.p.m.
E_g = e.m.f. of the generator = e.m.f./parallel path

Flux cut by one conductor in one revolution of the armature,

$d\phi = P\phi$ webers

Time taken to complete one revolution,

dt = 60/N second

e.m.f generated/conductor $= \frac{d\phi}{dt} = \frac{P\phi}{60/N} = \frac{P\phi N}{60}$ volts

e.m.f. of generator,

E_g = e.m.f. per parallel path
= (e.m.f/conductor) × No. of conductors in series per parallel path

$$= \frac{P\phi N}{60} \times \frac{Z}{A}$$

$$\therefore \quad E_g = \frac{P\phi ZN}{60 A}$$

where A = 2 for-wave winding

A= P for lap winding

Types of D.C. Generators

The magnetic field in a d.c. generator is normally produced by electromagnets rather than permanent magnets. Generators are generally classified according to their methods of field excitation. On this basis, d.c. generators are divided into the following two classes:

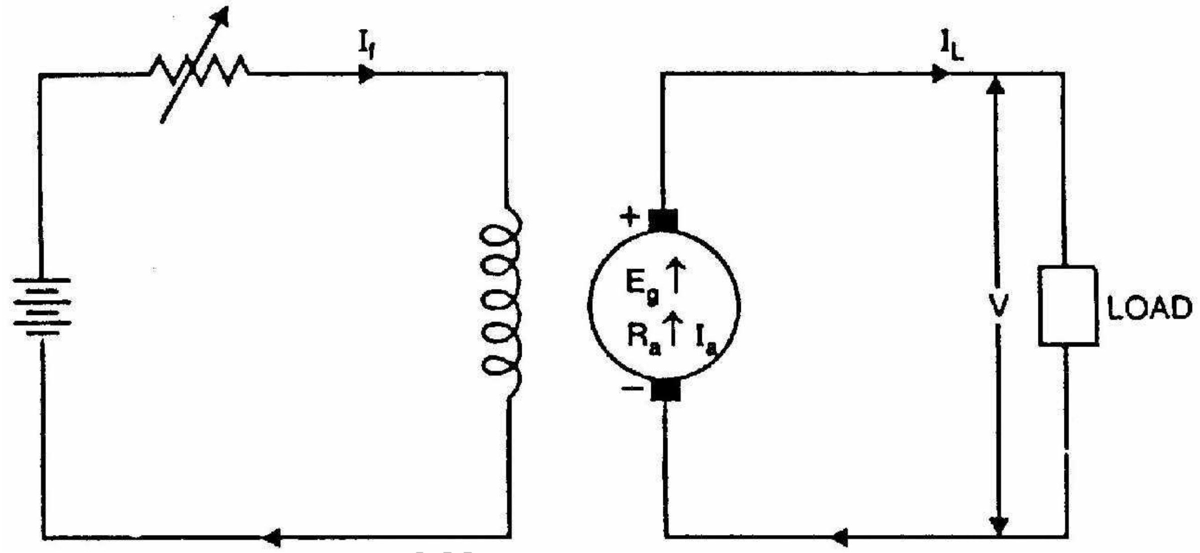
(i) Separately excited d.c. generators

(ii) Self-excited d.c. generators

The behaviour of a d.c. generator on load depends upon the method of field excitation adopted

Separately Excited D.C. Generators

A d.c. generator whose field magnet winding is supplied from an independent external d.c. source (e.g., a battery etc.) is called a separately excited generator. Fig. (1.32) shows the connections of a separately excited generator. The voltage output depends upon the speed of rotation of armature and the field current (Eg = P□□ZN/60 A). The greater the speed and field current, greater is the generatede.m.f. It may be noted that separately excited d.c. generators are rarely used in practice. The d.c. generators are normally of self-excited type.



Armature current, $I_a = I_L$

Terminal voltage, $V = E_g - I_aR_a$

Electric power developed $= E_gI_a$

Power delivered to load $= E_gI_a - I_a^2R_a = I_a(E_g - I_aR_a) = VI_a$

Self-Excited D.C. Generators

A d.c. generator whose field magnet winding is supplied current from the output of the generator itself is called a self-excited generator. There are three types of self-excited generators depending upon the manner in which the field winding is connected to the armature, namely;

(i) Series generator;

(ii) Shunt generator;

(iii) Compound generator

(i) Series generator

In a series wound generator, the field winding is connected in series with armature winding so that whole armature current flows through the field winding as well as the load. Fig. (1.33) shows the connections of a series wound generator. Since the field winding carries the whole of load current, it has a few turns of thick wire having low resistance. Series generators are rarely used except for special purposes e.g., as boosters.

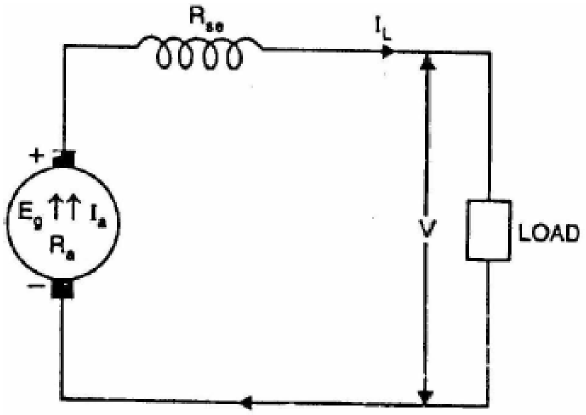
Armature current, $I_a = I_{se} = I_L = I(\text{say})$

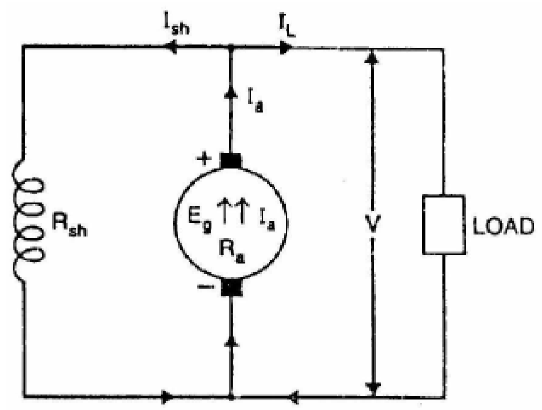
Terminal voltage, $V = E_G - I(R_a + R_{se})$

Power developed in armature = $E_g I_a$

Power delivered to load

$$= E_g I_a - I_a^2(R_a + R_{se}) = I_a[E_g - I_a(R_a - R_{se})] = VI_a \text{ or } VI_L$$





(ii) Shunt generator

In a shunt generator, the field winding is connected in parallel with the armature winding so that terminal voltage of the generator is applied across it. The shunt field winding has many turns of fine wire having high resistance. Therefore, only a part of armature current flows through shunt field winding and the rest flows through the load. Fig. (1.34) shows the connections of a shunt-wound generator.

Shunt field current, $I_{sh} = V/R_{sh}$

Armature current, $I_a = I_L + I_{sh}$

Terminal voltage, $V = E_g - I_a R_a$

Power developed in armature = $E_g I_a$

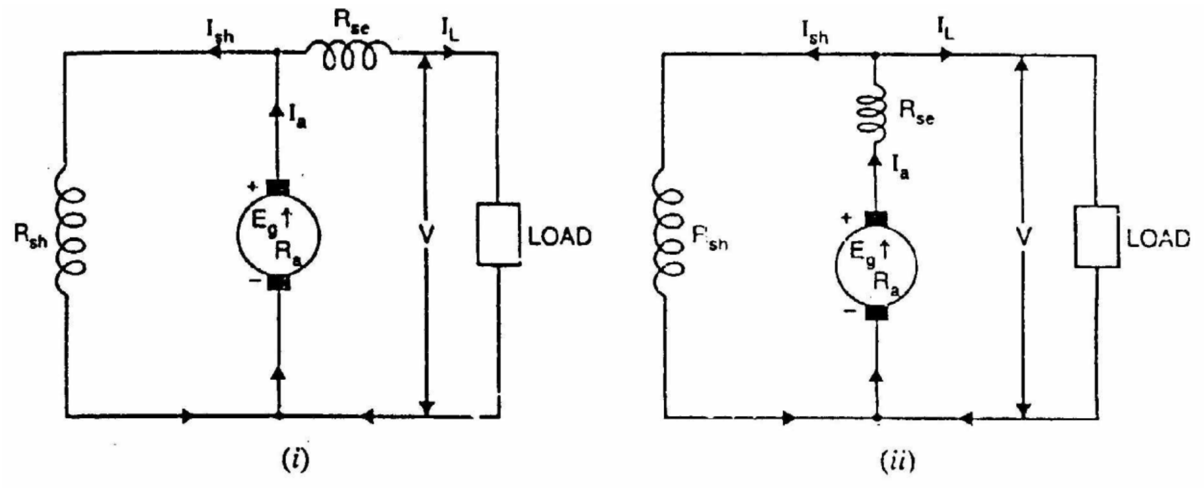
Power delivered to load = VI_L

(iii) Compound generator

In a compound-wound generator, there are two sets of field windings on each pole one is in series and the other in parallel with the armature. A compound wound generator may be:

(a) Short Shunt in which only shunt field winding is in parallel with the armature winding [See Fig. (i)].

(b) Long Shunt in which shunt field winding is in parallel with both series field and armature winding [See Fig. (ii)].



Short shunt

Series field current, $I_{se} = I_L$

Shunt field current, $I_{sh} = \dfrac{V + I_{se}R_{se}}{R_{sh}}$

Terminal voltage, $V = E_g - I_aR_a - I_{se}R_{se}$

Power developed in armature $= E_gI_a$

Power delivered to load $= VI_L$

Long shunt

Series field current, $I_{se} = I_a = I_L + I_{sh}$

Shunt field current, $I_{sh} = V/R_{sh}$

Terminal voltage, $V = E_g - I_a(R_a + R_{se})$

Power developed in armature $= E_gI_a$

Power delivered to load $= VI_L$

Q A 4-pole d.c. shunt generator has an armature resistance of 0.018 Ω. The armature is lap-wound with 520 conductors. When driven at 750 rev/min the machine produces a total armature current of 400 A at a terminal voltage of 200 V. Calculate the useful flux/pole.

A

$p = 2;\ a = 4;\ R_a = 0.018\,\Omega;\ z = 520;\ n = \dfrac{750}{60} = 12.5\ \text{rev/s}$

$I_a = 400\ \text{A};\ V = 200\ \text{V}$

$E = V + I_aR_a\ \text{volt} = 200\ + (400 \times 0.018)$

$E = 207.2\ \text{V}$

$E = \dfrac{2p\Phi zn}{a}\ \text{volt}$

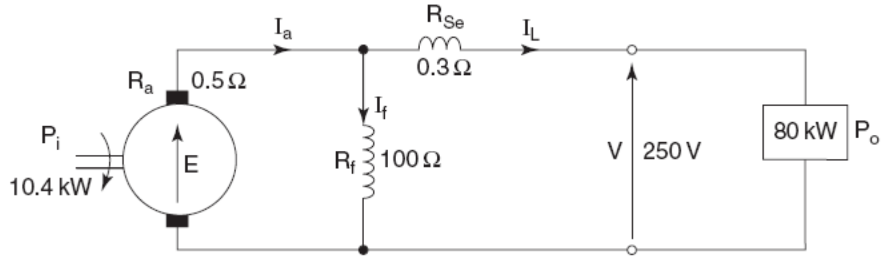
$\text{so, } \Phi = \dfrac{Ea}{2pzn}\ \text{weber} = \dfrac{207.2 \times 4}{4 \times 520 \times 12.5}$

$\Phi = 31.9\ \text{mWb}$ **Ans**

Q **A short-shunt compound generator has armature, shunt field and series field resistances of 0.5 Ω 100 Ω, and 0.3 Ω respectively. When supplying a load of 8 kW at a terminal voltage of 250 V the input power supplied by the driving motor is 10.4 kW. Calculate (a) the generated emf, (b) the efficiency, (c) the iron, friction and windage loss, and (d) the total fixed losses.**

A

$R_a = 0.5\,\Omega;\ R_f = 100\,\Omega;\ R_{Se} = 0.3\,\Omega;\ P_o = 8000\text{W};\ V = 250\text{V};\ P_i = 10\,400\text{W}$



(a) $I_L = \dfrac{P_O}{V_L}\ \text{amp} = \dfrac{8000}{250} = 32\ \text{A}$

$V_f = V + I_LR_{Se}\ \text{volt} = 250 + (32 \times 0.3)$

$V_f = 259.6\ \text{V}$

$I_f = \dfrac{V_f}{R_f}\ \text{amp} = \dfrac{259.6}{100} = 2.6\ \text{A}$

$I_a = I_L + I_f\ \text{amp} = 32 + 2.6 = 34.6\ \text{A}$

$E = V_f + I_aR_a\ \text{volt} = 259.6 + (34.6 \times 0.5)$

$E = 276.9\ \text{V}$ **Ans**

(b) $\eta = \frac{P_o}{P_i} \times 100\% = \frac{8}{10.4} \times 100\%$

$\eta = 76.92\%$ **Ans**

(c) From the power flow diagram

$P_{Fe} = P_i - EI_a$ watt $= 10\,400 - (276.9 \times 34.6)$

$P_{Fe} = 819.26$ W **Ans**

(d) total fixed losses $= P_{Fe} + I_f^2 R_f$ watt

$= 819.26 + (2.6 \times 100)$

total fixed losses $= 1.08$ kW **Ans**

D.C. Motors

Introduction

D. C. motors are seldom used in ordinary applications because all electric supply companies furnish alternating current However, for special applications such as in steel mills, mines and electric trains, it is advantageous to convert alternating current into direct current in order to use d.c. motors. The reason is that speed/torque characteristics of d.c. motors are much more superior to that of a.c. motors. Therefore, it is not surprising to note that for industrial drives, d.c. motors are as popular as 3-phase induction motors. Like d.c. generators, d.c. motors are also of three types viz., series-wound, shunt-wound and compound wound. The use of a particular motor depends upon the mechanical load it has to drive.

D.C. Motor Principle

A machine that converts d.c. power into mechanical power is known as a d.c. motor. Its operation is based on the principle that when a current carrying conductor is placed in a magnetic field, the conductor experiences a mechanical force. The direction of this force is given by Fleming's left hand rule and magnitude is given by; FBInewtons

Basically, there is no constructional difference between a d.c. motor and a d.c. generator. The same d.c. machine can be run as a generator or motor

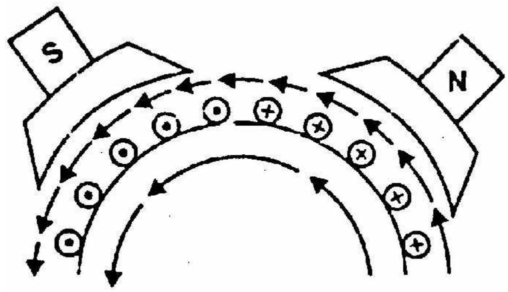
Working of D.C. Motor

Consider a part of a multipolar d.c. motor as shown in Fig. (4.1). When the terminals of the motor are connected to an external source of d.c. supply:

(i) the field magnets are excited developing alternate N and S poles

(ii) the armature conductors carry ^currents. All conductors under N-pole carry currents in one direction while all the conductors under S-pole carry currents in the opposite direction.

Suppose the conductors under N-pole carry currents into the plane of the paper and those under S-pole carry currents out of the plane of the paper as shown in
Fig.(4.1). Since each armature conductor is carrying current and is placed in the magnetic field, mechanical force acts on it.



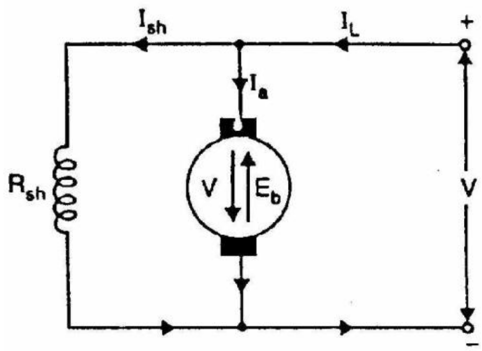
Referring to Fig. (4.1) and applying Fleming's left hand rule, it is clear that force on each conductor is tending to rotate the armature in anticlockwise direction. All these forces add together to produce a driving torque which sets the armature rotating.

When the conductor moves from one side of a brush to the other, the current in that conductor is reversed and at the same time it comes under the influence of next pole which is of opposite polarity.

Consequently, the direction of force on the conductor remains the same.

Back or Counter E.M.F.

When the armature of a d.c. motor rotates under the influence of the driving torque, the armature conductors move through the magnetic field and hence e.m.f. is induced in them as in a generator The induced e.m.f. acts in opposite direction to the applied voltage V(Lenz's law) and in known as back or counter e.m.f. Eb. The back e.m.f. Eb(= P □□ZN/60 A) is always less than the applied voltage V, although this difference is small when the motor is running under normal conditions.



Consider a shunt wound motor shown in Fig. (4.2). When d.c. voltage V is applied across the motor terminals, the field magnets are excited and armature conductors are supplied with current. Therefore, driving torque acts on the armature which begins to rotate. As the armature rotates, back e.m.f. Eb is induced which opposes the applied voltage V. The applied voltage V has to force current through the armature against the back e.m.f. Eb. The electric work done in overcoming and causing the current to flow against Eb is converted into mechanical energy developed in the armature. It follows, therefore, that energy conversion in a d.c. motor is only possible due to the production of back e.m.f. Eb.

$$\text{Net voltage across armature circuit} = V - E_b$$

$$\text{If } R_a \text{ is the armature circuit resistance, then, } I_a = \frac{V - E_b}{R_a}$$

Since V and Ra are usually fixed, the value of Eb will determine the current drawn by the motor. If the speed of the motor is high, then back e.m.f. Eb (= P □ ZN/60 A) is large and hence the motor will draw less armature current and viceversa.

Significance of Back E.M.F.

The presence of back e.m.f. makes the d.c. motor a self-regulating machine i.e., it makes the motor to draw as much armature current as is just sufficient to develop the torque required by the load.

$$\text{Armature current, } I_a = \frac{V - E_b}{R_a}$$

(i) When the motor is running on no load, small torque is required to overcome the friction and windage losses. Therefore, the armature current Ia is small and the back e.m.f. is nearly equal to the applied voltage.
(ii) If the motor is suddenly loaded, the first effect is to cause the armature to slow down. Therefore, the speed at which the armature conductors move through the field is reduced and hence the back e.m.f. Eb falls. The decreased back e.m.f. allows a larger current to flow through the armature and larger current means increased driving torque. Thus, the driving torque increases as the motor slows down. The motor will stop slowing down when the armature current is just sufficient to produce the increased torque required by the load.
(iii) If the load on the motor is decreased, the driving torque is momentarily in excess of the requirement so that armature is accelerated. As the armature speed increases, the back e.m.f. Eb also increases and causes the armature current Ia to decrease. The motor will stop accelerating when the armature current is just sufficient to produce the reduced torque required by the load.
It follows, therefore, that back e.m.f. in a d.c. motor regulates the flow of armature current i.e., it automatically changes the armature current to meet the load requirement.

Armature Torque of D.C. Motor

Torque is the turning moment of a force about an axis and is measured by the product of force (F) and radius (r) at right angle to which the force acts i.e. D.C. Motors

$$T = F \times r$$

In a d.c. motor, each conductor is acted upon by a circumferential force F at a distance r, the radius of the armature (Fig. 4.8). Therefore, each conductor exerts a torque, tending to rotate the armature. The sum of the torques due to all armature conductors is known as gross or armature torque (Ta).

Torque due to one conductor = F × r newton- metre

Total armature torque, $T_a = Z\,F\,r$ newton-metre

$$= Z\,B\,i\,\ell\,r$$

Now $i = I_a/A$, $B = \phi/a$ where a is the x-sectional area of flux path per pole at radius r. Clearly, $a = 2\pi r\ell/P$.

$$\therefore \quad T_a = Z \times \left(\frac{\phi}{a}\right) \times \left(\frac{I_a}{A}\right) \times \ell \times r$$

$$= Z \times \frac{\phi}{2\pi r\ell/P} \times \frac{I_a}{A} \times \ell \times r = \frac{Z\phi I_a P}{2\pi A} \text{ N - m}$$

or $$T_a = 0.159\, Z\phi I_a \left(\frac{P}{A}\right) \text{ N - m} \qquad \text{(i)}$$

Since Z, P and A are fixed for a given machine,

$$\therefore \quad T_a \propto \phi I_a$$

Hence torque in a d.c. motor is directly proportional to flux per pole and armature current.

(i) For a shunt motor, flux ϕ is practically constant.

$$\therefore \quad T_a \propto I_a$$

(ii) For a series motor, flux ϕ is directly proportional to armature current I_a provided magnetic saturation does not take place.

$$\therefore \quad T_a \propto I_a^2$$

Necessity of D.C. Motor Starter

At starting, when the motor is stationary, there is no back e.m.f. in the armature. Consequently, if the motor is directly switched on to the mains, the armature will draw a heavy current (Ia = V/Ra) because of small armature resistance.

As an example, 5 H.P., 220 V shunt motor has a full-load current of 20 A and an armature resistance of about 0.5 □. If this motor is directly switched on to supply, it would take an armature current of 220/0.5 = 440 A which is 22 times the full-load current. This high starting current may result in:

(i) burning of armature due to excessive heating effect,

(ii) damaging the commutator and brushes due to heavy sparking,

(iii) excessive voltage drop in the line to which the motor is connected. The result is that the operation of other appliances connected to the line may be impaired and in particular cases, they may refuse to work. In order to avoid excessive current at starting, a variable resistance (known as starting resistance) is inserted in series with the armature circuit. This resistance is gradually reduced as the motor gains speed (and hence Eb increases) and eventually it is cut out completely when the motor has attained full speed. The value of starting resistance is generally such that starting current is limited to 1.25 to 2 times the full-load current.

Types of D.C. Motor Starters

The stalling operation of a d.c. motor consists in the insertion of external resistance into the armature circuit to limit the starting current taken by the motor and the removal of this resistance in steps as the motor accelerates. When the motor attains the normal speed, this resistance is totally cut out of the armature circuit. It is very important and desirable to provide the starter with protective devices to enable the starter arm to return to OFF position

(i) when the supply fails, thus preventing the armature being directly across the mains when this voltage is restored. For this purpose, we use no-volt release coil.

(ii) when the motor becomes overloaded or develops a fault causing the motor to take an excessive current. For this purpose, we use overload release coil. There are two principal types of d.c. motor starters viz., three-point starter and four-point starter. As we shall see, the two types of starters differ only in the manner in which the no-volt release coil is connected.

Three-Point Starter

This type of starter is widely used for starting shunt and compound motors.

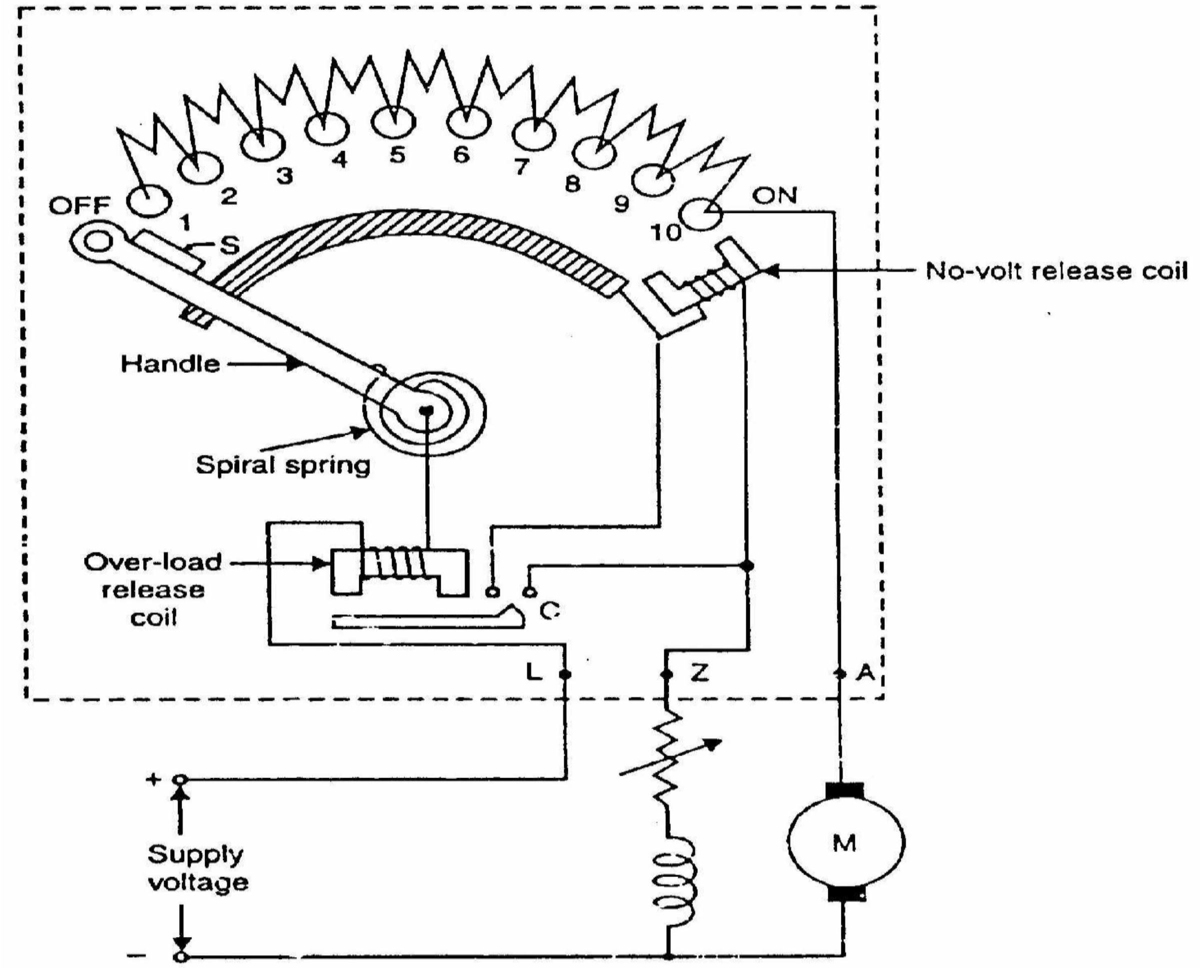
Schematic diagram

Fig. (5.16) shows the schematic diagram of a three-point starter for a shunt motor with protective devices. It is so called because it has three terminals L, Z and A. The starter consists of starting resistance divided into several sections and connected in series with the armature. The tapping points of the starting resistance are brought out to a number of studs. The three terminals L, Z and A of the starter are connected respectively to the positive line terminal, shunt field terminal and armature terminal. The other terminals of the armature and shunt field windings are connected to the negative terminal of the supply. The no-volt release coil is connected in the shunt field circuit. One end of the handle is connected to the terminal L through the over-load release coil. The other end of the handle moves against a spiral spring and makes contact with each stud during starting operation, cutting out more and more starting resistance as it passes over each stud in clockwise direction.

Operation

(i) To start with, the d.c. supply is switched on with handle in the OFF position.

(ii) The handle is now moved clockwise to the first stud. As soon as it comes in contact with the first stud, the shunt field winding is directly connected across the supply, while the whole starting resistance is inserted in series with the armature circuit.
(iii) As the handle is gradually moved over to the final stud, the starting resistance is cut out of the armature circuit in steps. The handle is now held magnetically by the no-volt release coil which is energized by shunt field current.
(iv) If the supply voltage is suddenly interrupted or if the field excitation is accidentally cut, the no-volt release coil is demagnetized and the handle goes back to the OFF position under the pull of the spring. If no-volt release coil were not used, then in case of failure of supply, the handle would remain on the final stud. If then supply is restored, the motor will be directly connected across the supply, resulting in an excessive armature current.
(v) If the motor is over-loaded (or a fault occurs), it will draw excessive current from the supply. This current will increase the ampere-turns of the over-load release coil and pull the armature C, thus short-circuiting the no-volt release coil. The no-volt coil is demagnetized and the handle is pulled to the OFF position by the spring. Thus, the motor is automatically disconnected from the supply.



Drawback

In a three-point starter, the no-volt release coil is connected in series with the shunt field circuit so that it carries the shunt field current. While exercising speed control through field regulator, the field current may be weakened to such an extent that the no-volt release coil may not be able to keep the starter arm in the ON position. This may disconnect the motor from the supply when it is not desired. This drawback is overcome in the four point starter.

Speed Control of D.C. Motors

Introduction

Although a far greater percentage of electric motors in service are a.c. motors, the d.c. motor is of considerable industrial importance. The principal advantage of a d.c. motor is that its speed can be changed over a wide range by a variety of simple methods. Such a fine speed control is generally not possible with a.c. motors. In fact, fine speed control is one of the reasons for the strong competitive position of d.c. motors in the modem industrial applications.

the various methods of-speed control of d.c. motors are:

Speed Control of D.C. Motors

The speed of a d.c. motor is given by:

$$N \propto \frac{E_b}{\phi}$$

$$N = K\frac{(V - I_a R)}{\phi} \text{ r.p.m.}$$

$R = R_a$ for shunt motor

$= R_a + R_{se}$. for series motor

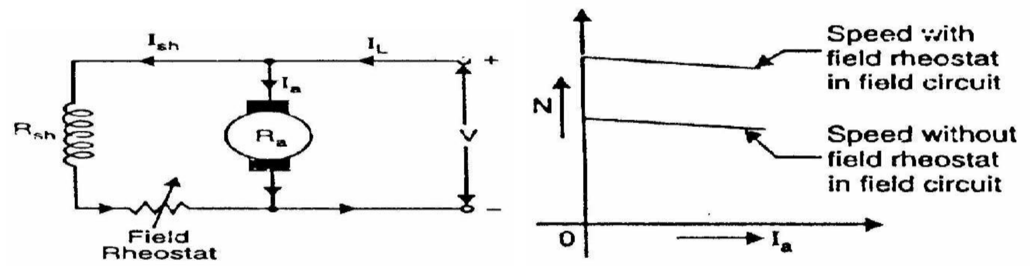
it is clear that there are three main methods of controlling the speed of a d.c. motor, namely:
(i) By varying the flux per pole (□). This is known as flux control method.
(ii) By varying the resistance in the armature circuit. This is known as armature control method.
(iii) By varying the applied voltage V. This is known as voltage control method.

Speed Control of D.C. Shunt Motors

The speed of a shunt motor can be changed by (i) flux control method
(ii) armature control method (iii) voltage control method.
The first method (i.e. flux control method) is frequently used because it is simple and inexpensive.

1. Flux control method

It is based on the fact that by varying the flux □, the motor speed (N □□1/□) canbe changed and hence the name flux control method. In this method, a variable resistance (known as shunt field rheostat) is placed in series with shunt field winding as shown in Fig.



The shunt field rheostat reduces the shunt field current Ish and hence the flux. Therefore, we can only raise the speed of the motor above the normal speed (See Fig. 5.2). Generally, this method permits to increase the speed in the ratio 3:1. Wider speed ranges tend to produce instability and poor commutation.

Advantages

(i) This is an easy and convenient method.

(ii) It is an inexpensive method since very little power is wasted in the shunt field rheostat due to relatively small value of Ish.

(iii) The speed control exercised by this method is independent of load on the machine.

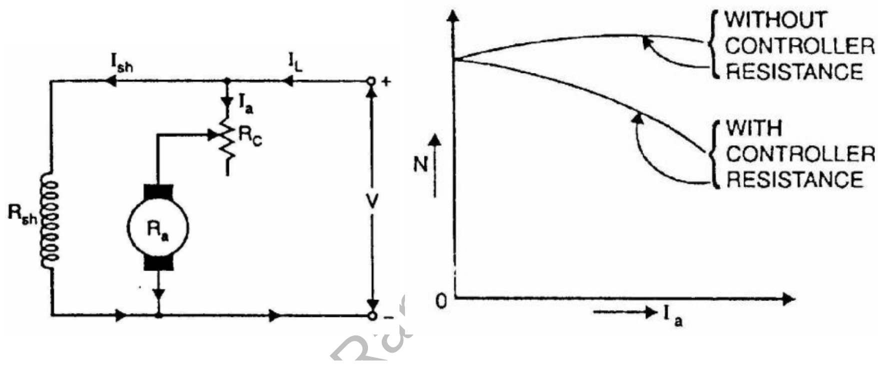
Disadvantages

(i) Only speeds higher than the normal speed can be obtained since the total field circuit resistance cannot be reduced below Rsh—the shunt field winding resistance.

(ii) There is a limit to the maximum speed obtainable by this method. It is because if the flux is too much weakened, commutation becomes poorer.

2. Armature control method

This method is based on the fact that by varying the voltage available across the armature, the back e.m.f and hence the speed of the motor can be changed. This is done by inserting a variable resistance RC (known as controller resistance) in series with the armature as shown in Fig



$$N \propto V - I_a(R_a + R_C)$$

$$R_C = \text{controller resistance}$$

Due to voltage drop in the controller resistance, the back e.m.f. (Eb) is decreased. Since N □□Eb, the speed of the motor is reduced. The highest speed obtainable is lhat corresponding to RC = 0 i.e., normal speed. Hence, this method can only provide speeds below the normal speed

Disadvantages

(i) A large amount of power is wasted in the controller resistance since it carries full armature current Ia.

(ii) The speed varies widely with load since the speed depends upon the voltage drop in the controller resistance and hence on the armature current demanded by the load.

(iii) The output and efficiency of the motor are reduced.

(iv) This method results in poor speed regulation.

Due to above disadvantages, this method is seldom used to control tie speed of shunt motors.

Note. The armature control method is a very common method for the speed control of d.c. series motors. The disadvantage of poor speed regulation is not important in a series motor which is used only where varying speed service is required.

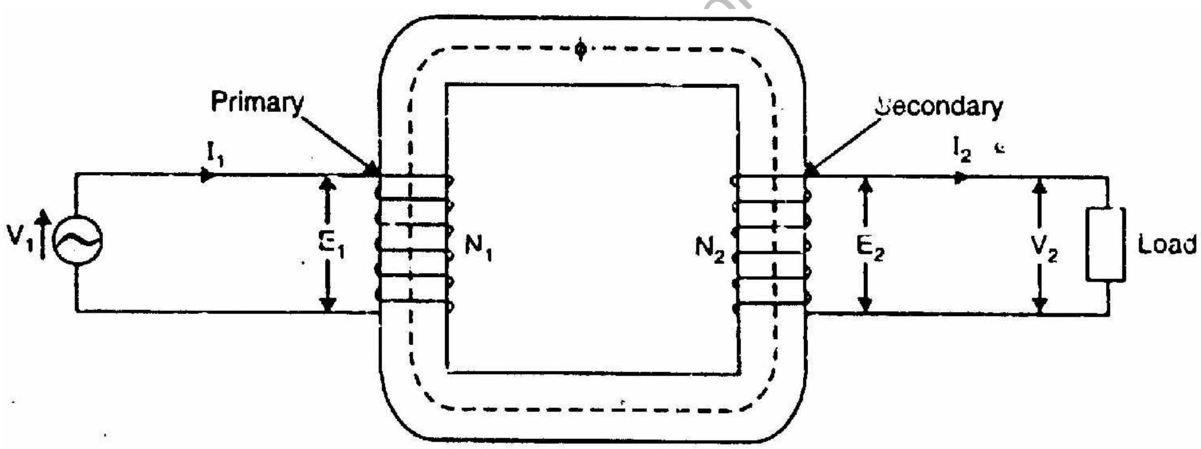
3. Transformer

Introduction

The transformer is probably one of the most useful electrical devices ever invented. It can change the magnitude of alternating voltage or current from one value to another. This useful property of transformer is mainly responsible for the widespread use of alternating currents rather than direct currents i.e., electric power is generated, transmitted and distributed in the form of alternating current. Transformers have no moving parts, rugged and durable in construction, thus requiring very little attention. They also have a very high efficiency—as high as 99%. In this chapter, we shall study some of the basic properties of transformers.

Transformer

A transformer is a static piece of equipment used either for raising or lowering the voltage of an a.c. supply with a corresponding decrease or increase in current. It essentially consists of two windings, the primary and secondary, wound on a common laminated magnetic core as shown in Fig. . The winding connected to the a.c. source is called primary winding (or primary) and the one connected to load is called secondary winding (or secondary). The alternating voltage V1 whose magnitude is to be changed is applied to the primary. Depending upon the number of turns of the primary (N1) and secondary (N2), an alternating e.m.f. E2 is induced in the secondary. This induced e.m.f. E2 in the secondary causes a secondary current I2. Consequently, terminal voltage V2 will appear across the load. If V2 > V1, it is called a step up-transformer. On the other hand, if V2 < V1, it is called a step-down transformer.



Working

When an alternating voltage V1 is applied to the primary, an alternating flux is set up in the core. This alternating flux links both the windings and induces e.m.f.s E1 and E2 in them according to Faraday's laws of electromagnetic induction. The e.m.f. E1 is termed as primary e.m.f. and e.m.f. E2 is termed as secondary e.m.f.

$$E_1 = -N_1 \frac{d\phi}{dt}$$

$$E_2 = -N_2 \frac{d\phi}{dt}$$

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

Note that magnitudes of E2 and E1 depend upon the number of turns on the secondary and primary respectively. If N2 > N1, then E2 > E1 (or V2 > V1) and we get a step-up transformer. On the other hand, if N2 < N1, then E2 < E1 (or V2 < V1) and we get a step-down transformer. If load is connected across the secondary winding, the secondary e.m.f. E2 will cause a current I2 to flow through the load. Thus, a transformer enables us to transfer a.c. power from one circuit to another with a change in voltage level. The following points may be noted carefully:

(i) The transformer action is based on the laws of electromagnetic induction.

(ii) There is no electrical connection between the primary and secondary.

The a.c. power is transferred from primary to secondary through magnetic flux.

(iii) There is no change in frequency i.e., output power has the same frequency as the input power.

(iv) The losses that occur in a transformer are:

(a) core losses—eddy current and hysteresis losses

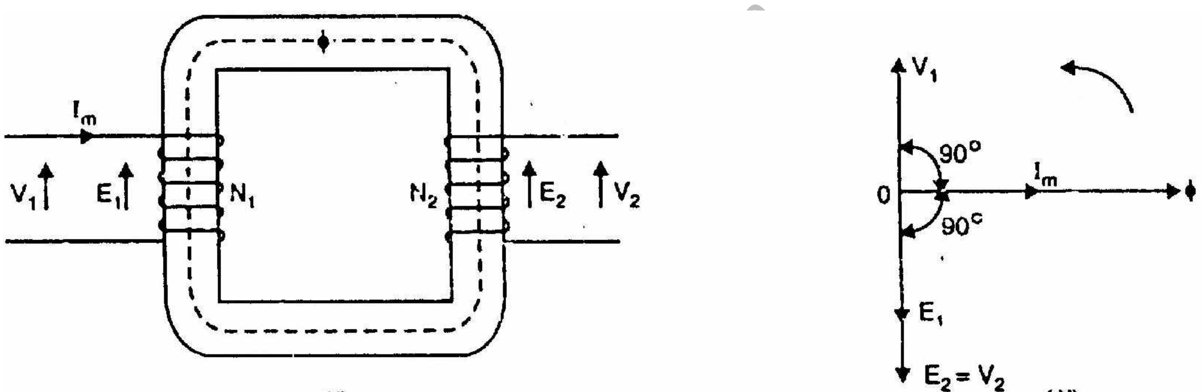
(b) copper losses—in the resistance of the windings

In practice, these losses are very small so that output power is nearly equal to the input primary power. In other words, a transformer has very high efficiency.

E.M.F. Equation of a Transformer

Consider that an alternating voltage V1 of frequency f is applied to the primary as shown in Fig. (i)). The sinusoidal flux □□produced by the primary can be represented as:

The instantaneous e.m.f. e1 induced in the primary is



(i) (ii)

$$e_1 = -N_1 \frac{d\phi}{dt} = -N_1 \frac{d}{dt}(\phi_m \sin\omega t)$$
$$= -\omega N_1 \phi_m \cos\omega t = -2\pi f N_1 \phi_m \cos\omega t$$
$$= 2\pi f N_1 \phi_m \sin(\omega t - 90°) \qquad (i)$$

It is clear from the above equation that maximum value of induced e.m.f. in the primary is

$$E_{m1} = 2\pi f N_1 \phi_m$$

The r.m.s. value E^ of the primary e.m.f. is

$$E_1 = \frac{E_{m1}}{\sqrt{2}} = \frac{2\pi f N_1 \phi_m}{\sqrt{2}}$$

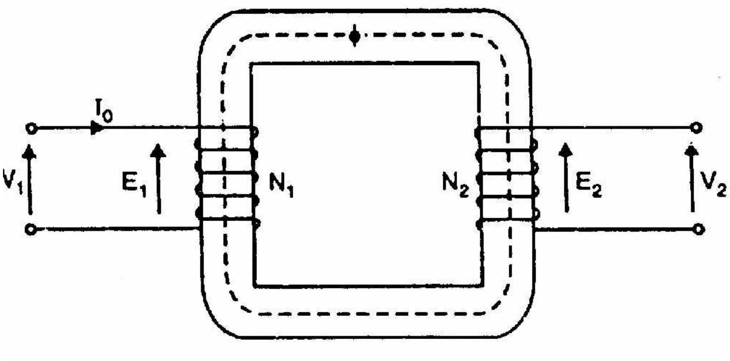
or $E_1 = 4.44 f N_1 \phi_m$

Similarly $E_2 = 4.44 f N_2 \phi_m$

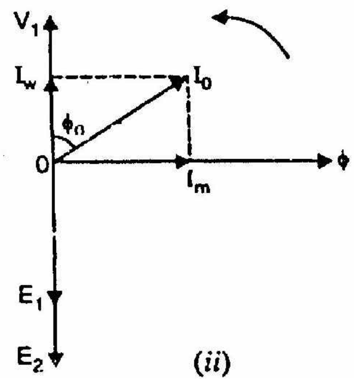
In an ideal transformer, $E_1 = V_1$ and $E_2 = V_2$.

Phasor diagram.

Consider a practical transformer on no load i.e., secondary on open-circuit as shown in Fig. (i)). The primary will draw a small current I0 to supply (i) the iron losses and (ii) a very small amount of copper loss in the primary. Hence the primary no load current I0 is not 90° behind the applied voltage V1 but lags it by an angle □0 < 90° as shown in the phasor diagram in Fig. ((ii)). No load input power, W0 = V1 I0 cos □0



(i)



(ii)

Fig. shows the phasor diagram for the usual case of inductive load.

Both E1 and E2 lag behind the mutual flux □□by 90°. The current I'2 represents the primary current to neutralize the demagnetizing effect of secondary current I2. Now I'2 = K I2 and is antiphase with I2. I0 is the no-load current of the transformer. The phasor sum of I'2 and

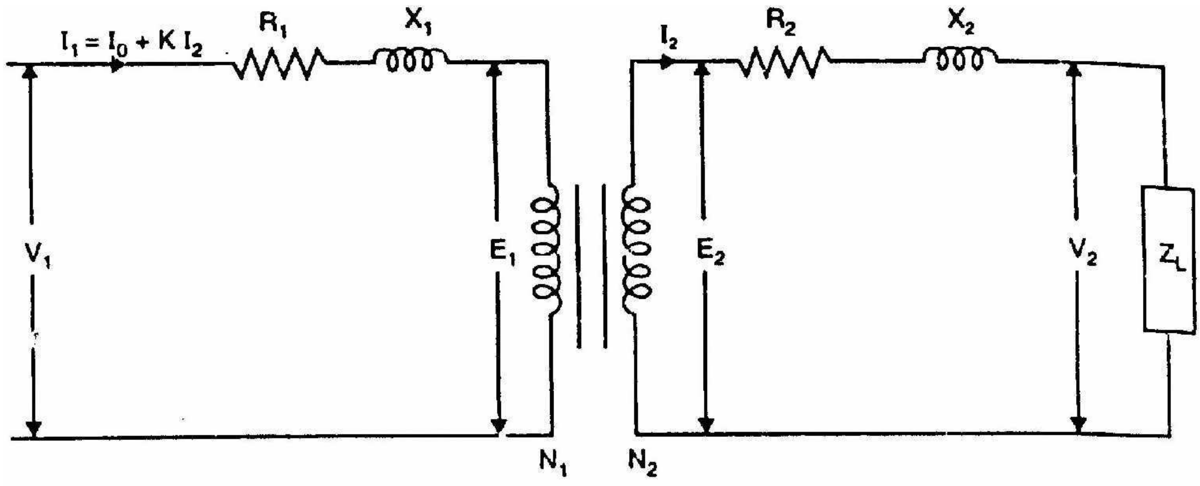
I_0 gives the total primary current I_1. Note that in drawing the phasor diagram, the value of K is assumed to be unity so that primary phasors are equal to secondary phasors.

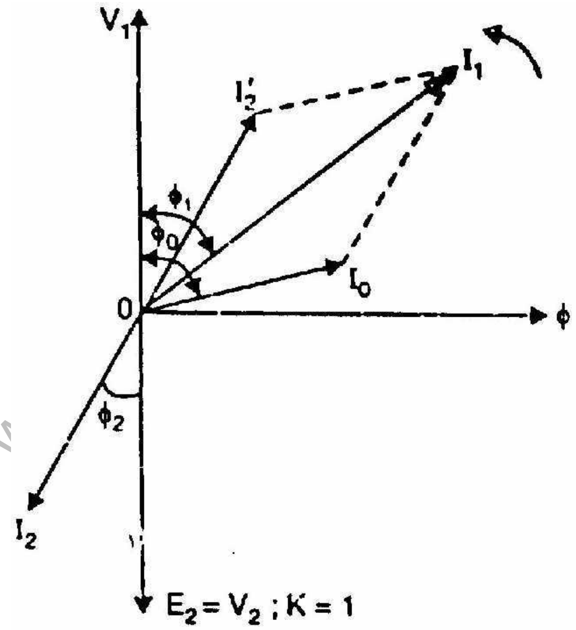
Primary p.f. = $\cos \phi_1$

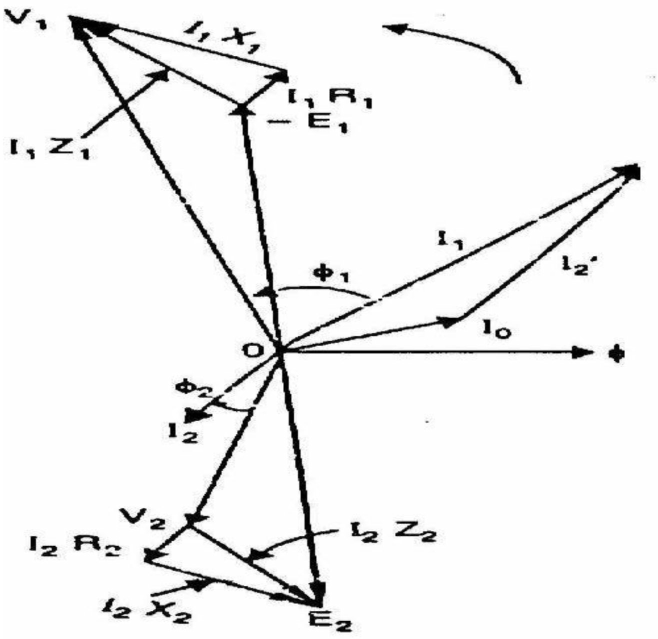
Secondary p.f. = $\cos \phi_2$

Primary input power = $V_1 I_1 \cos \phi_1$

Secondary output power = $V_1 I_2 \cos \phi_2$

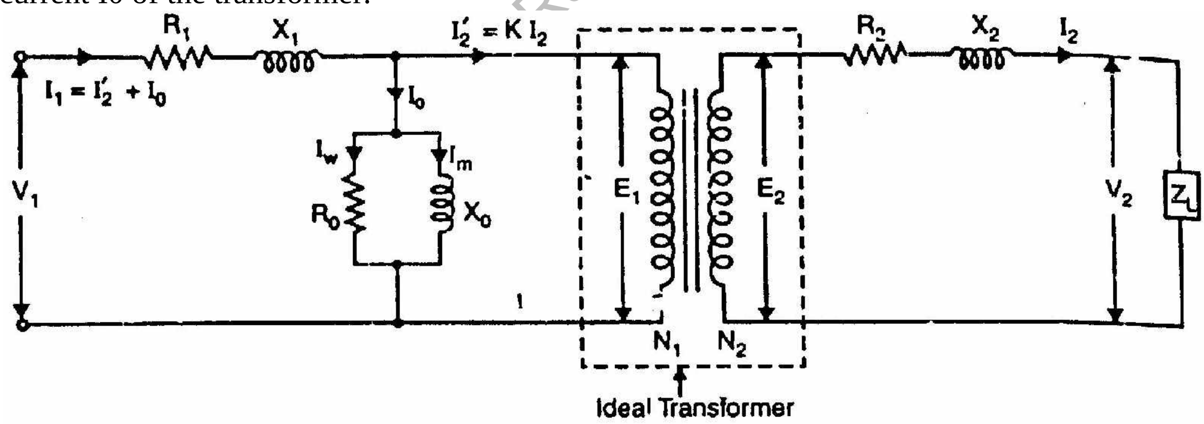






Equivalent Circuit of a Transformer

Fig shows the exact equivalent circuit of a transformer on load. Here R1 is the primary winding resistance and R2 is the secondary winding resistance. Similarly, X1 is the leakage reactance of primary winding and X2 is the leakage reactance of the secondary winding. The parallel circuit R0 □□X0 is the no-load equivalent circuit of the transformer. The resistance R0 represents the core losses (hysteresis and eddy current losses) so that current IW which supplies the core losses is shown passing through R0. The inductive reactance X0 represents a loss-free coil which passes the magnetizing current Im. The phasor sum of IW and Im is the no-load current I0 of the transformer.



Note that in the equivalent circuit shown in Fig. (7.19), the imperfections of the transformer have been taken into account by various circuit elements. Therefore, the transformer is now the ideal one. Note that equivalent circuit has created two normal electrical circuits separated only by an ideal transformer whose function is to change values according to the equation:

$$\frac{E_2}{E_1} = \frac{N_2}{N_1} = \frac{I'_2}{I_2}$$

The following points may be noted from the equivalent circuit:

(i) When the transformer is on no-load (i.e., secondary terminals are opencircuited), there is no current in the secondary winding. However, the primary draws a small no-load current I0. The no-load primary current I0 is composed of (a) magnetizing current (Im) to create magnetic flux in the core and (b) the current IW required to supply the core losses.

(ii) When the secondary circuit of a transformer is closed through some external load ZL, the voltage E2 induced in the secondary by mutual flux will produce a secondary current I2. There will be I2 R2 and I2 X2 drops in the secondary winding so that load voltage V2 will be less than E2.

(iii) When the transformer is loaded to carry the secondary current I2, the primary current consists of two components:

(a) The no-load current I0 to provide magnetizing current and the current required to supply the core losses.

(b) The primary current I'2 (= K I2) required to supply the load connected to the secondary.

(iv) Since the transformer in Fig. in now ideal, the primary induced voltage E1 can be calculated from the relation:

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

If we add I_1R_1 and I_1X_1 drops to E_1, we get the primary input voltage V_1

$$V_1 = -E_1 + I_1(R_1 + j\,X_1) = -E_1 + I_1Z_1$$

or $$V_1 = -E_1 + I_1Z_1$$

Voltage Drop in a Transformer

The approximate equivalent circuit of transformer referred to secondary is shown in Fig. At no-load, the secondary voltage is K V1. When a load having a lagging p.f. cos □2 is applied, the secondary carries a current I2 and voltage drops occur in (R2 + K2 R1) and (X2 + K2 X1). Consequently, the secondary voltage falls from K V1 to V2. Referring to Fig. (7.28), we have,

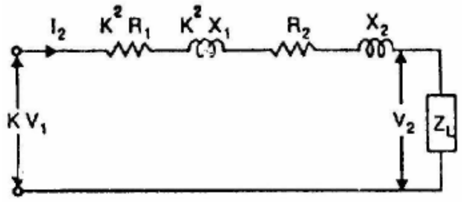
$$V_2 = KV_1 - I_2\left[\left(R_2 + K^2R_1\right) + j\left(X_2 + K^2X_1\right)\right]$$

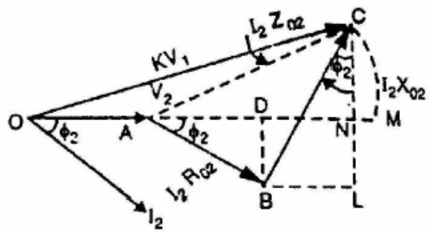
$$= KV_1 - I_2\left(R_{02} + j\,X_{02}\right)$$

$$= KV_1 - V_2 = I_2Z_{02}$$

Drop in secondary voltage $= KV_1 - V_2 = I_2 Z_{02}$

The phasor diagram is shown in Fig. (7.29). It is clear from the phasor diagram that drop in secondary voltage is AC = $I_2\ Z_{02}$. It can be found as follows. With O as centre and OC as radius, draw an arc cutting OA produced at M. Then AC = AM = AN. From B, draw BD perpendicular to OA produced. Draw CN perpendicular to OM and draw BL || OM.





Approximate drop in secondary voltage

$$= AN = AD + DN$$

$$= AD + BL \qquad (\because \quad BL = DN)$$

$$= I_2 R_{02} \cos\phi_2 + I_2 X_{02} \sin\phi_2$$

For a load having a leading p.f. cos ϕ_2, we have,

$$\text{Approximate voltage drop } = I_2 R_{02} \cos\phi_2 - I_2 X_{02} \sin\phi_2$$

Note: If the circuit is referred to primary, then it can be easily established that:

$$\text{Approximate voltage drop } = I_1 R_{01} \cos\phi_2 \pm I_1 X_{01} \sin\phi_2$$

Voltage Regulation

The voltage regulation of a transformer is the arithmetic difference (not phasor difference) between the no-load secondary voltage (0V2) and the secondary voltage V2 on load expressed as percentage of no-load voltage i.e.

$$\%\text{age voltage regulation } = \frac{{}_0V_2 - V_2}{{}_0V_2} \times 100$$

$${}_0V_2 = \text{No-load secondary voltage} = K\ V_1$$
$$V_2 = \text{Secondary voltage on load}$$

$$_0V_2 - V_2 = I_2R_{02}\cos\phi_2 \pm I_2X_{02}\sin\phi_2$$

The +ve sign is for lagging p.f. and –ve sign for leading p.f.

It may be noted that %age voltage regulation of the transformer will be the same whether primary or secondary side is considered.

Transformer Tests

The circuit constants, efficiency and voltage regulation of a transformer can be determined by two simple tests (i) open-circuit test and (ii) short-circuit lest. These tests are very convenient as they provide the required information without actually loading the transformer. Further, the power required to carry out these tests is very small as compared with full-load output of the transformer. These tests consist of measuring the input voltage, current and power to the primary first with secondary open-circuited (open-circuit test) and then with the secondary short-circuited (short circuit test).

Open-Circuit or No-Load Test

This test is conducted to determine the iron losses (or core losses) and parameters R0 and X0 of the transformer. In this test, the rated voltage is applied to the primary (usually low-voltage winding) while the secondary is left opencircuited.

The applied primary voltage V1 is measured by the voltmeter, the noload current I0 by ammeter and no-load input power W0 by wattmeter as shown in Fig. (7.30 (i)). As the normal rated voltage is applied to the primary, therefore, normal iron losses will occur in the transformer core. Hence wattmeter will record the iron losses and small copper loss in the primary. Since no-load current I0 is very small (usually 2-10 % of rated current). Cu losses in the primary under no-load condition are negligible as compared with iron losses.

Hence, wattmeter reading practically gives the iron losses in the transformer. It is reminded that iron losses are the same at all loads. Fig. (7.30 (ii)) shows the equivalent circuit of transformer on no-load.

Iron losses, Pi = Wattmeter reading = W0
No load current = Ammeter reading = I0
Applied voltage = Voltmeter reading = V1

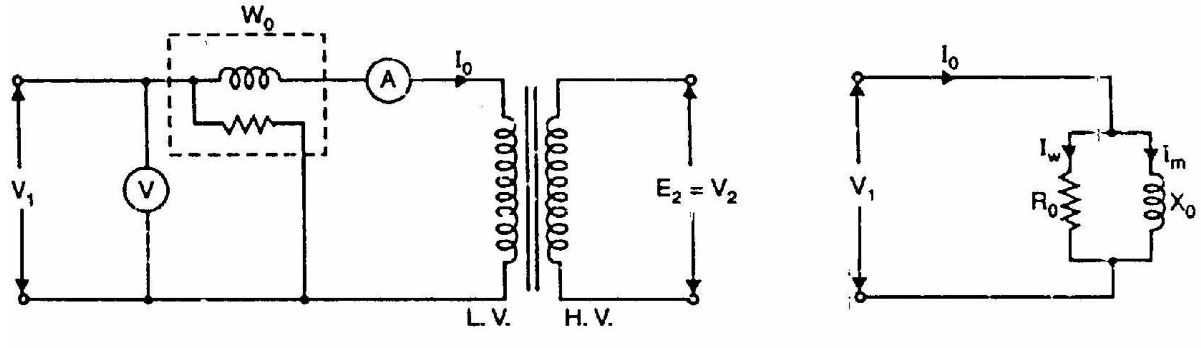
Inputpower,

$$\therefore \quad \text{No-load p.f.,}\ \cos\phi_0 = \frac{W_0}{V_1} I_0$$

$$I_W = I_0\cos\phi_0; \qquad I_m = I_0\sin\phi_0$$

$$R_0 = \frac{V_1}{I_W} \quad \text{and} \quad X_0 = \frac{V_1}{I_m}$$

Thus open-circuit test enables us to determine iron losses and parameters R0 and X0 of the transformer.



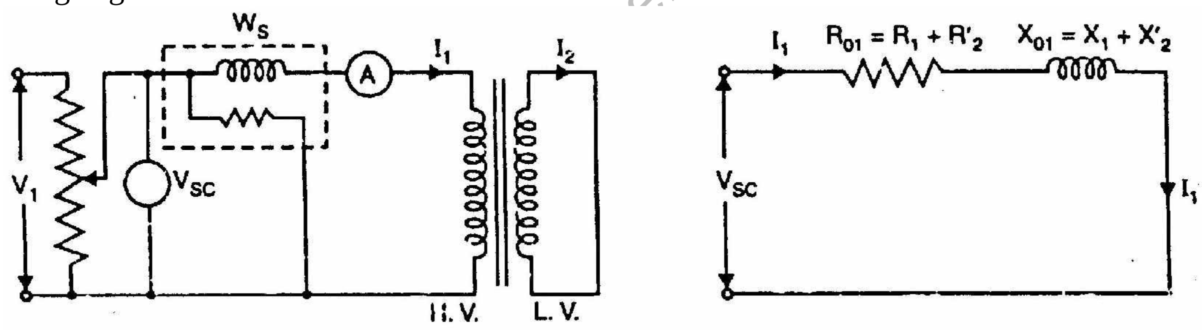
(i) (ii)

7.19 Short-Circuit or Impedance Test

This test is conducted to determine R01 (or R02), X01 (or X02) and full-load copper losses of the transformer. In this test, the secondary (usually low-voltage winding) is short-circuited by a thick conductor and variable low voltage is applied to the primary as shown in Fig. (i)). The low input voltage is gradually raised till at voltage VSC, full-load current I1 flows in the primary.

Then I2 in the secondary also has full-load value since I1/I2 = N2/N1. Under such conditions, the copper loss in the windings is the same as that on full load.

There is no output from the transformer under short-circuit conditions. Therefore, input power is all loss and this loss is almost entirely copper loss. It is because iron loss in the core is negligibly small since the voltage VSC is very small. Hence, the wattmeter will practically register the full-load copper losses in the transformer windings. Fig. (7.31 (ii)) shows the equivalent circuit of a transformer on short circuit as referred to primary; the no-load current being neglected due to its smallness.



(i) (ii)

Full load Cu loss, P_C = Wattmeter reading = W_S
Applied voltage = Voltmeter reading = V_{SC}
F.L. primary current = Ammeter reading = I_1

$$P_C = I_1^2 R_1 + I_1^2 R'_2 = I_1^2 R_{01}$$

$$\therefore \quad R_{01} = \frac{P_C}{I_1^2}$$

where R_{01} is the total resistance of transformer referred to primary.

Total impedance referred to primary, $Z_{01} = \frac{V_{SC}}{I_1}$

Total leakage reactance referred to primary, $X_{01} = \sqrt{Z_{01}^2 - R_{01}^2}$

Short-circuit p.f, $\cos\phi_2 = \frac{P_C}{V_{SC} I_1}$

Thus short-circuit lest gives full-load Cu loss, R_{01} and X_{01}.

Losses in a Transformer

The power losses in a transformer are of two types, namely;
1. Core or Iron losses 2. Copper losses
These losses appear in the form of heat and produce (i) an increase in temperature and (ii) a drop in efficiency.

1. Core or Iron losses (Pi)

These consist of hysteresis and eddy current losses and occur in the transformer core due to the alternating flux. These can be determined by open-circuit test. Hysteresis loss, □□kh $f^{1.6}$ Bm watts /m^3 Eddy current loss □□ke f^2 B^2 t watts /m^3

Both hysteresis and eddy current losses depend upon (i) maximum flux density Bm in the core and (ii) supply frequency f. Since transformers are connected to constant-frequency, constant voltage supply, both f and Bm are constant. Hence, core or iron losses are practically the same at all loads.

Iron or Core losses, Pi = Hysteresis loss + Eddy current loss = Constant losses

The hysteresis loss can be minimized by using steel of high silicon content whereas eddy current loss can be reduced by using core of thin laminations.

2. Copper losses

These losses occur in both the primary and secondary windings due to their ohmic resistance. These can be determined by short-circuit test.

$$\text{Total Cu losses,} \quad P_C = I_1^2 R_1 + I_2^2 R_2$$
$$= I_1^2 R_{01} \text{ or } I_2^2 R_{02}$$

It is clear that copper losses vary as the square of load current Thus if copper losses are 400 W at a load current of 10 A, then they will be $(1/2)^2 \times 400 = 100$ W at a load current of 5A.

$$\text{Total losses in a transformer} = P_1 + P_C$$
$$= \text{Constant losses} + \text{Variable losses}$$

It may be noted that in a transformer, copper losses account for about 90% of the total losses.

Efficiency of a Transformer

Like any other electrical machine, the efficiency of a transformer is defined as the ratio of output power (in watts or kW) to input power (watts or kW) i.e.,

$$\text{Efficiency} = \frac{\text{Output power}}{\text{Input power}}$$

It may appear that efficiency can be determined by directly loading the transformer and measuring the input power and output power. However, this method has the following drawbacks:

(i) Since the efficiency of a transformer is very high, even 1% error in each wattmeter (output and input) may give ridiculous results. This test, for instance, may give efficiency higher than 100%.

(ii) Since the test is performed with transformer on load, considerable amount of power is wasted. For large transformers, the cost of power alone would be considerable.

(iii) It is generally difficult to have a device that is capable of absorbing all of the output power.

(iv) The test gives no information about the proportion of various losses.

Due to these drawbacks, direct loading method is seldom used to determine the efficiency of a transformer. In practice, open-circuit and short-circuit tests are carried out to find the efficiency.

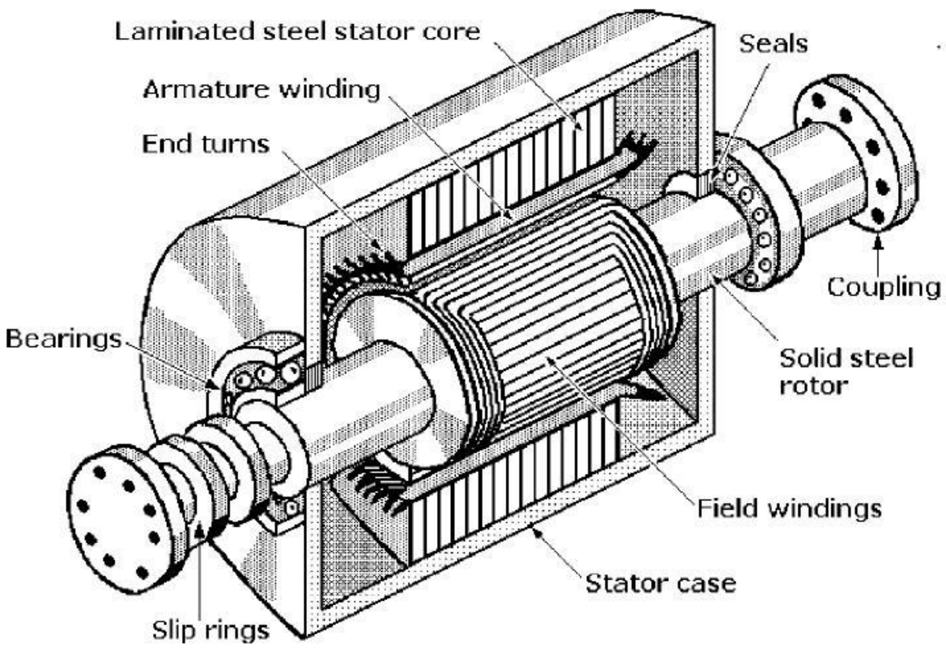
$$\text{Efficiency} = \frac{\text{Output}}{\text{Input}} = \frac{\text{Output}}{\text{Output} + \text{Losses}}$$

4. A.C.MACHINES

Introduction to Alternators:

Definition of Alternator

The definition of alternator is hidden in the name of this machine itself. An alternator is such a machine which produces alternation electricity. It is a kind of generators which converts mechanical energy into alternating electrical energy. It is also known as synchronous generator.



Cutaway view of a synchronous AC generator with a solid cylindrical rotor capable of high-speed rotation.

History of Alternator

Michael Faraday and HippolytePixii gave the very first concept of alternator. Michael Faraday designed a rotating rectangular turn of conductor inside a magnetic field to produce alternating current in the external static circuit. After that in the year of 1886 J.E.H. Gordon, designed and produced first prototype of useful model. After that Lord Kelvin and Sebastian Ferranti designed a model of 100 to 300 Hz synchronous generator. Nikola Tesla in 1891, designed a commercially useful 15 KHz generator. After this year, poly phase alternators were come into picture which can deliver currents of multiple phases.

Use of Alternator

The power for electrical system of modern vehicles produces from alternator. In previous days, DC generators or dynamos were used for this purpose but after development of alternator, the dc dynamos are replaced by more robust and light weight alternator. Although the electrical system of motor vehicles generally requires direct current but still an alternator along with diode rectifier instead of a DC generator is better choice as the complicated commutation is absent here. This special type of generator which is used in vehicle is known as automotive alternator. Another use of alternator is in diesel electric locomotive. Actually the engine of this locomotive is nothing but an alternator driven by diesel engine. The alternating current produced by this generator is converted to DC by integrated silicon diode rectifiers to feed all the dc traction motors. And these dc traction motors drive the wheel of the locomotive.

This machine is also used in marine similar to diesel electric locomotive. The synchronous generator used in marine is specially designed with appropriate adaptations to the salt-water environment. The typical output level of marine alternator is about 12 or 24 volt. In large marine, more than one units are used to provide large power. In this marine system the power produced by alternator is first rectified then used for charging the engine starter battery and auxiliary supply battery of marine.

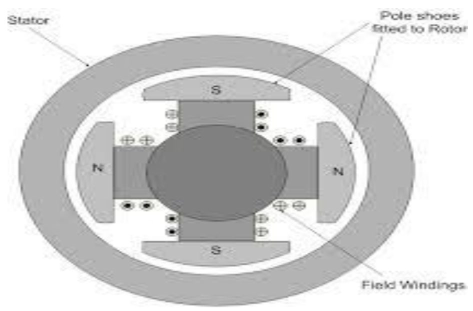
Types of Alternator:

Alternators or synchronous generators can be classified in many ways depending upon their application and design. According to application these machines are classified as-

1. Automotive type - used in modern automobile.
2. Diesel electric locomotive type - used in diesel electric multiple unit.
3. Marine type - used in marine.
4. Brush less type - used in electrical power generation plant as main source of power.
5. Radio alternators - used for low brand radio frequency transmission.

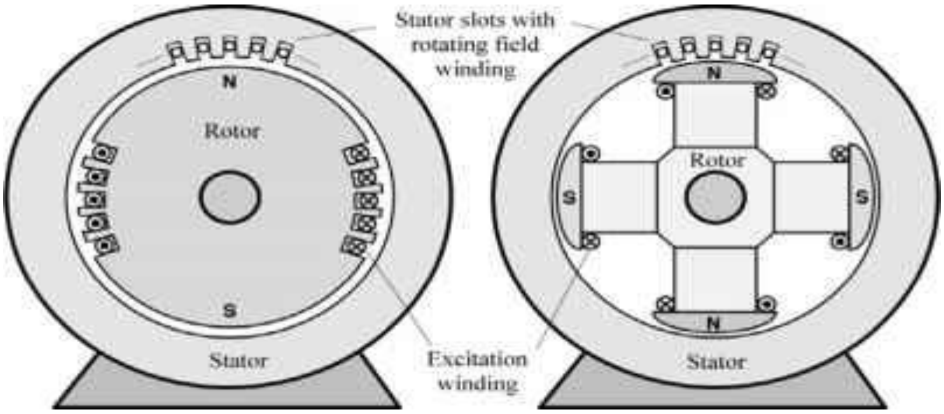
These ac generators can be divided in many ways but we will discuss now two main types of alternator categorized according to their design. These are

1. Salient pole type is used as low and medium speed alternator. It has a large number of projecting poles having their cores bolted or dovetailed onto a heavy magnetic wheel of cast iron or steel of good magnetic quality. Such generators are characterized by their large diameters and short axial lengths. These generators are look like big wheel. These are mainly used for low speed turbine such as in hydra power plant.



A salient 4-pole Generator. Carefully observe the location of North & South poles

2. Smooth cylindrical type It is used for steam turbine driven alternator. The rotor of this generator rotates in very high speed. The rotor consists of a smooth solid forged steel cylinder having a number of slots milled out at intervals along the outer periphery for accommodation of field coils. These rotors are designed mostly for 2 pole or 4 pole turbo generator running at 36000 rpm or 1800 rpm respectively.



Working Principle of Alternator:

The alternators work on the principle of electromagnetic induction.When there is a relative motion between the conductors and the flux,emf gets induced in the conductors .The dc generators also work on the same principle .The only difference in practical alternator and a dc generator is that in an alternator the conductors are stationary and field is rotating.But for understanding purpose we can always consider relative motion of conductors w.r.t the flux produced by the field winding.

Consider a relative motion of a single conductor under the magnetic field produced by two stationary poles.The magnetic axis of two poles produced by field is vertical,shown dotted in below figure.

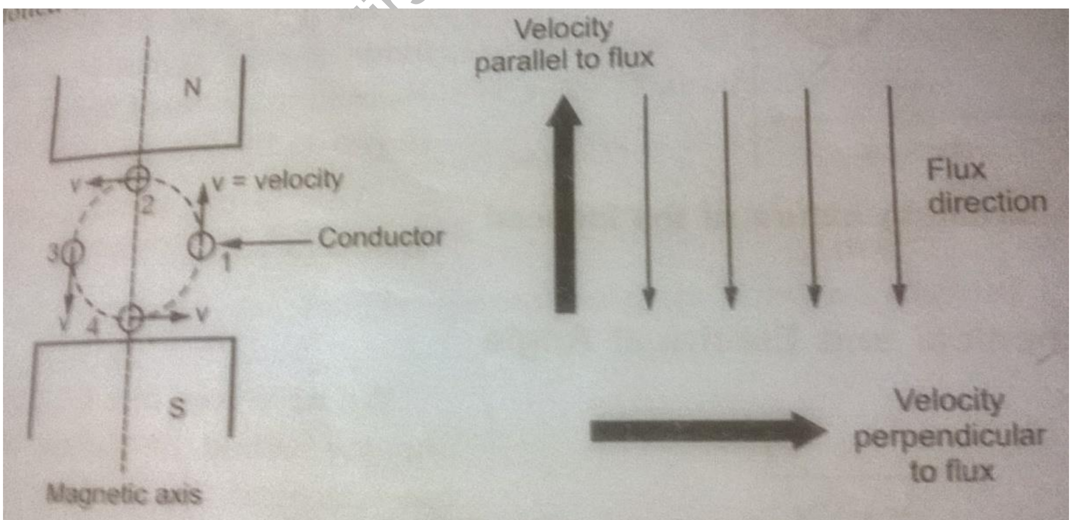
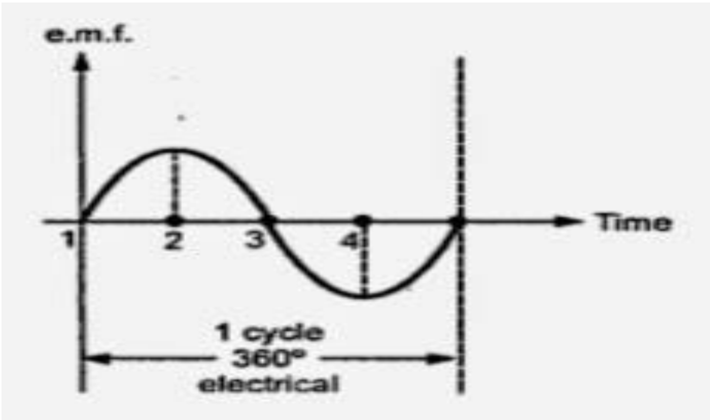


Fig. 1.6 Two pole alternator

Let conductor starts rotating from position 1.at this instant,the entire velocity component is parallel to the flux lines .Hence there is no cutting of flux lines by the conductor.So d@/dt at this instant is zero and hence induced emf in the conductor is also zero. As the conductor moves from position 1 to position 2,the part of the velocity component becomes perpendicular to the flux lines and proportional to that,emf gets induced in the conductor.The magnitude of such an induced emf increases as conductor moves from position 1 to 2.

At position 2 ,the entire velocity component is perpendicular to the flux lines .Hence there exists cutting of the flux lines.And at this instant,the induced emf in the conductor is at its maximum.As the position of conductor changes from 2 to 3 ,the velocity component perpendicular to the flux starts decreasing and hence induced emf magnitude also starts decreasing.At position 3,again the entire velocity component is parallel to the flux lines and hence at this instant induced emf in the conductor is zero.

As the conductor moves from 3 to 4 ,velocity component perpendicular to the flux lines again starts increasing.But the direction of velocity component now is opposite to the direction of velocity component existing during the movement of the conductor from position 1 to 2.Hence an induced emf in the conductor increase but in the opposite direction.



At position 4,it achieves maxima in the opposite direction, as the entire velocity component becomes perpendicular to flux lines.Again from position 4 to 1, induced emf decreases and finally at position again becomes zero.This cycle continues as conductor rotates at a certain speed. So if we plot the magnitudes of the induced emf against the time,we get an alternating nature of the induced emf shown figure above.

REGULATION OF SYNCHRONOUS GENERATOR

Voltage Regulation:

When an alternator is subjected to a varying load, the voltage at the armature terminals varies to a certain extent, and the amount of this variation determines the regulation of the machine. When the alternator is loaded the terminal voltage decreases as the drops in the machine stars increasing and hence it will always be different than the induced emf.

Voltage regulation of an alternator is defined as the change in terminal voltage from no load to full load expressed as a percentage of rated voltage when the load at a given power factor is removed without change in speed and excitation or the numerical value of the regulation is defined as the percentage rise in voltage when full load at the specified power-factor is switched off with speed and field current remaining unchanged expressed as a percentage of rated voltage. Hence regulation can be expressed as

$$\% \text{ Regulation} = (Eph – Vph / Vph) \times 100$$

where Eph = induced emf /phase, Vph = rated terminal voltage/phase

EMF method:

This method is also known as synchronous impedance method. Here the magnetic circuit is assumed to be unsaturated. In this method the MMFs (fluxes) produced by rotor and stator are replaced by their equivalent emf, and hence called emf method.

To predetermine the regulation by this method the following information is to be determined. Armature resistance /phase of the alternator, open circuit and short circuit characteristics of the alternator.

Open Circuit Characteristic (O.C.C.)

The open-circuit characteristic or magnetization curve is really the B-H curve of the complete magnetic circuit of the alternator. Indeed, in large turbo-alternators, where the air gap is relatively long, the curve shows a gradual bend. It is determined by inserting resistance in the field circuit and measuring corresponding value of terminal voltage and field current. Two voltmeters are connected across the armature terminals.

The machine is run at rated speed and field current is increased gradually to $If1$ till armature voltage reaches rated value or even 25% more than the rated voltage. Figure1 illustrates OC and SC curve. The major portion of the exciting ampere-turns is required to force the flux across the air gap, the reluctance of which is assumed to be constant. A straight line called the air gap line can therefore be drawn as shown, dividing theexcitation for any voltage into two portions, (a) that required to force the flux across the air gap, and (b) that required to force it through the remainder of the magnetic circuit. The shorter the air gap, the steeper is the air gap line.

Procedure to conduct OC test:

(i) Start the prime mover and adjust the speed to the synchronous speed of the alternator.

(ii) Keep the field circuit rheostat in cut in position and switch on DC supply.

(iii) Keep the TPST switch of the stator circuit in open position.

(iv)Vary the field current from minimum in steps and take the readings of field current and stator terminal voltage, till the voltage read by the voltmeter reaches up to 110% of rated voltage. Reduce the field current and stop the machine.

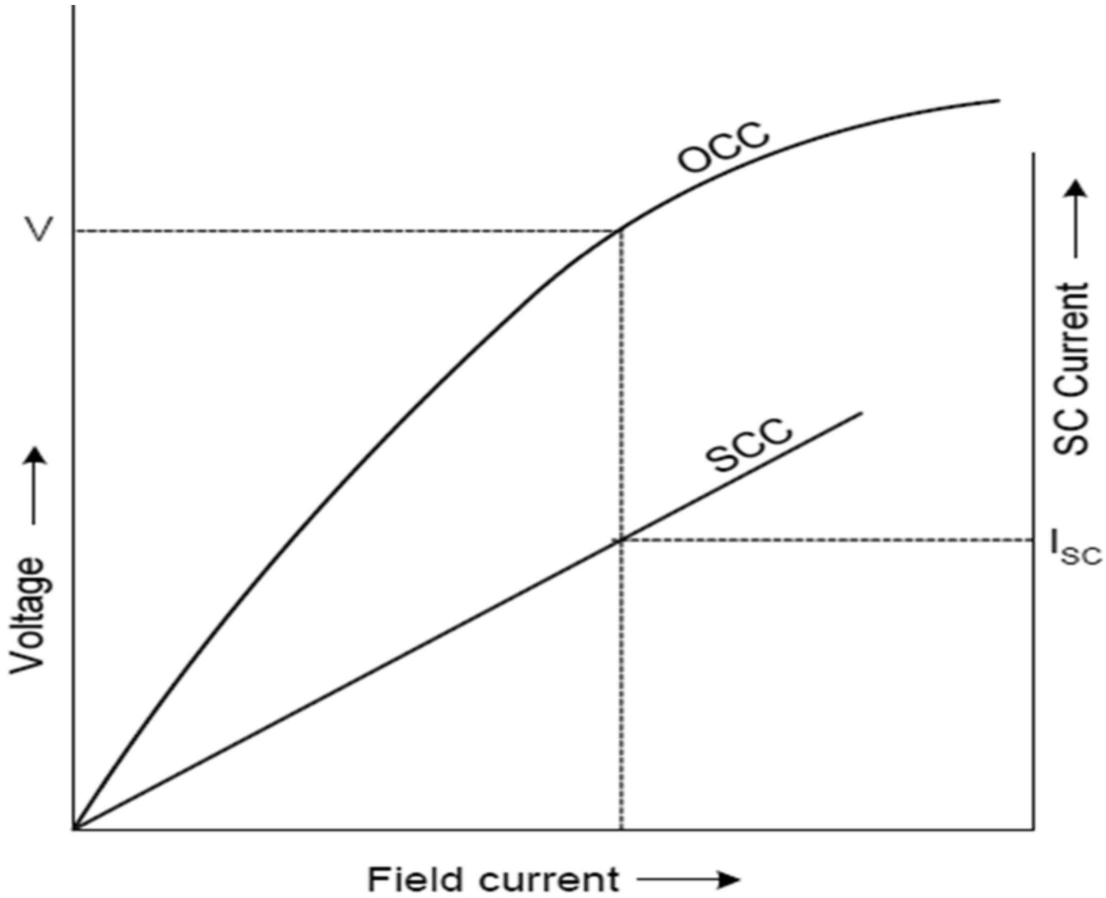
(v) Plot of terminal voltage/ phase vs field current gives the OC curve.

Short Circuit Characteristic (S.C.C.)

The short-circuit characteristic, as its name implies, refers to the behavior of the alternator when its armature is short-circuited. In a single-phase machine the armature terminals are short-circuited through an ammeter, but in a three-phase machine all three phases must be short-circuited. An ammeter is connected in series with each armature terminal, the three remaining ammeter terminals being short-circuited. The machine is run at rated speed and field current is increased gradually to I*f*2 till armature current reaches rated value. The armature short-circuit current and the field current are found to be proportional to each other over a wide range, as shown in Figure, so that the short- circuit characteristic is a straight line.

Under short-circuit conditions the armature current is almost 90° out of phase with the voltage, and the armature mmf has a direct demagnetizing action on the field. The resultant ampere − turns inducing the armature emf are, therefore, very small and is equal to the difference between the field and the armature ampere − turns. This results in low mmf in the magnetic circuit, which remains in unsaturated condition and hence the small value of induced emf increases linearly with field current. This small induced armature emf is equal to the voltage drop in the winding itself, since the terminal voltage is zero by assumption. It is the voltage required to circulate the short- circuit current through the armature windings. The armature resistance is usually small compared with the reactance.

Air Gap line



Short-Circuit Ratio:

The short-circuit ratio is defined as the ratio of the field current required to produce rated volts on open circuit to field current required to circulate full-load current with the armature short-circuited.

Short-circuit ratio = If1/If2

Determination of synchronous impedance Zs:

As the terminals of the stator are short circuited in SC test, the short circuit current is circulated against the impedance of the stator called the synchronous impedance. This impedance can be estimated form the oc and sc characteristics.

The ratio of open circuit voltage to the short circuit current at a particular field current, or at a field current responsible for circulating the rated current is called the synchronous impedance.

synchronous impedance Zs = (open circuit voltage per phase)/(short circuit current per phase) for same If

Hence Zs = (Voc) / (Isc) for same If

From figure 1 synchronous impedance Zs = V/Isc

Armature resistance Ra of the stator can be measured using Voltmeter – Ammeter method. Using synchronous impedance and armature resistance synchronous reactance and hence regulation can be calculated as follows using emf method.

Zs = √(Ra)2 + (XS)2 and Synchronous reactance Xs = √(Zs)2 - (Ra)2

Hence induced emf per phase can be found as Eph = √[(V cos + IRa)2 + (V sin ± IXS)2]

where V = phase voltage per phase = Vph , I = load current per phase in the above expression in second term + sign is for lagging pwer factor ans – sign is for leading power factor.

% Regulation = [(Eph – Vph / Vph)] x 100

where Eph = induced emf /phase, Vph = rated terminal voltage/phase

Synchronous impedance method is easy but it gives approximate results. This method gives the value of regulation which is greater (poor) than the actual value and hence thismethod is called pessimistic method. The complete phasor diagram for the emf method is shown in figure 2

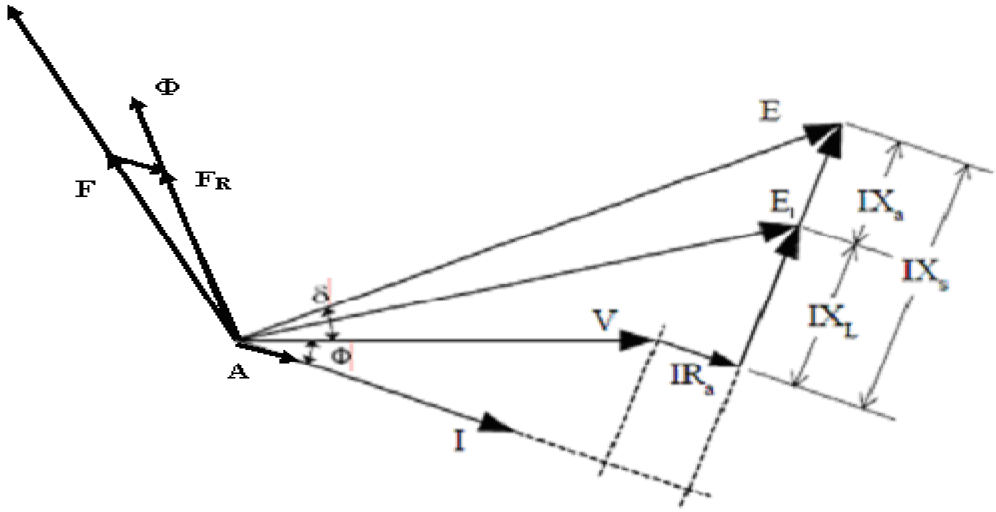


Fig2.phasor diagram

Three Phase Induction Motor

Construction:

` The three phase induction motor is the most widely used electrical motor. Almost 80% of the mechanical power used by industries is provided by three phase induction motors because of its simple and rugged construction, low cost, good operating characteristics, absence of commutator and good speed regulation. In three phase induction motor the power is transferred from stator to rotor winding through induction. The Induction motor is also called asynchronous motor as it runs at a speed other than the synchronous speed. Like any other electrical motor induction motor also have two main parts namely rotor and stator.

1. Stator: As its name indicates stator is a stationary part of induction motor. A stator winding is placed in the stator of induction motor and the three phase supply is given to it.
2. Rotor: The rotor is a rotating part of induction motor. The rotor is connected to the mechanical load through the shaft.

The rotor of the three phase induction motor are further classified as

1. Squirrel cage rotor,
2. Slip ring rotor or wound rotor or phase wound rotor.

Depending upon the type of rotor construction used the three phase induction motor are classified as:

1. Squirrel cage induction motor,
2. Slip ring induction motor or wound induction motor or phase wound induction motor.

The construction of stator for both the kinds of three phase induction motor remains the same and is discussed in brief in next paragraph. The other parts, which are required to complete the induction motor, are:

1. Shaft for transmitting the torque to the load. This shaft is made up of steel.
2. Bearings for supporting the rotating shaft.

3. One of the problems with electrical motor is the production of heat during its rotation. In order to overcome this problem we need fan for cooling.
4. For receiving external electrical connection Terminal box is needed.
5. There is a small distance between rotor and stator which usually varies from 0.4 mm to 4 mm. Such a distance is called air gap.

Types of Three Phase Induction Motor

Squirrel cage three phase induction motor: The rotor of the squirrel cage three phase induction motor is cylindrical in shape and have slots on its periphery. The slots are not made parallel to each other but are bit skewed (skewing is not shown in the figure of squirrel cadge rotor beside) as the skewing prevents magnetic locking of stator and rotor teeth and makes the working of motor more smooth and quieter. The squirrel cage rotor consists of aluminum, brass or copper bars (copper bras rotor is shown in the figure beside). These aluminum, brass or copper bars are called rotor conductors and are placed in the slots on the periphery of the rotor. The rotor conductors are permanently shorted by the copper or aluminum rings called the end rings. In order to provide mechanical strength these rotor conductor are braced to the end ring and hence form a complete closed circuit resembling like a cage and hence got its name as "squirrel cage induction motor". The squirrel cage rotor winding is made symmetrical. As the bars are permanently shorted by end rings, the rotor resistance is very small and it is not possible to add external resistance as the bars are permanently shorted. The absence of slip ring and brushes make the construction of Squirrel cage three phase induction motor very simple and robust and hence widely used three phase induction motor. These motors have the advantage of adapting any number of pole pairs. The below diagram shows squirrel cage induction rotor having aluminum bars short circuit by aluminum end rings.

Advantages of squirrel cage induction rotor-

1. Its construction is very simple and rugged.
2. As there are no brushes and slip ring, these motors requires less maintenance.

Applications: Squirrel cage induction motor is used in lathes, drilling machine, fan, blower printing machines etc

Slip ring or wound three phase induction motor : In this type of three phase induction motor the rotor is wound for the same number of poles as that of stator but it has less number of slots and has less turns per phase of a heavier conductor.The rotor also carries star or delta winding similar to that of stator winding. The rotor consists of numbers of slots and rotor winding are placed inside these slots. The three end terminals are connected together to form star connection. As its name indicates three phase slip ring induction motor consists of slip rings connected on same shaft as that of rotor. The three ends of three phase windings are permanently connected to these slip rings. The external resistance can be easily connected through the brushes and slip rings and hence used for speed control and improving the starting torque of three phase induction motor. The brushes are used to carry current to and from the rotor winding. These brushes are further connected to three phase star connected resistances. At starting, the resistance are connected in rotor circuit and is gradually cut out as the rotor pick up its speed. When the motor is running the slip ring are shorted by connecting a metal collar, which connect all slip ring together and the brushes are also removed. This reduces wear and tear of the brushes.

Advantages of slip ring induction motor -

It has high starting torque and low starting current. Possibility of adding additional resistance to control speed.

Application:
Slip ring induction motor are used where high starting torque is required i.e in hoists, cranes, elevator etc.

Difference between Slip Ring and Squirrel Cage Induction Motor

Slip ring or phase wound Induction motor	Squirrel cage induction motor
Construction is complicated due to presence of slip ring and brushes	Construction is very simple
The rotor winding is similar to the stator winding	The rotor consists of rotor bars which are permanently shorted with the help of end rings
We can easily add rotor resistance by using slip ring and brushes	Since the rotor bars are permanently shorted, its not possible to add external resistance
Due to presence of external resistance high starting torque can be obtained	Staring torque is low and cannot be improved
Slip ring and brushes are present	Slip ring and brushes are absent
Frequent maintenance is required due to presence of brushes	Less maintenance is required
The construction is complicated and the presence of brushes and slip ring makes the motor more costly	The construction is simple and robust and it is cheap as compared to slip ring induction motor
This motor is rarely used only 10 % industry uses slip ring induction motor	Due to its simple construction and low cost. The squirrel cage induction motor is widely used
Rotor copper losses are high and hence less efficiency	Less rotor copper losses and hence high efficiency
Speed control by rotor resistance method is possible	Speed control by rotor resistance method is not possible
Slip ring induction motor are used where high starting torque is required i.e in hoists, cranes, elevator etc	Squirrel cage induction motor is used in lathes, drilling machine, fan, blower printing machines etc

Working Principle of Three Phase Induction Motor

An electrical motor is such an electromechanical device which converts electrical energy into a mechanical energy. In case of three phase AC operation, most widely used motor is three phase induction motor as this type of motor does not require any starting device or we can say they are self starting induction motor. For better understanding the principle of three phase induction motor, the basic constructional feature of this motor must be known to us.

This Motor consists of two major parts:

Stator: Stator of three phase induction motor is made up of numbers of slots to construct a 3 phase winding circuit which is connected to 3 phase AC source. The three phase winding are arranged in such a manner in the slots that they produce a rotating magnetic field after 3Ph. AC supply is given to them.

Rotor: Rotor of three phase induction motor consists of cylindrical laminated core with parallel slots that can carry conductors. Conductors are heavy copper or aluminum bars which fits in each slots & they are short circuited by the end rings. The slots are not exactly made parallel to the axis of the shaft but are slotted a little skewed because this arrangement reduces magnetic humming noise & can avoid stalling of motor.

Production of Rotating Magnetic Field

The stator of the motor consists of overlapping winding offset by an electrical angle of 120°. When the primary winding or the stator is connected to a 3 phase AC source, it establishes a rotating magnetic field which rotates at the synchronous speed. Secrets behind the rotation: According to Faraday's law an emf induced in any circuit is due to the rate of change of magnetic flux linkage through the circuit. As the rotor winding in an induction motor are either closed through an external resistance or directly shorted by end ring, and cut the stator rotating magnetic field, an emf is induced in the rotor copper bar and due to this emf a current flows through the rotor conductor. Here the relative speed between the rotating flux and static rotor conductor is the cause of current generation; hence as per Lenz's law the rotor will rotate in the same direction to reduce the cause i.e. the relative velocity.

Thus from the working principle of three phase induction motor it may observed that the rotor speed should not reach the synchronous speed produced by the stator. If the speeds equals, there would be no such relative speed, so no emf induced in the rotor, & no current would be flowing, and therefore no torque would be generated. Consequently the rotor can not reach the synchronous speed. The difference between the stator (synchronous speed) and rotor speeds is called the slip. The rotation of the magnetic field in an induction motor has the advantage that no electrical connections need to be made to the rotor. Thus the three phase induction motor is:

- Self-starting.
- Less armature reaction and brush sparking because of the absence of commutators and brushes that may cause sparks.
- Robust in construction.
- Economical.
- Easier to maintain.

Losses and Efficiency of Induction Motor

There are two types of losses occur in three phase induction motor. These losses are,

1. Constant or fixed losses,
2. Variable losses.

1) Constant or Fixed Losses

Constant losses are those losses which are considered to remain constant over normal working range of induction motor. The fixed losses can be easily obtained by performing no-load test on the three phase induction motor. These losses are further classified as-

1. Iron or core losses,
2. Mechanical losses,
3. Brush friction losses.

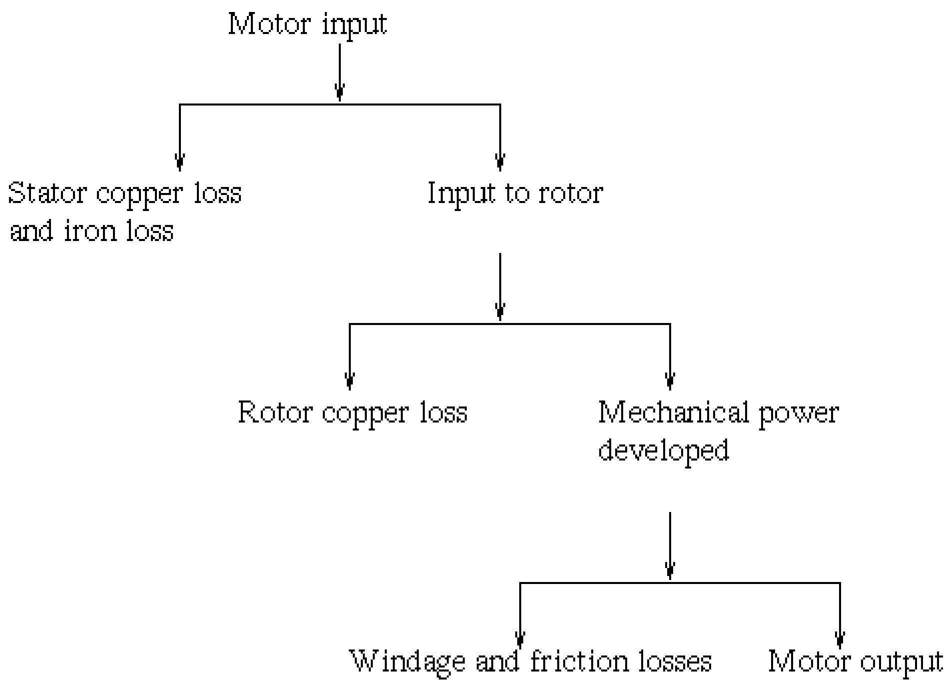
Iron or Core Losses

Iron or core losses are further divided into hysteresis and eddy current losses. Eddy current losses are minimized by using lamination on core. Since by laminating the core, area decreases and hence resistance increases, which results in decrease in eddy currents. Hysteresis losses are minimized by using high grade silicon steel. The core losses depend upon frequency of the supply voltage. The frequency of stator is always supply frequency, f and the frequency of rotor is slip times the supply frequency, (sf) which is always less than the stator frequency. For stator frequency of 50 Hz, rotor frequency is about 1.5 Hz because under normal running condition slip is of the order of 3 %. Hence the rotor core loss is very small as compared to stator core loss and is usually neglected in running conditions.

Mechanical and Brush Friction Losses

Mechanical losses occur at the bearing and brush friction loss occurs in wound rotor induction motor. These losses are zero at start and with increase in speed these losses increases. In three phase induction motor the speed usually remains constant. Hence these losses almost remains constant.

Variable Losses



These losses are also called copper losses. These losses occur due to current flowing in stator and rotor windings. As the load changes, the current flowing in rotor and stator winding also changes and hence these losses also changes. Therefore these losses are called variable losses. The copper losses are obtained by performing blocked rotor test on three phase induction motor.

The main function of induction motor is to convert an electrical power into mechanical power. During this conversion of electrical energy into mechanical energy the power flows through different stages. This power flowing through different stages is shown by power flow diagram.

As we all know the input to the three phase induction motor is three phase supply. So, the three phase supply is given to the stator of three phase induction motor.

Let,

P_{in} = electrical power supplied to the stator of three phase induction motor,

V_L = line voltage supplied to the stator of three phase induction motor,

I_L = line current,

$\cos\varphi$ = power factor of the three phase induction motor.

Electrical power input to the stator, $P_{in} = \sqrt{3}V_L I_L \cos\varphi$ A part of this power input is used to supply stator losses which are stator iron loss and stator copper loss.

The remaining power i.e (input electrical power – stator losses) are supplied to rotor as rotor input.

So, rotor input $P_2 = P_{in}$ – stator losses (stator copper loss and stator iron loss).

Now, the rotor has to convert this rotor input into mechanical energy but this complete input cannot be converted into mechanical output as it has to supply rotor losses. As explained earlier the rotor losses are of two types rotor iron loss and rotor copper loss. Since the iron loss depends upon the rotor frequency, which is very small when the rotor rotates, so it is usually neglected. So, the rotor has only rotor copper loss.

Therefore the rotor input has to supply these rotor copper losses. After supplying the rotor copper losses, the remaining part of Rotor input, P_2 is converted into mechanical power, P_m.

Let P_c be the rotor copper loss, I_2 be the rotor current under running condition, R_2 is the rotor resistance, P_m is the gross mechanical power developed.

$$P_c = 3I_2^2R_2 \quad P_m = P_2 - P_c$$

Now this mechanical power developed is given to the load by the shaft but there occur some mechanical losses like friction and windage losses.

So, the gross mechanical power developed has to be supplied to these losses. Therefore the net output power developed at the shaft, which is finally given to the load is P_{out}.

$P_{out} = P_m$ – Mechanical losses (friction and windage losses).

P_{out} is called the shaft power or useful power.

Efficiency of Three Phase Induction Motor

Efficiency is defined as the ratio of the output to that of input,

$$Efficiency,\ \eta = \frac{output}{input}$$

Rotor efficiency of the three phase induction motor ,

$$= \frac{rotor\ output}{rotor\ input}$$

= Gross mechanical power developed / rotor input

$$= \frac{P_m}{P_2}$$

Three phase induction motor efficiency

$$= \frac{power\ developed\ at\ shaft}{electrical\ input\ to\ the\ motor}$$

Three phase induction motor efficiency

$$\eta = \frac{P_{out}}{P_{in}}$$

Power Flow in an Induction Motor

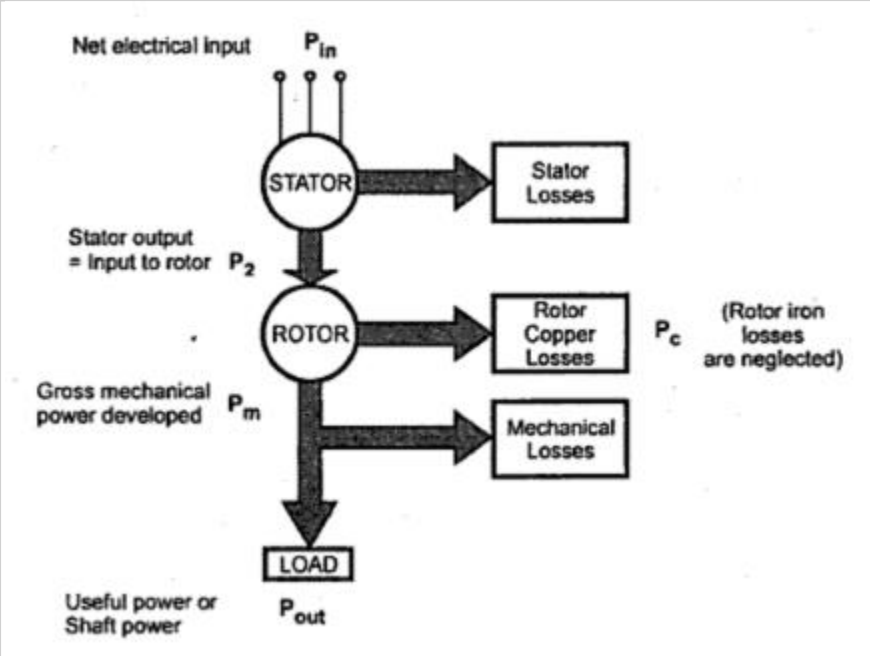


Fig. 1 Power flow diagram

Ques1: A 12 pole 3 φ alternator driver at speed of 500 r.p.m. supplies power to an 8 pole 3 φ induction motor. If the slip of motor is 0.03p.u, calculate the speed.

Solution

Frequency of supply from alternator, f=PN/120

=12*500/120 = 50hz

where P= no of poles on alternatev
N=alternator speed is r.p.m.
Synchronous speed of 3 φ induction motor
N=120f/Pm
=120*50/8 = 750 r.p.m.

Speed of 3 φ induction motor N=Ns (1-s)
=750(1-0.03) = 727.5 r.p.m.

Ques2: A 3 φ 4 pole 50 hz induction motor runs at 1460 r.p.m. find its %age slip.

Solution

N_s = 120f/p = 120*50/4 = 1500r.p.m.

Running speed of motor = n= 1460r.p.m.
Slip S=(N_s–N)/ N_s*100

=(1500-1460) x 100 / 1500

= 2.667%

Ques 3: A 3-φ 4 pole induction motor is supplied from 3φ 50Hz ac supply. Find
(1) synchronous speed
(2) rotor speed when slip is 4%
(3) the rotor frequency when runs at 600r.p.m.
Solution
1) N_s =120f/p
=120*50/4

= 1500 r.p.m.

2) speed when slip is 4% or .04
N=N_s (1-s)
=1500(1-0.04) = 1440 r.p.m.

3) slip when motor runs at 600 r.p.m.
S'=(N_s –N)/N_s
=(1500-600)/1500
= 0.6

Rotor frequency f' = S'f

= 0.6*50

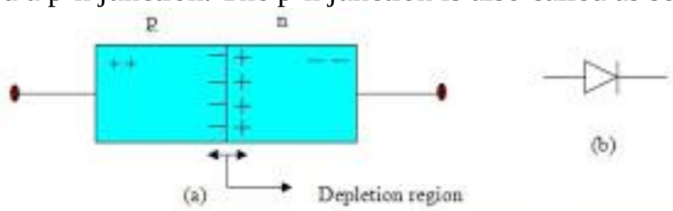
= 30Hz.

4. RECTIFIERS & LINEAR ICs

SEMICONDUCTOR

DIODE

When a p-type semiconductor material is suitably joined to n-type semiconductor the contact surface is called a p-n junction. The p-n junction is also called as semiconductor diode.



(a) p-n junction (b) symbolic representation

The left side material is a p-type semiconductor having –ve acceptor ions and +vely charged holes. The right side material is n-type semiconductor having +ve donor ions and free electrons.

• Suppose the two pieces are suitably treated to form pn junction, then there is a tendency for the free electrons from n-type to diffuse over to the p-side and holes from p-type to the n-side . This process is called diffusion.

• As the free electrons move across the junction from n-type to p-type, +ve donor ions are uncovered. Hence a +ve charge is built on the n-side of the junction. At the same time, the free electrons cross the junction and uncover the –ve acceptor ions by filling in the holes. Therefore a net –ve charge is established on p-side of the junction.

• When a sufficient number of donor and acceptor ions is uncovered further diffusion is prevented.

• Thus a barrier is set up against further movement of charge carriers. This is called potential barrier or junction barrier Vo. The potential barrier is of the order of 0.1 to 0.3V.

Note: outside this barrier on each side of the junction, the material is still neutral. Only inside the barrier, there is a +ve charge on n-side and –ve charge on p-side. This region is called depletion layer.

2.1 Biasing: Connecting a p-n junction to an external d.c. voltage source is called biasing.

1. Forward biasing
2. Reverse biasing

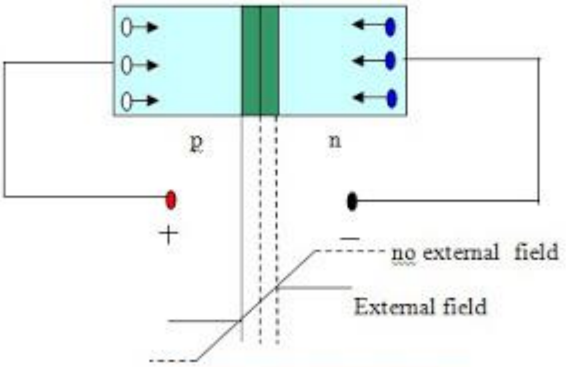
1. Forward biasing

• When external voltage applied to the junction is in such a direction that it cancels the potential barrier, thus permitting current flow is called forward biasing.

• To apply forward bias, connect +ve terminal of the battery to p-type and –ve terminal to n-type as shown in fig.2.1 below.

• The applied forward potential establishes the electric field which acts against the field due to potential barrier. Therefore the resultant field is weakened and the barier height is reduced at the junction as shown in fig. 2.1.

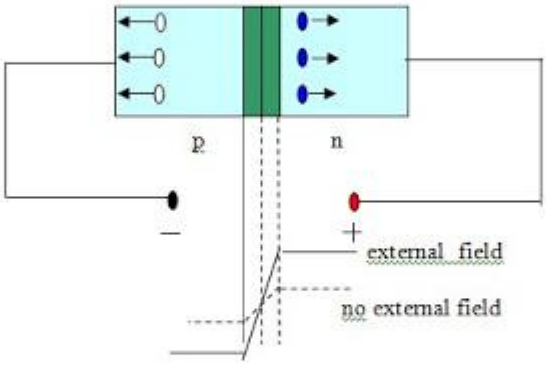
• Since the potential barrier voltage is very small, a small forward voltage is sufficient to completely eliminate the barrier. Once the potential barrier is eliminated by the forward voltage, junction resistance becomes almost zero and a low resistance path is established for the entire circuit. Therefore current flows in the circuit. This is called forward current.



forward biasing of p-n junction

2. Reverse biasing

• When the external voltage applied to the junction is in such a direction the potential barrier is increased it is called reverse biasing.
• To apply reverse bias, connect –ve terminal of the battery to p-type and +ve terminal to n-type as shown in figure below.
• The applied reverse voltage establishes an electric field which acts in the same direction as the field due to potential barrier. Therefore the resultant field at the junction is strengthened and the barrier height is increased as shown in fig.
• The increased potential barrier prevents the flow of charge carriers across the junction. Thus a high resistance path is established for the entire circuit and hence current does not flow.



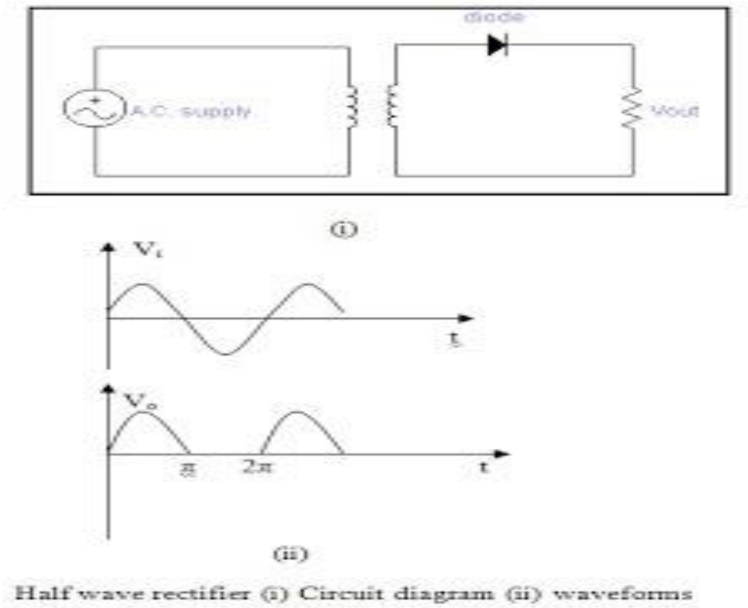
Reverse biasing of p-n junction

<u>RECTIFIERS</u>

"Rectifiers are the circuit which converts ac to dc" Rectifiers are grouped into tow categories depending on the period of conductions.

1.Half-wave ectifier
2. Full- wave rectifier.

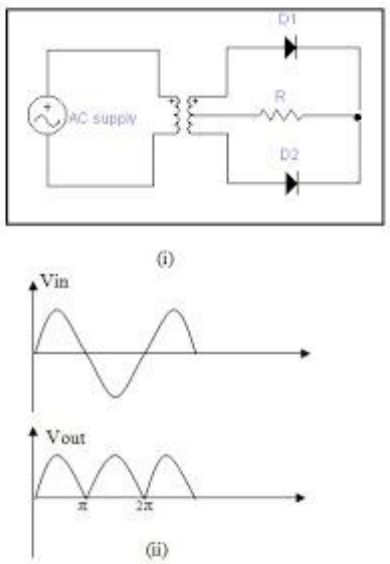
Half-wave rectifier
The circuit diagram of a half-wave rectifier is shown in fig below along with the I/P and O/P waveforms.



Half wave rectifier (i) Circuit diagram (ii) waveforms

• The transformer is employed in order to step-down the supply voltage and also to prevent from shocks.
• The diode is used to rectify the a.c. signal while , the pulsating d.c. is taken across the load resistor RL.
• During the +ve half cycle, the end X of the secondary is +ve and end Y is -ve . Thus , forward biasing the diode. As the diode is forward biased, the current flows through the load RL and a voltage is developed across it.
• During the –ve half-cycle the end Y is +ve and end X is –ve thus, reverse biasing the diode. As the diode is reverse biased there is no flow of current through RL thereby the output voltage is zero.

Full-wave rectifier
Full-wave rectifier are of two types
1. Centre tapped full-wave rectifier
2. Bridge rectifier
Centre tapped full –wave rectifier
Centre tapped Full wave rectifier (i) Circuit diagram (ii) waveforms

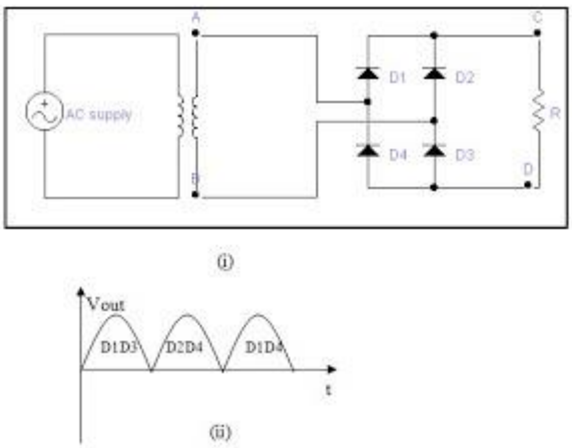


Centre tapped Full wave rectifier (i) Circuit diagram (ii) waveforms

• The circuit diagram of a center tapped full wave rectifier is shown in fig. 2.6 above. It employs two diodes and a center tap transformer. The a.c. signal to be rectified is applied to the primary of the transformer and the d.c. output is taken across the load RL.
• During the +ve half-cycle end X is +ve and end Y is –ve this makes diode D1 forward biased and thus a current i1 flows through it and load resistor RL.Diode D2 is reverse biased and the current i2 is zero.
• During the –ve half-cycle end Y is +Ve and end X is –Ve. Now diode D2 is forward biased and thus a current i2 flows through it and load resistor RL. Diode D1 is reversed & the current i1 = 0.

Disadvantages

• Since, each diode uses only one-half of the transformer secondary voltage the d.c. output is comparatively small.
• It is difficult to locate the center-tap on secondary winding of the transformer.
• The diodes used must have high Peak-inverse voltage.



Full wave bridge wave rectifier (i) Circuit diagram (ii) waveforms.

Bridge rectifier

Full wave bridge wave rectifier (i) Circuit diagram (ii) waveforms.

• The circuit diagram of a bridge rectifer is shown above. It uses four diodes and a transformer.

• During the +ve half-cycle, end A is +ve and end B is –ve thus diodes D1 and D3 are forward bias while diodes D2 and D4 are reverse biased thus a current flows through diode D1, load RL (C to D) and diode D3.

• During the –ve half-cycle, end B is +ve and end A is –ve thus diodes D2 and D4 are forward biased while the diodes D1 and D3 are reverse biased. Now the flow of current is through diode D4 load RL (D to C) and diode D2. Thus, the waveform is same as in the case of center-tapped full wave rectifier.

Advantages

• The need for center-taped transformer is eliminated.

• The output is twice when compared to center-tapped full wave rectifier for the same secondary voltage.

• The peak inverse voltage is one-half(1/2) compared to center-tapped full wave rectifier.

• Can be used where large amount of power is required.

Disadvantages

• It requires four diodes.

• The use of two extra diodes cause an additional voltage drop thereby reducing the output voltage.

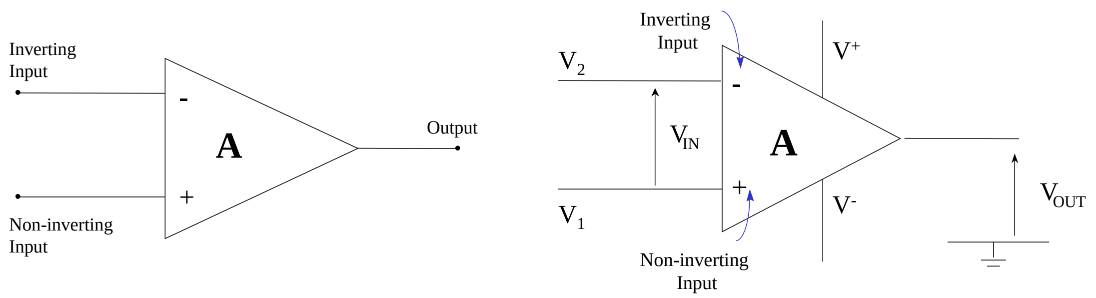
The Operational Amplifier

Introduction

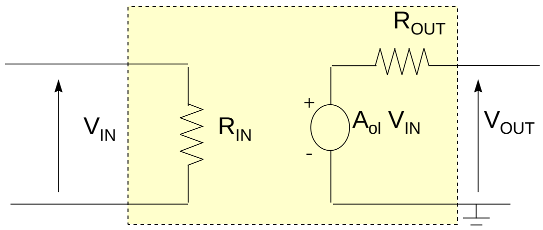
In this chapter we will introduce a general purpose integrated circuit (IC), the Operational Amplifier (Op-Amp), which is a most versatile and widely used linear integrated circuit. The Op-Amp is a direct-coupled high-gain amplifier to which feedback is added to control its overall response characteristics.

The standard Op-Amp symbol is shown in left-hand figure below. It has two input terminals, the inverting (-) input and the non-inverting (+) input. The typical Op-Amp operates with two dc supply voltages, one positive and the other negative, as shown in the right-hand figure below. Usually these dc voltage terminals are left off the schematic symbol for simplicity but are always understood to be there.

SCHEMATIC SYMBOL



The equivalent circuit for an Op-Amp is as follows:



Equivalent Circuit

Where

R_{IN} is the total resistance between the inverting and the non-inverting inputs
R_{OUT} is the resistance viewed from the output terminal
A_{ol} is the Open-Loop Voltage Gain i.e. when there are no external components

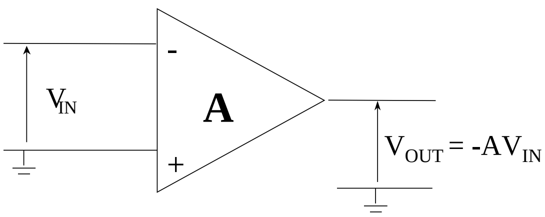
Op-amp Characteristics

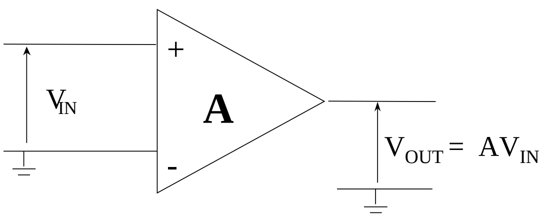
Open-Loop Voltage Gain

The open-loop voltage gain, A_{OL}, of an op-amp is the internal voltage gain of the device and represents the ratio of output voltage to input voltage when there are no external components. The open-loop voltage gain is set entirely by the internal design. Open-loop voltage gain can range up to 200,00 and is not a well-controlled parameter. Data sheets often refer to the open-loop voltage gain as the ***large-signal voltage gain***.

Signal-Ended Input

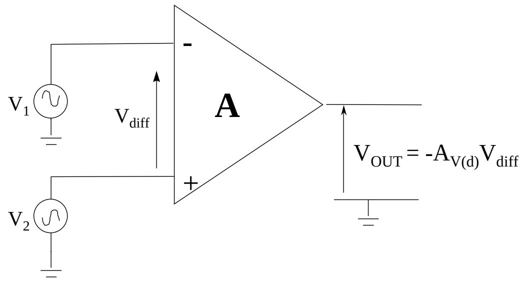
Signal-Ended input => one input is grounded and the signal voltage is applied only to the other input as shown below.





<u>Differential Input (Double-Ended Input)</u>

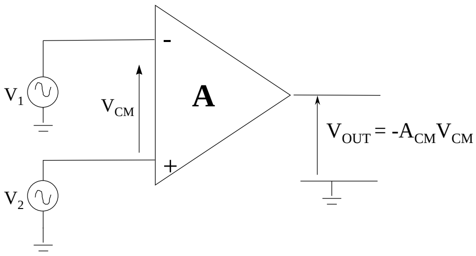
In this mode, two signals are applied to the inputs, as shown below. The output is the sum of the respective single ended outputs.

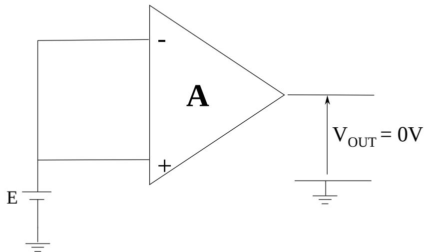


<u>Common-Mode Input</u>

In this mode, two identical polarity signals (same phase) are applied to the inputs, as shown in the left-hand figure below.

Note that there is no output due to V_{CM}, the common mode voltage because $V_{CM} = V_1 - V_2 = 0$, as shown in the right-hand figure below.





This is very useful as unwanted signals (noise) appearing with the same polarity on both input lines are essentially cancelled out and do not appear on the output.

The common-mode input voltage range is the range of input voltages which, when applied to both inputs, will not cause clipping or other output distortion. Many op-amps have common-mode rages of no more than +/-10 V with dc supply voltages of +/- 15 V, while in others the output can go as high as the supply voltages (this is called rail-to-rail).

<u>Common-Mode-Rejection-ratio (CMRR).</u>

The ability of an Op-Amp to suppress common signals is expressed in terms of its **Common-Mode-Rejection-ratio (CMRR).**

$$\mathbf{CMRR} = \frac{A_{V(d)}}{A_{CM}}$$

The higher the CMRR, the better. A very high value of CMRR means that the differential gain $A_{V(d)}$ is high and the common-mode gain A_{CM} is low. The CMRR is often expressed in decibels (dB) as:

$$\text{CMRR'} = 20\log\left(\frac{A_{V(d)}}{A_{CM}}\right)$$

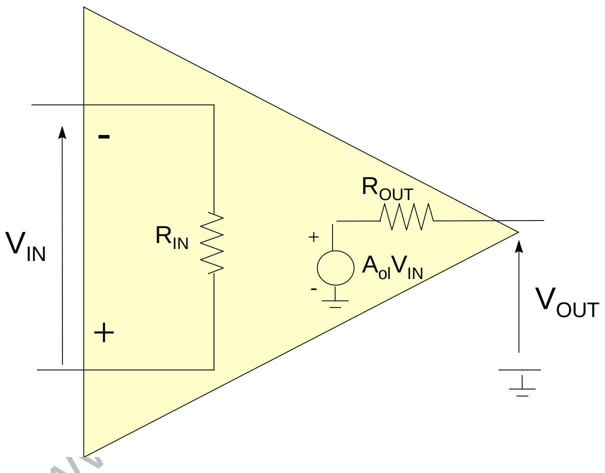
Ideally, an Op-Amp provides infinite gain for desired signals (single ended or differential) and zero gain for common-mode signals,

Input and Output Impedance

Two basic ways of specifying the input impedance of an op-amp are the differential and the common mode. The differential input impedance is the total resistance between the inverting and the non-inverting inputs. The common-mode input impedance is the resistance between each input and ground.

The output impedance is the resistance viewed from the output terminal of the op-amp.

Characteristics of an Ideal Op-Amp:



The ideal op-Amp has the following characteristics

- Input Resistance $R_{IN} = \infty$. (i.e. no current demanded at amplifier input terminals)
- Output Resistance $R_{OUT} = 0$. (i.e. Output Voltage unaffected by load)
- Voltage Gain $A_{ol} = \infty$ (i.e. Open Loop Voltage gain is infinite)

The ideal Op-Amp also has the following characteristics:

- Bandwidth= ∞ (i.e. the response extends from dc to ∞)
- Infinite CMRR (i.e. ideally $V_{OUT} = 0$ for common mode inputs where the Common-Mode Rejection Ratio (CMRR) is a measure of an Op-Amp's ability to reject common-mode signals)

- Slew rate= ∞ i.e. the maximum rate of change of V_{OUT} is ∞ $\frac{dV_{OUT}}{dt} = \infty$

  where slew rate is the maximum rate of change of the output voltage in response to a step input voltage and is dependent upon the high frequency response of the amplifier stages within the Op- Amp.

Characteristics of a Practical Op-Amp

In practice the IC Op-Amp falls short of the ideal characteristics, however the following applies

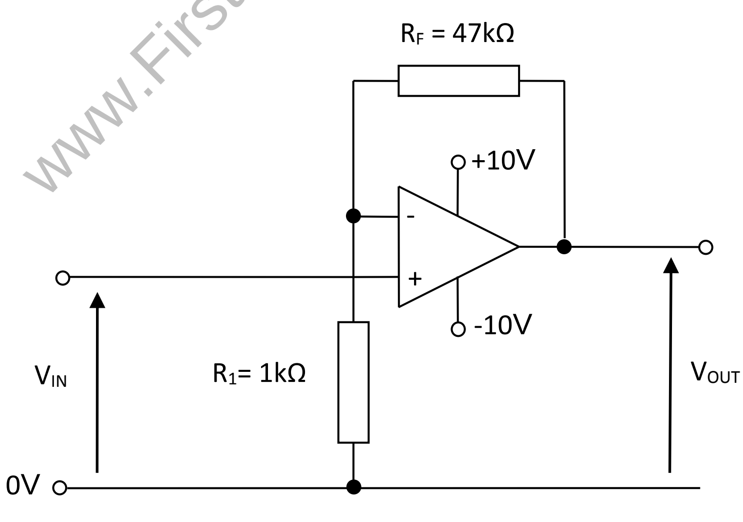
- Very HIGH input resistance
- Very LOW output resistance
- Very large Open Loop Voltage Gain

For example, a popular 741 Op-Amp has the following characteristics:

- Open-Loop voltage gain ≈ 200,000
- Input impedance ≈ 2 MΩ
- Output impedance ≈ 75 Ω
- Bandwidth for unit gain ≈ 1 MHz
- CMRR ≈ 90dB
- Slew rate ≈ 0.5V/µs

Example 1:

The following circuit shows a non-inverting amplifier connected to a ±10V power supply. The saturation voltage is ±8V.



(a) What is the voltage gain of this amplifier?

$$\text{Gain} = 1 + \frac{R_F}{R_1}$$

$$\text{Gain} = 1 + \frac{47}{1} = +48$$

(b) If the peak value of V_{IN} = 100mV, determine the peak value of V_{OUT}.

$$Gain = \frac{V_{OUT}}{V_{IN}}$$

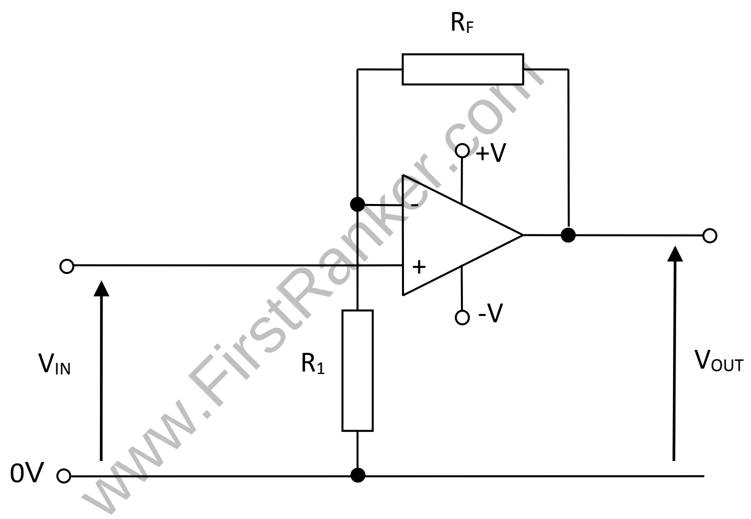
$$+48 = \frac{V_{OUT}}{100}$$

$$V_{OUT} = 48 \times 100 = 4800mV = 4.8V$$

Example 2:

A non-inverting amplifier is required to act as a preamplifier for a microphone. The amplifier requires a voltage gain of +100.

(a) Draw the circuit diagram for a non-inverting amplifier.



(b) Determine a suitable resistor for R_F if $R_1 = 1k\Omega$
In the question we are told that the gain needs to be +100, so we now apply the gain formula as shown below;

$$\text{Gain} = 1 + \frac{R_F}{R_1}$$

$$100 = 1 + \frac{R_F}{R_1}$$

$$100 - 1 = \frac{R_F}{R_1}$$

$$R_F = 99 \times R_1$$

$$R_F = 99 \times 1k\Omega = 99k\Omega$$

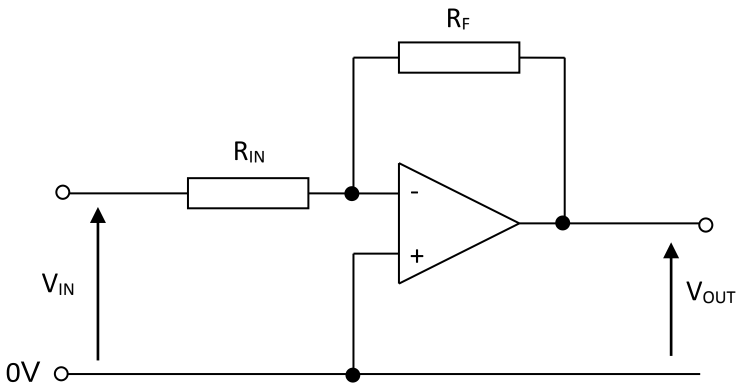
OR if you find it difficult to rearrange the formula try this method:

For a non-inverting op-amp with a gain of 100, R_F is 99 times bigger than R_{IN} so:

$$R_F = 99 \times 1k\Omega = 99k\Omega$$

Example 3: An inverting amplifier is required with a voltage gain of -20.

(a) Draw the circuit diagram for an inverting amplifier.



(b) Determine a suitable resistor for R_F if R_{IN} has a value of 10kΩ.
We apply the gain formula as shown below;

$$\text{Gain} = -\frac{R_F}{R_{IN}}$$

$$-20 = -\frac{R_F}{10}$$

$$-R_F = -20 \times 10$$

$$R_F = 200k\Omega$$

OR if you find it difficult to rearrange the formula try this method:

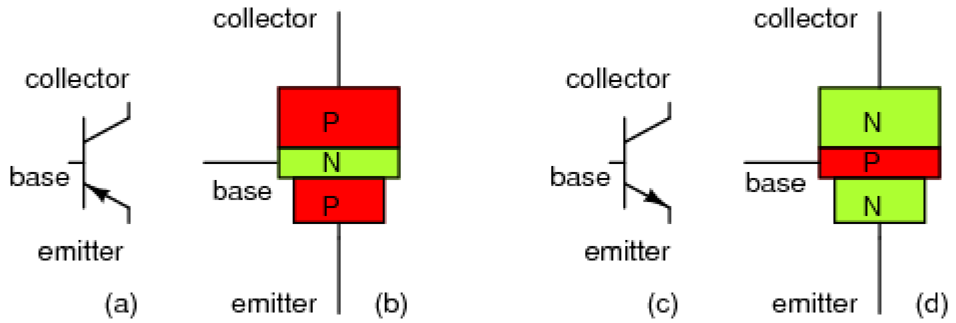
For an inverting op-amp with a voltage gain of -20, R_F is 20 times bigger than R_{IN} so:

$$R_F = 20 \times 10k\Omega = 200k\Omega$$

6. TRANSISTORS

Introduction to Bipolar Junction Transistors (BJT)

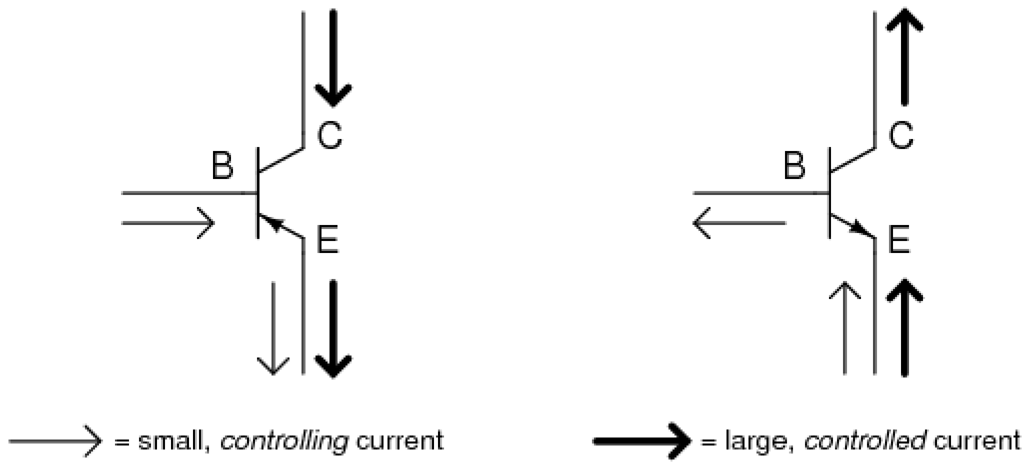
A bipolar transistor consists of a three-layer "sandwich" of doped (extrinsic) semiconductor materials, either P-N-P in Figure below (b) or N-P-N at (d). Each layer forming the transistor has a specific name, and each layer is provided with a wire contact for connection to a circuit. The schematic symbols are shown in Figure below (a) and (d).



BJT transistor: (a) PNP schematic symbol, (b) physical layout (c) NPN symbol, (d) layout.

The functional difference between a PNP transistor and an NPN transistor is the proper biasing (polarity) of the junctions when operating. For any given state of operation, the current directions and voltage polarities for each kind of transistor are exactly opposite each other.

Bipolar transistors work as current-controlled current *regulators*. In other words, transistors restrict the amount of current passed according to a smaller, controlling current. The main current that is *controlled* goes from collector to emitter, or from emitter to collector, depending on the type of transistor it is (PNP or NPN, respectively). The small current that *controls* the main current goes from base to emitter, or from emitter to base, once again depending on the kind of transistor it is (PNP or NPN, respectively). The arrow always points *against* the direction of electron flow



Small Base-Emitter current controls large Collector-Emitter current flowing against emitter arrow.

Bipolar transistors are called *bi*polar because the main flow of electrons through them takes place in *two* types of semiconductor material: P and N, as the main current goes from emitter to collector (or vice versa). In other words, two types of charge carriers—electrons and holes—comprise this main current through the transistor.

As you can see, the *controlling* current and the *controlled* current always mesh together through the emitter wire, and their electrons always flow *against* the direction of the transistor's arrow. This is the first and foremost rule in the use of transistors: all currents must be going in the proper directions for the device to work as a current regulator. The small, controlling current is usually referred to as simply as the *base current* because it is the only current that goes through the base wire of the transistor. Conversely, the large, controlled current is referred to as the *collector current* because it is the only current that goes through the collector wire. The emitter current is the sum of the base and collector currents, in compliance with Kirchhoff's Current Law.

No current through the base of the transistor, shuts it off like an open switch and prevents current through the collector. A base current, turns the transistor on like a closed switch and allows a proportional amount of current through the collector. Collector current is primarily limited by the base current, regardless of the amount of voltage available to push it.

NPN and a PNP Transistor

Both NPN and PNP are bipolar junction transistors (BJTs). BJTs are current-controlled transistors that allow for current amplification.

A current input into the base of the transistor allows for a much larger current across the emitter and collector leads. NPN and PNPs are exactly the same in their function, they provide amplification and/or switching capability.

How they differ is how power must be allocated to the pins for them to provide this amplification or switching. Since they are internally constructed very different, current and voltage must be allocated differently in order for them to work. Also, since voltage is allocated different, they have opposite current flows. In an NPN transistor, current flows from the collector to the emitter. In a PNP transistor, current flows from the emitter to the collector.

How they turn on and off is also different. An NPN transistor is powered on when a sufficient current is supplied to the base of the transistor. Therefore, the base of an NPN transistor must be connected to positive voltage for current to flow in. A PNP transistor is the opposite. Only when there is no current at the base will it turn on. And to ensure that no current enters the base, the base must be grounded (connected to ground). If any current goes into the base of a PNP transistor at all, the transistor will not conduct across from emitter to collector.

So knowing this, an NPN transistor turns on by a high signal (current). And a PNP transistor turns on by a low signal (ground).

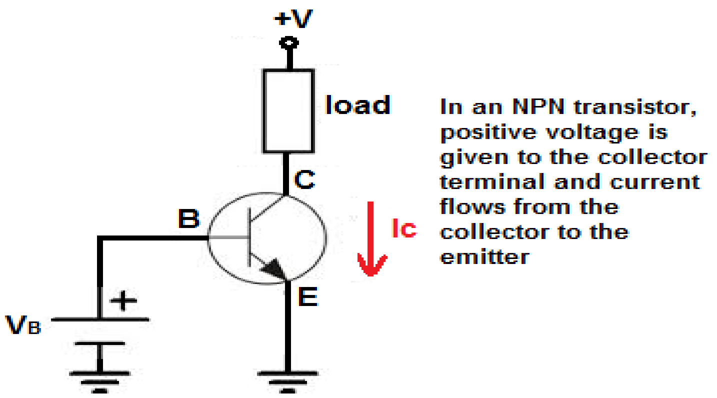
Voltage Allocation and Current Flow are Switched

Since PNP and NPN are composed of different materials, how voltage is biased to them to produce current flow is different, and their current flow is opposite as well. In an NPN transistor, current flows from the collector to the emitter. In a PNP transistor, current flows from the emitter to the collector.

PNP transistors are made up of 2 layers of P material sandwiching a layer of N material, while NPN transistors are made up of 2 layers of N material sandwiching 1 layer of P material. Really opposites. Therefore, to produce current flow from collector to emitter in an NPN, positive voltage is given at the collector terminal. For a PNP transistor, to produce current flow from emitter to collector, positive voltage is given at the emitter terminal.

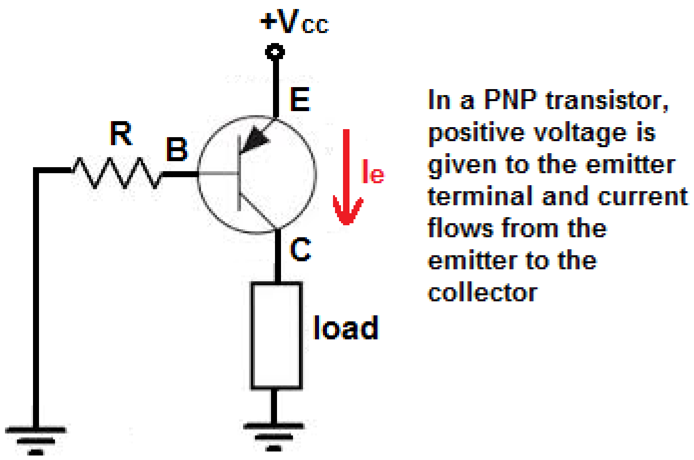
NPN Transistor

An NPN transistor receives positive voltage at the collector terminal. This positive voltage to the collector allows current to flow across from the collector to emitter, given that there is a sufficient base current to turn the transistor on.



PNP Transistor

A PNP transistor receives positive voltage at the emitter terminal. The positive voltage to the emitter allows current to flow from the emitter to the collector, given that there is no current flowing into the base.



How They Turn On and Off

NPN Transistor

This is how a NPN transistor works:

As you increase current to the base of a NPN transistor, the transistor is turned on more and more until it conducts fully from collector to emitter.

And as you decrease current to the base of a NPN transistor, the transistor turns on less and less, until the current is so low, the transistor no longer conducts across collector to emitter, and shuts off.

PNP Transistor

A PNP transistor functions the total opposite way.

When there is current at the base, the transistor is off and does not conduct to power the load connected to it. When there is no current at the base, the transistor is on and conducts across to power on the output load.

The Common Base Configuration :

If the base is common to the input and output circuits, it is know as common base configuration as shown in **fig. 1**.

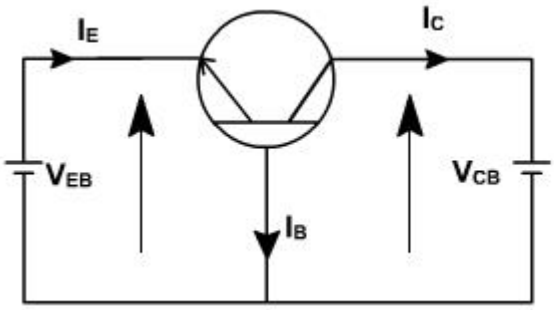


Fig. 1

For a pnp transistor the largest current components are due to holes. Holes flow from emitter to collector and few holes flow down towards ground out of the base terminal. The current directions are shown in **fig. 1**.

$(I_E = I_C + I_B)$.

For a forward biased junction, V_{EB} is positive and for a reverse biased junction V_{CB} is negative. The complete transistor can be described by the following two relations, which give the input voltage V_{EB} and output current I_C in terms of the output voltage (V_{CB}) and input current I_E.

$$V_{EB} = f_1(V_{CB}, I_E)$$

$$I_C = f_2(V_{CB}, I_E)$$

The output characteristic:

The collector current I_C is completely determined by the input current I_E and the V_{CB} voltage. The relationship is given in **fig. 2**. It is a plot of I_C versus V_{CB}, with emitter current I_E as parameter. The curves are known as the output or collector or static characteristics. The transistor consists of two diodes placed in series back to back (with two cathodes connected together). The complete characteristic can be divided in three regions.

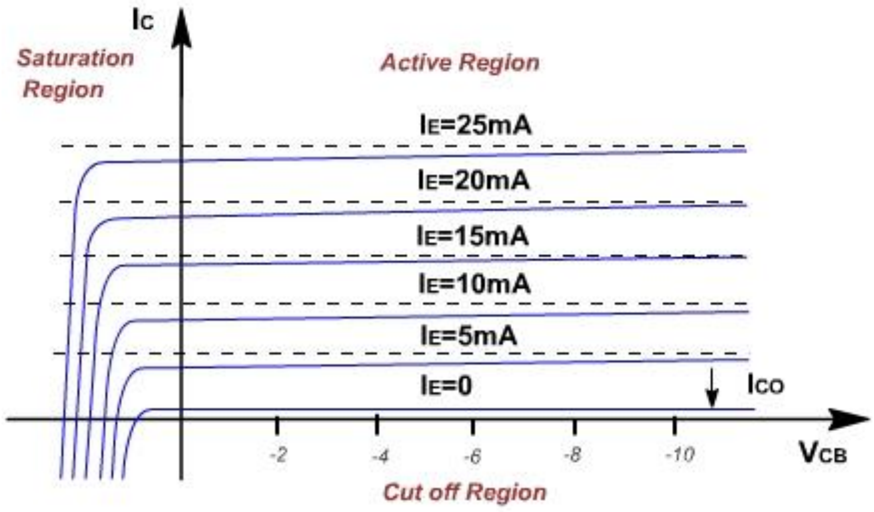


Figure 2

(1). Active region:

In this region the collector diode is reverse biased and the emitter diode is forward biased. Consider first that the emitter current is zero. Then the collector current is small and equals the reverse saturation current I_{CO} of the collector junction considered as a diode.

If the forward current I_B is increased, then a fraction of I_E ie. $a_{dc}I_E$ will reach the collector. In the active region, the collector current is essentially independent of collector voltage and depends only upon the emitter current. Because a_{dc} is, less than one but almost equal to unity, the magnitude of the collector current is slightly less that of emitter current. The collector current is almost constant and work as a current source.

The collector current slightly increases with voltage. This is due to early effect. At higher voltage collector gathers in a few more electrons. This reduces the base current. The difference is so small, that it is usually neglected. If the collector voltage is increased, then space charge width increases; this decreased the effective base width. Then there is less chance for recombination within the base region.

(2). Saturation region:

The region to the left of the ordinate V_{CB} = 0, and above the I_E = 0, characteristic in which both emitter and collector junction are forward biased, is called saturation region.

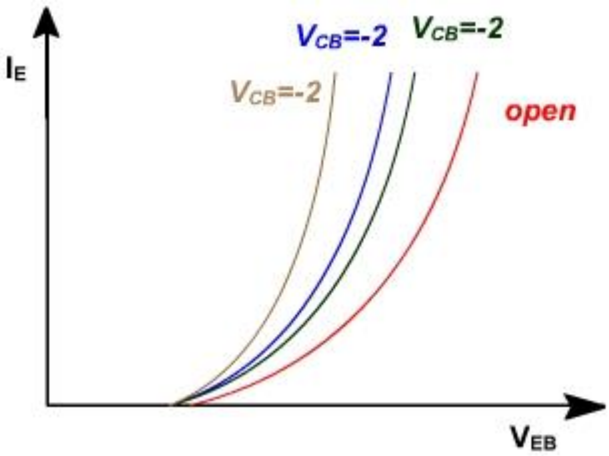
When collector diode is forward biased, there is large change in collector current with small changes in collector voltage. A forward bias means, that p is made positive with respect to n, there is a flow of holes from p to n. This changes the collector current direction. If diode is sufficiently forward biased the current changes rapidly. It does not depend upon emitter current.

(3). Cut off region:

The region below $I_E = 0$ and to the right of V_{CB} for which emitter and collector junctions are both reversed biased is referred to cutoff region. The characteristics $I_E = 0$, is similar to other characteristics but not coincident with horizontal axis. The collector current is same as I_{CO}. I_{CBO} is frequently used for I_{CO}. It means collector to base current with emitter open. This is also temperature dependent.

The Input Characteristic:

In the active region the input diode is forward biased, therefore, input characteristic is simply the forward biased characteristic of the emitter to base diode for various collector voltages. Below cut in voltage (0.7 or 0.3) the emitter current is very small. The curve with the collector open represents the forward biased emitter diode. Because of the early effect the emitter current increases for same V_{EB}. (The diode becomes better diode).



When the collector is shorted to the base, the emitter current increases for a given V_{EB} since the collector now removes minority carriers from the base, and hence base can attract more holes from the emitter. This mean that the curve V_{CB}= 0, is shifted from the character when V_{CB} = open.

Common Emitter Configuration:

The common emitter configuration of BJT is shown.

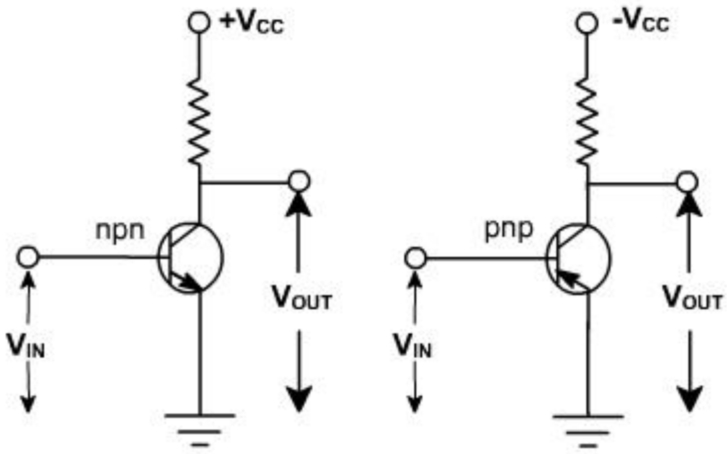


Fig. 1

In C.E. configuration the emitter is made common to the input and output. It is also referred to as grounded emitter configuration. It is most commonly used configuration. In this, base current and output voltages are taken as impendent parameters and input voltage and output current as dependent parameters

$V_{BE} = f_1 (I_B, V_{CE})$

$I_C = f_2(I_B, V_{CE})$

Input Characteristic:

The curve between I_B and V_{BE} for different values of V_{CE} are shown in **fig. 2**. Since the base emitter junction of a transistor is a diode, therefore the characteristic is similar to diode one. With higher values of V_{CE} collector gathers slightly more electrons and therefore base current reduces. Normally this effect is neglected. (Early effect). When collector is shorted with emitter then the input characteristic is the characteristic of a forward biased diode when V_{BE} is zero and I_B is also zero.

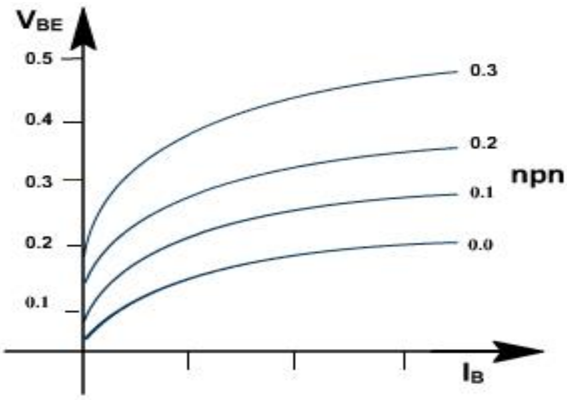


Fig. 2

Output Characteristic:

The output characteristic is the curve between V_{CE} and I_C for various values of I_B. For fixed value of I_B and is shown in **fig. 3**. For fixed value of I_B, I_C is not varying much dependent on V_{CE} but slopes are greater than CE characteristic. The output characteristics can again be divided into three parts.

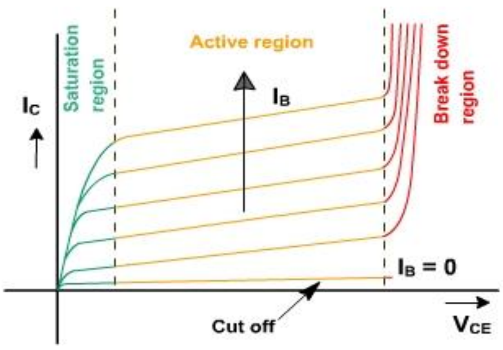


Fig. 3

(1) Active Region:

In this region collector junction is reverse biased and emitter junction is forward biased. It is the area to the right of V_{CE} = 0.5 V and above I_B= 0. In this region transistor current responds most sensitively to I_B. If transistor is to be used as an amplifier, it must operate in this region.

$$I_E = I_C + I_B$$
$$\text{Since, } I_C = I_{Co} + \alpha_{dc} I_E$$
$$I_C = I_{Co} + \alpha_{dc}(I_C + I_B)$$
$$\text{or } (1-\alpha_{dc})I_C = \alpha_{dc} I_B + I_{CO}$$
$$\text{or } I_C = \left(\frac{\alpha_{dc}}{1-\alpha_{dc}}\right) I_B + \left(\frac{1}{1-\alpha_{dc}}\right) I_{CO}$$
$$\text{Let, } \beta_{dc} = \frac{\alpha_{dc}}{1-\alpha_{dc}}$$
$$\therefore I_C = (1+\beta_{dc}) I_{CO} + \beta_{dc} I_B$$

β_{dc} is defined as current gain of the transistor is given by

$$\beta_{dc} = \frac{I_C - I_{CO}}{I_B + I_{CO}}$$

If a_{dc} is truly constant then I_C would be independent of V_{CE}. But because of early effect, a_{dc} increases by 0.1% (0.001) e.g. from 0.995 to 0.996 as V_{CE} increases from a few volts to 10V. Then b_{dc} increases from 0.995 / (1-0.995) = 200 to 0.996 / (1-0.996) = 250 or about 25%. This shows that small change in a reflects large change in b. Therefore the curves are subjected to large variations for the same type of transistors.

(2) Cut Off:

Cut off in a transistor is given by I_B = 0, I_C= I_{CO}. A transistor is not at cut off if the base current is simply reduced to zero (open circuited) under this condition,

$$I_C = I_E = I_{CO} / (1-\alpha_{dc}) = I_{CEO}$$

The actual collector current with base open is designated as I_{CEO}. Since even in the neighborhood of cut off, a $_{dc}$ may be as large as 0.9 for Ge, then I_C=10 I_{CO}(approximately), at zero base current. Accordingly in order to cut off transistor it is not enough to reduce I_B to zero, but it is necessary to reverse bias the emitter junction slightly. It is found that reverse voltage of 0.1 V is sufficient for cut off a transistor. In Si, the a $_{dc}$ is very nearly equal to zero, therefore, I_C = I_{CO}. Hence even with I_B= 0, I_C= I_E= I_{CO} so that transistor is very close to cut off.

In summary, cut off means I_E = 0, I_C = I_{CO}, I_B = -I_C = -I_{CO} , and V_{BE} is a reverse voltage whose magnitude is of the order of 0.1 V for Ge and 0 V for Si.

Reverse Collector Saturation Current I_{CBO}:

When in a physical transistor emitter current is reduced to zero, then the collector current is known as I_{CBO} (approximately equal to I_{CO}). Reverse collector saturation current I_{CBO} also varies with temperature, avalanche multiplication and variability from sample to sample. Consider the circuit shown in **fig. 4**. V_{BB} is the reverse voltage applied to reduce the emitter current to zero.

$$I_E = 0, \qquad I_B = -I_{CBO}$$

If we require, $V_{BE} = -0.1$ V

Then $-V_{BB} + I_{CBO} R_B < -0.1$ V

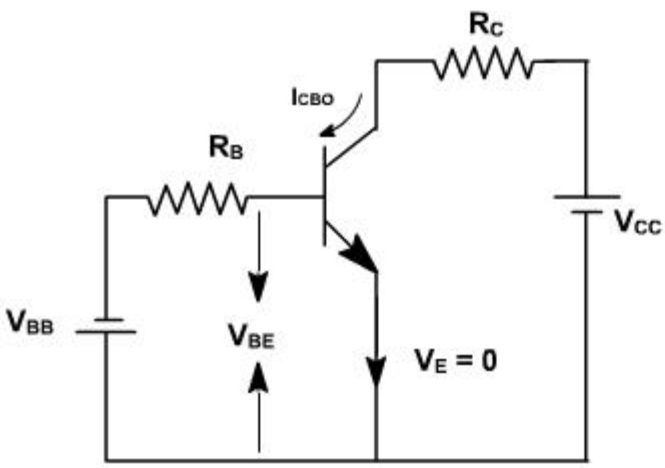


Fig. 4

If $R_B = 100$ K, $I_{CBO} = 100$ m A, Then V_{BB} must be 10.1 Volts. Hence transistor must be capable to withstand this reverse voltage before breakdown voltage exceeds.

(3).Saturation Region:

In this region both the diodes are forward biased by at least cut in voltage. Since the voltage V_{BE} and V_{BC} across a forward is approximately 0.7 V therefore, $V_{CE} = V_{CB} + V_{BE} = -V_{BC} + V_{BE}$ is also few tenths of volts. Hence saturation region is very close to zero voltage axis, where all the current rapidly reduces to zero. In this region the transistor collector current is approximately given by V_{CC} / R_C and independent of base current. Normal transistor action is last and it acts like a small ohmic resistance.

Small Signal CE Amplifiers:

CE amplifiers are very popular to amplify the small signal ac. After a transistor has been biased with a Q point near the middle of a dc load line, ac source can be coupled to the base.

This produces fluctuations in the base current and hence in the collector current of the same shape and frequency. The output will be enlarged sine wave of same frequency.

The amplifier is called linear if it does not change the wave shape of the signal. As long as the input signal is small, the transistor will use only a small part of the load line and the operation will be linear.

On the other hand, if the input signal is too large. The fluctuations along the load line will drive the transistor into either saturation or cut off. This clips the peaks of the input and the amplifier is no longer linear.

The CE amplifier configuration is shown in **fig. 1**.

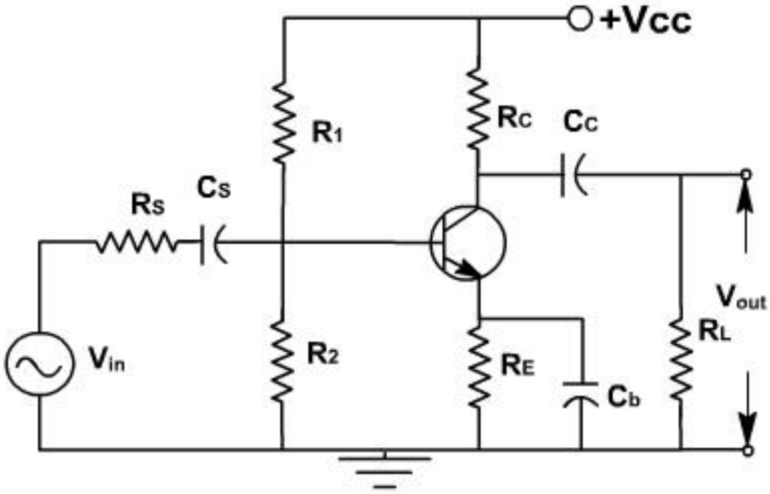


Fig. 1

The coupling capacitor (C_C) passes an ac signal from one point to another. At the same time it does not allow the dc to pass through it. Hence it is also called blocking capacitor.

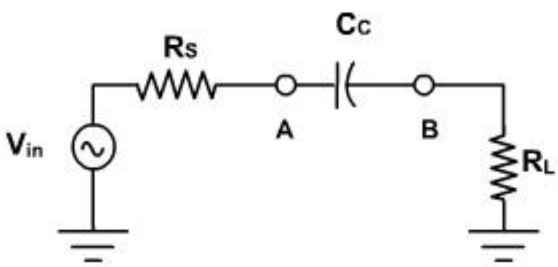


Fig. 2

For example in **fig. 2**, the ac voltage at point A is transmitted to point B. For this series reactance X_C should be very small compared to series resistance R_S. The circuit to the left of A may be a source and a series resistor or may be the Thevenin equivalent of a complex circuit. Similarly R_L may be the load resistance or equivalent resistance of a complex network. The current in the loop is given by

$$i = \frac{v_{in}}{\sqrt{(R_s + R_L)^2 + X_C^2}} = \frac{v_{in}}{\sqrt{R^2 + X^2}}$$

As frequency increases, $X_C\left(= \frac{1}{2\pi fc}\right)$ decreases, and current increases until it reaches to its maximum value v_{in} / R. Therefore the capacitor couples the signal properly from A to B when $X_C << R$. The size of the coupling capacitor depends upon the lowest frequency to be coupled. Normally, for lowest frequency X_C £ 0.1R is taken as design rule.

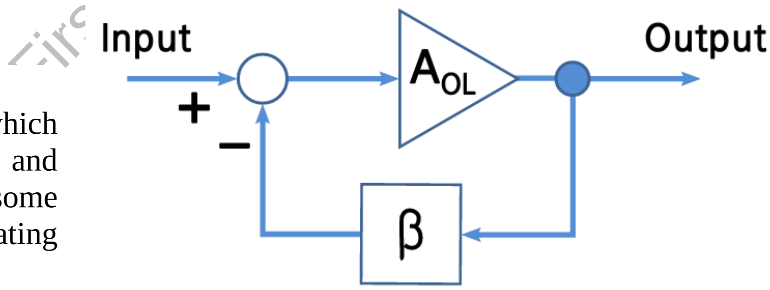
The coupling capacitor acts like a switch, which is open to dc and shorted for ac.

The bypass capacitor C_b is similar to a coupling capacitor, except that it couples an ungrounded point to a grounded point. The C_b capacitor looks like a short to an ac signal and therefore emitter is said ac grounded. A bypass capacitor does not disturb the dc voltage at emitter because it looks open to dc current. As a design rule $X_{Cb} <= 0.1R_E$ at lowest frequency.

Feedback Amplifiers

A **negative feedback amplifier** (or **feedback amplifier**) is an electronic amplifier that subtracts a fraction of its output from its input, so that negative feedback opposes the original signal. The applied negative feedback improves performance (gain stability, linearity, frequency response, step response) and reduces sensitivity to parameter variations due to manufacturing or environment. Because of these advantages, many amplifiers and control systems use negative feedback.

An idealized negative feedback amplifier as shown in the diagram is a system of three elements



- An *amplifier* with gain A_{OL}
- A *feedback network* β, which senses the output signal and possibly transforms it in some way (for example by attenuating or filtering it)
- A summing circuit that acts as a *subtractor* (the circle in the figure), which combines the input and the transformed output
- **Gain reduction**
- Below, the voltage gain of the amplifier with feedback, the **closed-loop gain** A_{FB}, is derived in terms of the gain of the amplifier without feedback, the **open-loop gain** A_{OL} and the **feedback factor** β, which governs how much of the output signal is applied to the input. See Figure 1, top right. The open-loop gain A_{OL} in general may be a function of both frequency and voltage; the feedback parameter β is determined by the feedback network that is connected around the amplifier. For an operational amplifier two resistors forming a voltage divider may be used for the feedback network to set β between 0 and 1. This network

may be modified using reactive elements like capacitors or inductors to (a) give frequency-dependent closed-loop gain as in equalization/tone-control circuits or (b) construct oscillators. The gain of the amplifier with feedback is derived below in the case of a voltage amplifier with voltage feedback.

- Without feedback, the input voltage V'_{in} is applied directly to the amplifier input. The according output voltage is
- $V_{\text{out}} = A_{\text{OL}} \cdot V'_{\text{in}}$
- Suppose now that an attenuating feedback loop applies a fraction $\beta \cdot V_{\text{out}}$ of the output to one of the subtractor inputs so that it subtracts from the circuit input voltage V_{in}applied to the other subtractor input. The result of subtraction applied to the amplifier input is
- $V'_{\text{in}} = V_{\text{in}} - \beta \cdot V_{\text{out}}$
- Substituting for V'_{in} in the first expression,
- $V_{\text{out}} = A_{\text{OL}}(V_{\text{in}} - \beta \cdot V_{\text{out}})$
- Rearranging
- $V_{\text{out}}(1 + \beta \cdot A_{\text{OL}}) = V_{\text{in}} \cdot A_{\text{OL}}$
- Then the gain of the amplifier with feedback, called the closed-loop gain, A_{FB} is given by,
- $A_{\text{FB}} = \frac{V_{\text{out}}}{V_{\text{in}}} = \frac{A_{\text{OL}}}{1 + \beta \cdot A_{\text{OL}}}$
- If $A_{OL} >> 1$, then $A_{FB} \approx 1 / \beta$ and the effective amplification (or closed-loop gain) A_{FB} is set by the feedback constant β, and hence set by the feedback network, usually a simple reproducible network, thus making linearizing and stabilizing the amplification characteristics straightforward. Note also that if there are conditions where $\beta A_{OL} = -1$, the amplifier has infinite amplification – it has become an oscillator, and the system is unstable. The stability characteristics of the gain feedback product βA_{OL} are often displayed and investigated on a Nyquist plot (a polar plot of the gain/phase shift as a parametric function of frequency). A simpler, but less general technique, uses Bode plots.
- The combination $L = -\beta A_{OL}$ appears commonly in feedback analysis and is called the loop gain. The combination $(1 + \beta A_{OL})$ also appears commonly and is variously named as the **desensitivity factor**, **return difference**, or **improvement factor**.
- **Summary of terms**:[9][10][11][12]
- Open-loop gain = A_{OL}
- Closed-loop gain = $\frac{A_{\text{OL}}}{1 + \beta \cdot A_{\text{OL}}}$
- Feedback factor = β
- Noise gain = $1/\beta$
- Loop gain = $-\beta \cdot A_{\text{OL}}$
- Desensitivity factor = $1 + \beta \cdot A_{\text{OL}}$
- **Bandwidth extension**[edit]

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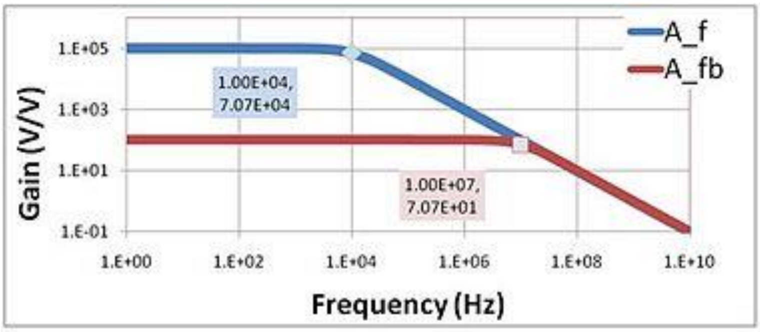
- 

- Figure 2: Gain vs. frequency for a single-pole amplifier with and without feedback; corner frequencies are labeled.
- Feedback can be used to extend the bandwidth of an amplifier at the cost of lowering the amplifier gain.[13] Figure 2 shows such a comparison. The figure is understood as follows. Without feedback the so-called **open-loop** gain in this example has a single time constant frequency response given by
- $$A_{\mathrm{OL}}(f) = \frac{A_0}{1 + jf/f_{\mathrm{C}}},$$
- where f_C is the cutoff or corner frequency of the amplifier: in this example $f_C = 10^4$ Hz and the gain at zero frequency $A_0 = 10^5$ V/V. The figure shows the gain is flat out to the corner frequency and then drops. When feedback is present the so-called **closed-loop** gain, as shown in the formula of the previous section, becomes,
- $$A_{\mathrm{FB}}(f) = \frac{A_{\mathrm{OL}}}{1 + \beta A_{\mathrm{OL}}}$$
- $$= \frac{A_0/(1 + jf/f_{\mathrm{C}})}{1 + \beta A_0/(1 + jf/f_{\mathrm{C}})}$$
- $$= \frac{A_0}{1 + jf/f_{\mathrm{C}} + \beta A_0}$$
- $$= \frac{A_0}{(1 + \beta A_0)\left(1 + j\frac{f}{(1+\beta A_0) f_{\mathrm{C}}}\right)}.$$
- The last expression shows the feedback amplifier still has a single time constant behavior, but the corner frequency is now increased by the improvement factor ($1 + \beta A_0$), and the gain at zero frequency has dropped by exactly the same factor. This behaviour is called the gain-bandwidth tradeoff. In Figure 2, ($1 + \beta A_0$) = 10^3, so $A_{FB}(0) = 10^5 / 10^3 = 100$ V/V, and f_C increases to $10^4 \times 10^3 = 10^7$ Hz.

Advantages of negative feedback

Stabilization of Voltage Gain

One of the benefits of negative feedback is the stabilization of the voltage gain of an amplifier against changes in the components (e.g., with temperature, frequency, etc.). If you represent the gain without feedback (the open loop gain) by A_0 , then the system gain with negative feedback is

$$A_f = \frac{V_{out}}{V_{in}} = \frac{A_0}{1 + A_0 B} \approx \frac{1}{B}$$

where B is the fraction of the output which feeds back as a negative voltage at the input. The extent of this stabilizing influence can be illustrated as follows:

for B= .01

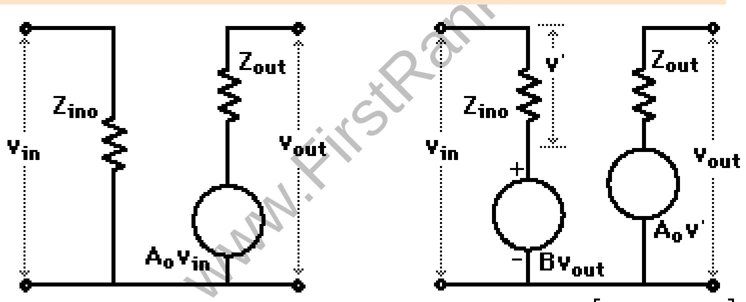
A_0	$A_f = A_0/(1 + A_0 B)$
1,000	90.9
5,000	98.3
10,000	99.0
20,000	99.5

This stabilization increases the effective bandwidth.

Increasing Input Impedance

The input impedance $\frac{v_{in}}{i_{in}}$ which without negative feedback is Z_{in0} .

But with feedback, the current is reduced to $i_{in} = \frac{v'}{Z_{ino}} = \frac{v_{in} - Bv_{out}}{Z_{ino}}$



Using the gain expression $v_{out} = v_{in}\frac{A_o}{1+A_oB}$ gives $i_{in} = \frac{v_{in}\left[1 - \frac{BA_o}{1+A_oB}\right]}{Z_{ino}}$

so the effective impedance is $Z_{inf} = \frac{v_{in}}{i_{in}} = (1 + A_oB)Z_{ino}$

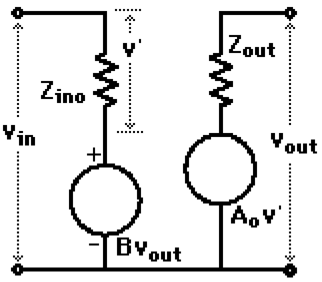
Decreasing Output Impedance

As in the approach to input impedance, the effect of negative feedback on output impedance can be obtained by analysis of the equivalent circuit.

$$Z_{outf} = \frac{v_{out}}{i_{out}} = \frac{A_o v' - i_{out} Z_{out}}{i_{out}}$$

$$= \frac{A_o(v_{in} - B v_{out}) - i_{out} Z_{out}}{i_{out}}$$

This gives $$v_{out} = \frac{A_o v_{in} - i_{out} Z_{out}}{1 + A_o B}$$



Things become more subtle here because the input voltage $\mathbf{v_{in}}$ must be held constant while we see how $\mathbf{v_{out}}$ varies with $\mathbf{i_{out}}$. The easiest way to do this is with the partial derivative

$$Z_{outf} = -\frac{\partial v_{out}}{\partial i_{out}} = \frac{Z_{out}}{1 + A_o B}$$

This decreases the impedance by a factor of 10 to 100 in transistor circuits and to practically zero in op-amps.