BASIC ELECTRICAL & ELECTRONICS ENGINEERING

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G. DEVANAND

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NRI INSTITUTE OF TECHNOLOGY

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DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

BASIC ELECTRICAL AND ELECTRONICS ENGINEERING SYLLABUS:

UNIT - I : Electrical Circuits:

Basic definitions - Types of network elements - Ohm's Law - Kirchhoff's Laws - Inductive networks - Capacitive networks – Series - Parallel circuits - Star-delta and delta-star transformations.

UNIT - II : Dc Machines:

Principle of operation of DC generator – EMF equation - Types of DC machine – Torque equation – Applications – Three point starter - Speed control methods of DC motor – Swinburne's Test.

Transformers:

Principle of operation and construction of single phase transformers – EMF equation – Losses – OC & SC tests - Efficiency and regulation.

UNIT - III: AC Rotating Machines

Principle of operation and construction of alternators– Types of alternators – Principle of operation of synchronous motor - Principle of operation of 3-Phase induction motor – Slip-torque characteristics - Efficiency – Applications.

UNIT IV : Rectifiers & Linear ICs:

PN junction diodes - Diode applications(Half wave and bridge rectifiers). Characteristics of operation amplifiers (OP-AMP) - application of OP-AMPs (inverting, non-inverting, integrator and differentiator).

UNIT V : Transistors:

PNP and NPN junction transistor, transistor as an amplifier- Transistor amplifier - Frequency response of CE amplifier - Concepts of feedback amplifier.

PRE-REQUISITES:

Get your basics strong, and **real strong** especially your 12th Physics, chapters leading to Electricity , Magnetism and Semiconductors and Maths. Nobody is going to teach those again! Try to learn the basics with a physical understanding. For eg: Difference between Average Value of Current and RMS value of current - Learn the physical significance of both (Everybody knows mathematical expression!)

REFERNCE TEXT BOOKS:

1. Electrical Technology by Surinder Pal Bali, Pearson Publications.
2. Electronic Devices and Circuits, R.L. Boylestad and Louis Nashelsky, 9th edition, PEI/PHI 2006.
3. Fundamentals of Electrical Engineering by Rajendra Prasad, PHI Publications,2nd edition

Learning Outcomes:

- Able to analyse the various electrical networks.
- Able to understand the operation of DC generators,3-point starter and DC machine testing by Swinburne's Test.
- Able to analyse the performance of single-phase transformer.
- Able to explain the operation of 3-phase alternator and 3-phase induction motors.
- Able to analyse the operation of half wave, full wave bridge rectifiers and OP-AMPs.
- Able to explain the single stage CE amplifier and concept of feedback amplifier.

UNIT - I

ELECTRICAL CIRCUITS

Classification of Electric network.:

1) **Linear Network:** A Network whose parameter elements are like capacitor, Inductance & Resistance are always constant irrespective of the change in time, temperature, voltage etc. It also follows ohms law.

2) **Bilateral Network**: The Circuit whose behaviour & characteristics are same irrespective direction of current through various elements of it.

3) **Unilateral Network** : Those Circuit whose operation, behaviour is dependent on the direction of the current through various elements is called is called unilateral network.

4) **Active Network:** A Circuit which contains at least one source of energy is called Active, may be a voltage or a current source.
Example: Op-Amp

5) **Passive Network:** A Circuit which does not contain any source of energy in the network or a circuit is known as passive network.
Example: R,L,C

6) **Lumped Network**: A Network in which all the network elements are physically separable .

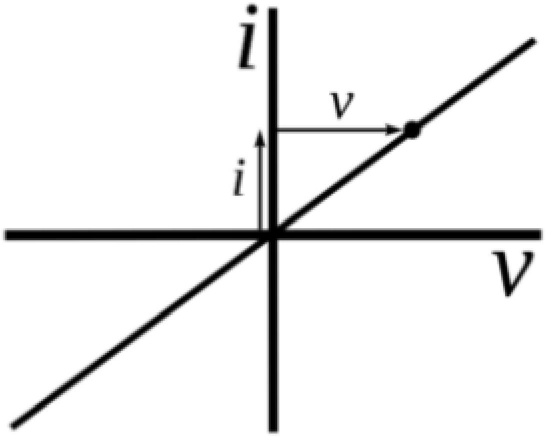
7) **Distributed Network**: A Network in which all the elements like R, L, C etc are not physically separable is known as Distributed Network.

Ohm's Law:

Ohm's law states that the voltage or potential difference between two points is directly proportional to the current or electricity passing through the resistance, and inversely proportional to the resistance of the circuit. The formula for Ohm's law is **V=I/R**. This relationship between current, voltage, and relationship was discovered by German scientist Georg Simon Ohm. Let us learn more about Ohms Law, Resistance, and its applications.

Definition:

Most basic components of electricity are voltage, current, and resistance. Ohm's law shows a simple relation between these three quantities. **Ohm's law** states that the current through a conductor between two points is directly proportional to the voltage across the two points.



Ohm's Law Formula:

Voltage= Current× Resistance
V= I×R
V= voltage, I= current and R= resistance

The SI unit of resistance is **ohms** and is denoted by **Ω**

This law is one of the most basic laws of electricity. It helps to calculate the power, efficiency, current, voltage, and resistance of an element of an electrical circuit.

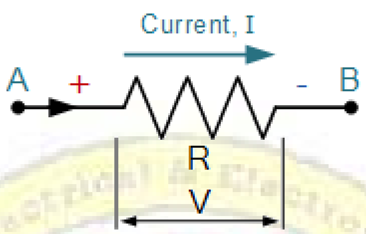
Applications of Ohm's Law:

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

Kirchhoff's Laws:

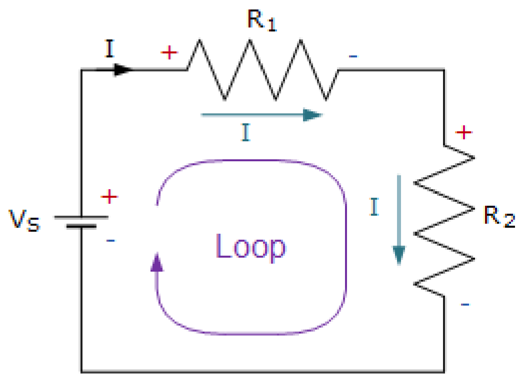
Kirchhoff's Voltage Law is the second of his fundamental laws we can use for circuit analysis. His voltage law states that for a closed loop series path **the algebraic sum of all the voltages around any closed loop in a circuit is equal to zero**. This is because a circuit loop is a closed conducting path so no energy is lost.
In other words the algebraic sum of ALL the potential differences around the loop must be equal to zero as: ΣV = 0. Note here that the term "algebraic sum" means to take into account the polarities and signs of the sources and voltage drops around the loop.
This idea by Kirchhoff is commonly known as the **Conservation of Energy**, as moving around a closed loop, or circuit, you will end up back to where you started in the circuit and therefore back to the same initial potential with no

loss of voltage around the loop. Hence any voltage drops around the loop must be equal to any voltage sources met along the way.
So when applying Kirchhoff's voltage law to a specific circuit element, it is important that we pay special attention to the algebraic signs, (+ and -) of the voltage drops across elements and the emf's of sources otherwise our calculations may be wrong.
But before we look more closely at Kirchhoff's voltage law (KVL) lets first understand the voltage drop across a single element such as a resistor.
A Single Circuit Element:



For this simple example we will assume that the current, I is in the same direction as the flow of positive charge, that is conventional current flow.
Here the flow of current through the resistor is from point A to point B, that is from positive terminal to a negative terminal. Thus as we are travelling in the same direction as current flow, there will be a *fall* in potential across the resistive element giving rise to a -IR voltage drop across it.
If the flow of current was in the opposite direction from point B to point A, then there would be a *rise* in potential across the resistive element as we are moving from a -potential to a + potential giving us a +I*R voltage drop.
Thus to apply Kirchhoff's voltage law correctly to a circuit, we must first understand the direction of the polarity and as we can see, the sign of the voltage drop across the resistive element will depend on the direction of the current flowing through it. As a general rule, you will loose potential in the same direction of current across an element and gain potential as you move in the direction of an emf source.
The direction of current flow around a closed circuit can be assumed to be either clockwise or anticlockwise and either one can be chosen. If the direction chosen is different from the actual direction of current flow, the result will still be correct and valid but will result in the algebraic answer having a minus sign.
To understand this idea a little more, lets look at a single circuit loop to see if Kirchhoff's Voltage Law holds true.

A Single Circuit Loop:



Kirchhoff’s voltage law states that the algebraic sum of the potential differences in any loop must be equal to zero as: ΣV = 0. Since the two

resistors, R_1 and R_2 are wired together in a series connection, they are both part of the same loop so the same current must flow through each resistor. Thus the voltage drop across resistor, $R_1 = I*R_1$ and the voltage drop across resistor, $R_2 = I*R_2$ giving by KVL:

$$V_S + (-IR_1) + (-IR_2) = 0$$

$$\therefore V_S = IR_1 + IR_2$$

$$V_S = I(R_1 + R_2)$$

$$V_S = IR_T$$

$$\text{Where: } R_T = R_1 + R_2$$

We can see that applying Kirchhoff’s Voltage Law to this single closed loop produces the formula for the equivalent or total resistance in the series circuit and we can expand on this to find the values of the voltage drops around the loop.

$$R_T = R_1 + R_2$$

$$I = \frac{V_S}{R_T} = \frac{V_S}{R_1 + R_2}$$

$$V_{R1} = IR_1 = V_S\left(\frac{R_1}{R_1 + R_2}\right)$$

$$V_{R2} = IR_2 = V_S\left(\frac{R_2}{R_1 + R_2}\right)$$

Kirchhoff's Voltage Law Example No1:

Three resistor of values: 10 ohms, 20 ohms and 30 ohms, respectively are connected in series across a 12 volt battery supply. Calculate: a) the total resistance, b) the circuit current, c) the current through each resistor, d) the voltage drop across each resistor, e) verify that Kirchhoff's voltage law, KVL holds true.

a) Total Resistance (R_T)

$R_T = R_1 + R_2 + R_3 = 10\Omega + 20\Omega + 30\Omega = 60\Omega$

Then the total circuit resistance R_T is equal to 60Ω

b) Circuit Current (I)

$$I = \frac{V_S}{R_T} = \frac{12}{60} = 0.2A$$

Thus the total circuit current I is equal to 0.2 amperes or 200mA

c) Current Through Each Resistor

The resistors are wired together in series, they are all part of the same loop and therefore each experience the same amount of current. Thus:

$I_{R1} = I_{R2} = I_{R3} = I_{SERIES} = 0.2$ amperes

d) Voltage Drop Across Each

Resistor $V_{R1} = I \times R_1 = 0.2 \times 10 = 2$

volts

$V_{R2} = I \times R_2 = 0.2 \times 20 = 4$ volts V_{R3}
$= I \times R_3 = 0.2 \times 30 = 6$ volts

e) Verify Kirchhoff's Voltage Law

$$V_S + (-IR_1) + (-IR_2) + (-IR_3) = 0$$

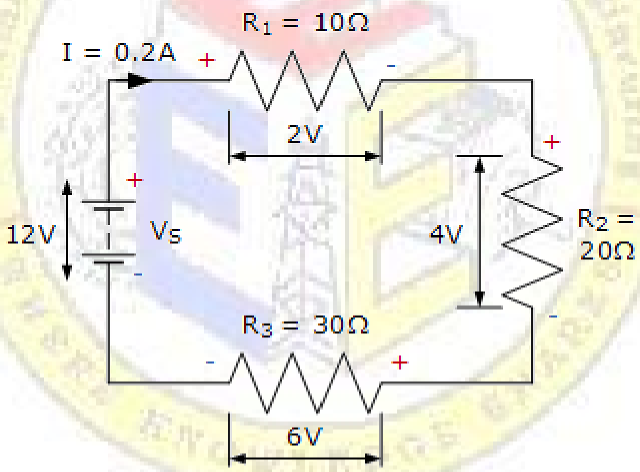
$$12 + (-0.2\times10) + (-0.2\times20) + (-0.2\times30) = 0$$

$$12 + (-2) + (-4) + (-6) = 0$$

$$\therefore 12 - 2 - 4 - 6 = 0$$

Thus Kirchhoff's voltage law holds true as the individual voltage drops around the closed loop add up to the total.

Kirchhoff's Circuit Loop:



We have seen here that Kirchhoff's voltage law, KVL is Kirchhoff's second law and states that the algebraic sum of all the voltage drops, as you go around a closed circuit from some fixed point and return back to the same point, and taking polarity into account, is always zero. That is $\Sigma V = 0$
The theory behind Kirchhoff's second law is also known as the law of conservation of voltage, and this is particularly useful for us when dealing with series circuits, as series circuits also act as voltage dividers and the voltage divider circuit is an important application of many series circuits.

<u>Inductive networks</u>:

Admittance (symbolized *Y*) is an expression of the ease with which alternating current (AC) flows through a complex circuit or system. Admittance is a vector quantity comprised of two independent scalar phenomena: conductance and susceptance .

Conductance, denoted *G* , is a measure of the ease with which charge carriers can pass through a component or substance. The more easily the charge carriers move in response to a given applied electric potential, the higher the conductance, which is expressed in positive real-number siemens . Conductance is observed with AC and also with direct current (DC).

Susceptance, denoted *B* , is an expression of the readiness with which an electronic component, circuit, or system releases stored energy as the current and voltage fluctuate. Susceptance is expressed in imaginary number siemens. It is observed for AC, but not for DC. When AC passes through a component that contains susceptance, energy might be stored and released in the form of a magnetic field, in which case the susceptance is inductive (denoted $-jB_L$), or energy might be stored and released in the form of an electric field, in which case the susceptance is capacitive (denoted $+jB_C$).

Admittance is the vector sum of conductance and susceptance. Susceptance is conventionally multiplied by the positive square root of -1, the unit imaginary number called symbolized by j , to express Y as a complex quantity $G - jB_L$ (when the net susceptance is inductive) or $G + jB_C$ (when the net susceptance is capacitive).

In parallel circuits, conductance and susceptance add together independently to yield the composite admittance. In series circuits, conductance and susceptance combine in a more complicated manner. In these situations, it is easier to convert conductance to resistance, susceptance to reactance, and then calculate the composite impedance.

Capacitive networks:

Impedance, denoted *Z*, is an expression of the opposition that an electronic component, circuit, or system offers to alternating and/or direct electric current.Impedance is a vector (two-dimensional)quantity consisting of two independent scalar (one-dimensional) phenomena: resistance and reactance.

Resistance, denoted *R*, is a measure of the extent to which a substance opposes the movement of electrons among its atoms.The more easily the atoms give up and/or accept electrons, the lower the resistance, which is expressed in positive real number ohms.Resistance is observed with alternating current (AC) and also with direct current (DC). Examples of materials with low resistance, known as electrical conductors, include copper, silver, and gold.High-resistance substances are called insulators or dielectrics, and include materials such as polyethylene, mica, and glass.A material with an intermediate levels of resistance is classified as a semiconductor. Examples are silicon, germanium, and gallium arsenide.

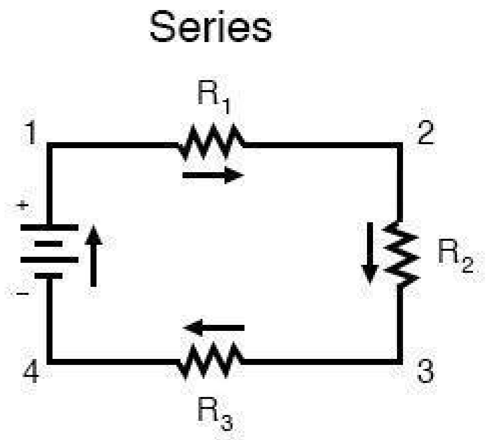
Reactance, denoted *X*, is an expression of the extent to which an electronic component, circuit, or system stores and releases energy as the current and voltage fluctuate with each AC cycle.Reactance is expressed in imaginary number ohms.It is observed for AC, but not for DC.When AC passes through a component that contains reactance, energy might be stored and released in the form of a magnetic field, in which case the reactance is inductive (denoted $+jX_L$); or energy might be stored and released in the form of an electric field, in which case the reactance is capacitive (denoted $-jX_C$). Reactance is conventionally multiplied by the positive square root of -1, which is the unit imaginary number called the *j operator*, to express *Z* as a complex number of the form $R + jX_L$ (when the net reactance is inductive) or $R - jX_C$ (when the net reactance is capacitive).

Series - Parallel circuits:

There are two basic ways in which to connect more than two circuit components: *series* and *parallel*.

Series Configuration Circuit

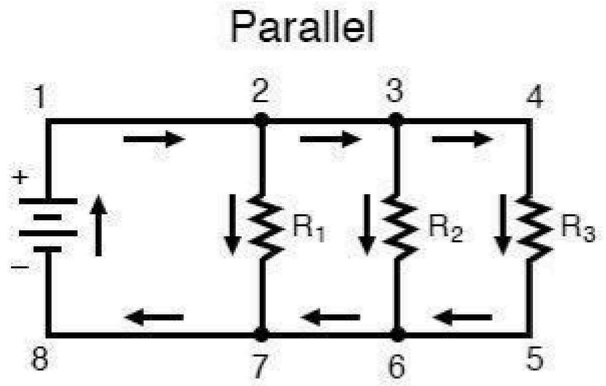
First, an example of a series circuit:



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 current to flow. In this circuit, the current flows in a clockwise direction, from point 1 to point 2 to point 3 to point 4 and back around to 1

Parallel Circuit Configuration:

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

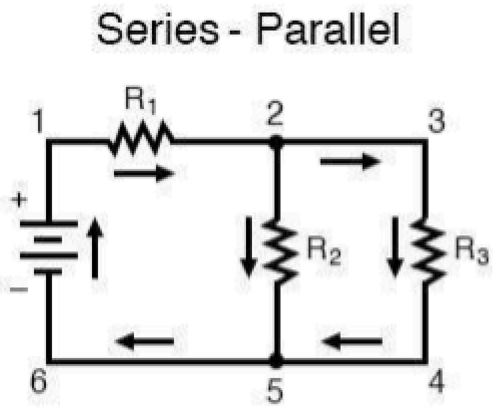


Again, we have three resistors, but this time they form more than one continuous path for current to flow. There's one path from 1 to 2 to 7 to 8 and back to 1 again. There's another from 1 to 2 to 3 to 6 to 7 to 8 and back to 1 again. And then there's a third path from 1 to 2 to 3 to 4 to 5 to 6 to 7 to 8 and back to 1 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 Configuration Circuit:



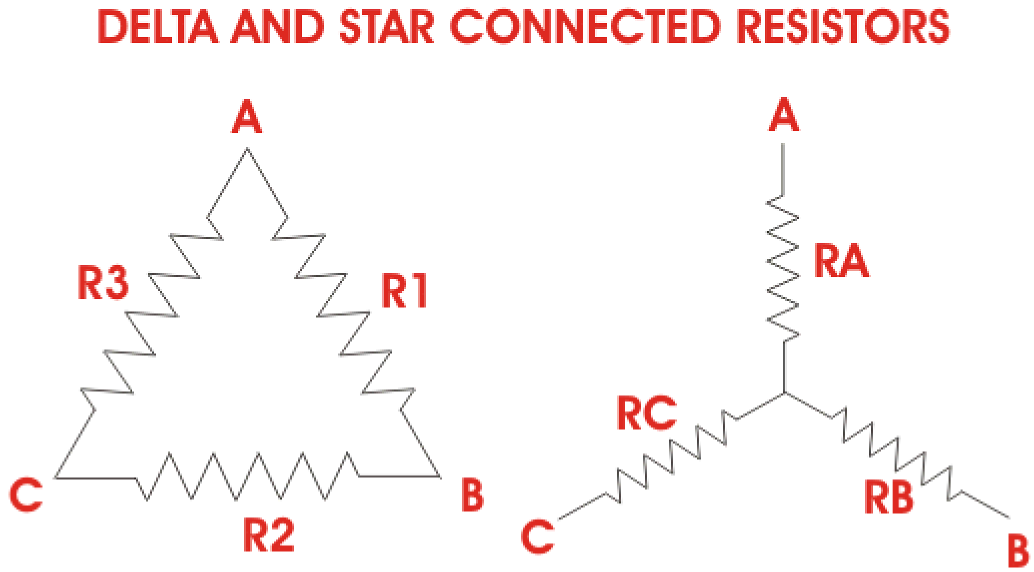
In this circuit, we have two loops for the current to flow through: one from 1 to 2 to 5 to 6 and back to 1 again, and another from 1 to 2 to 3 to 4 to 5 to 6 and back to 1 again. Notice how both current paths pass through R_1 (from point 1 to point 2). In this configuration, we'd say that R_2 and R_3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

Star-delta and delta-star transformations:

Three branches in an electrical network can be connected in numbers of forms but most common among them is either star or delta form. In delta connection, three branches are so connected, that they form a closed loop. As these three branches are connected nose to tail, they form a triangular closed loop, this configuration is referred as delta connection. On the other hand, when either terminal of three branches is connected to a common point to form a Y like pattern is known as star connection. But these star and delta connections can be transformed from one form to another. For simplifying complex network, delta to star or **star to delta transformation** is often required.

Delta To Star Conversion:

The replacement of delta or mesh by equivalent star connection is known as **delta – star transformation**. The two connections are equivalent or identical to each other if the impedance is measured between any pair of lines. That means, the value of impedance will be the same if it is measured between any pair of lines irrespective of whether the delta is connected between the lines or its equivalent star is connected between that lines.



Consider a delta system that's three corner points are A, B and C as shown in the figure. Electrical resistance of the branch between points A and B, B and C and C and A are R_1, R_2 and R_3 respectively.
The resistance between the points A and B will be,

$$R_{AB} = R_1||(R_2 + R_3) = \frac{R_1.(R_2 + R_3)}{R_1 + R_2 + R_3}$$

Now, one star system is connected to these points A, B, and C as shown in the figure. Three arms R_A, R_B and R_C of the star system are connected with A, B and C respectively. Now if we measure the resistance value between points A and B, we will get,

$$R_{AB} = R_A + R_B$$

Since the two systems are identical, resistance measured between terminals A and B in both systems must be equal.

$$R_A + R_B = \frac{R_1.(R_2 + R_3)}{R_1 + R_2 + R_3} \cdots\cdots\cdots\cdots (i)$$

Similarly, resistance between points B and C being equal in the two systems,

$$R_B + R_C = \frac{R_2.(R_3 + R_1)}{R_1 + R_2 + R_3} \cdots\cdots\cdots\cdots (ii)$$

And resistance between points C and A being equal in the two systems,

$$R_C + R_A = \frac{R_3.(R_1 + R_2)}{R_1 + R_2 + R_3} \cdots\cdots\cdots\cdots (iii)$$

Adding equations (I), (II) and (III) we get,

$$2(R_A + R_B + R_C) = \frac{2(R_1.R_2 + R_2.R_3 + R_3.R_1)}{R_1 + R_2 + R_3}$$

$$R_A + R_B + R_C = \frac{R_1.R_2 + R_2.R_3 + R_3.R_1}{R_1 + R_2 + R_3} ....(iv)$$

Subtracting equations (I), (II) and (III) from equation (IV) we get,

$$R_A = \frac{R_3.R_1}{R_1 + R_2 + R_3} \ldots\ldots\ldots\ldots\ldots\ldots(v)$$

$$R_B = \frac{R_1.R_2}{R_1 + R_2 + R_3} \ldots\ldots\ldots\ldots\ldots\ldots(vi)$$

$$R_C = \frac{R_2.R_3}{R_1 + R_2 + R_3} \ldots\ldots\ldots\ldots\ldots\ldots(vii)$$

The relation of delta – star transformation can be expressed as follows.
The equivalent star resistance connected to a given terminal, is equal to the product of the two delta resistances connected to the same terminal divided by the sum of the delta connected resistances.
If the delta connected system has same resistance R at its three sides then equivalent star resistance r will be,

$$r = \frac{R.R}{R + R + R} = \frac{R}{3}$$

Star To Delta Conversion:

For **star – delta transformation** we just multiply equations (v), (VI) and (VI), (VII) and (VII), (V) that is by doing (v) × (VI) + (VI) × (VII) + (VII) × (V) we get,

$$R_A R_B + R_B R_C + R_C R_A = \frac{R_1.{R_2}^2.R_3 + R_1.R_2.{R_3}^2 + {R_1}^2.R_2.R_3}{(R_1 + R_2 + R_3)^2}$$

$$= \frac{R_1.R_2.R_3(R_1 + R_2 + R_3)}{(R_1 + R_2 + R_3)^2}$$

$$= \frac{R_1.R_2.R_3}{R_1 + R_2 + R_3} \ldots\ldots\ldots\ldots\ldots(viii)$$

Now dividing equation (VIII) by equations (V), (VI) and equations (VII) separately we get,

$$R_3 = \frac{R_A R_B + R_B R_C + R_C R_A}{R_A}$$

$$R_1 = \frac{R_A R_B + R_B R_C + R_C R_A}{R_B}$$

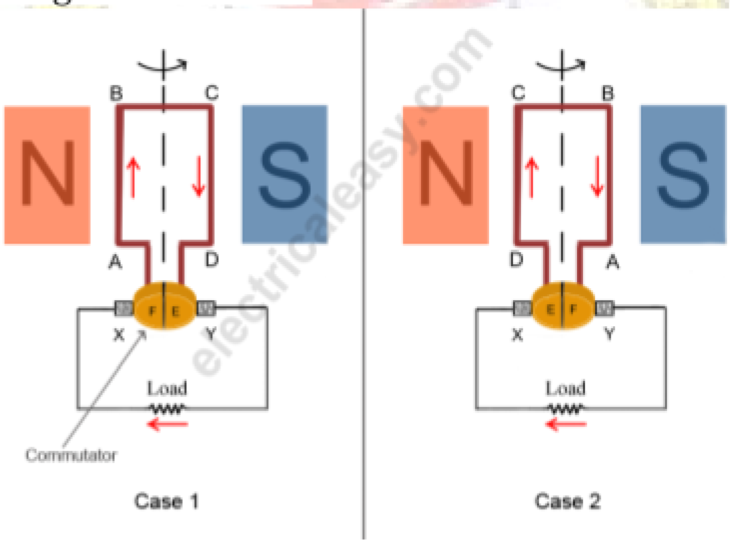
$$R_2 = \frac{R_A R_B + R_B R_C + R_C R_A}{R_C}$$

UNIT-2 DC MACHINES

Principle of operation of DC generator:

According to Faraday's laws of electromagnetic induction, whenever a conductor is placed in a varying magnetic field (OR a conductor is moved in a magnetic field), an emf (electromotive force) gets induced in the conductor. The magnitude of induced emf can be calculated from the emf equation of dc generator. If the conductor is provided with a closed path, the induced current will circulate within the path. In a DC generator, field coils produce an electromagnetic field and the armature conductors are rotated into the field. Thus, an electromagnetically induced emf is generated in the armature conductors. The direction of induced current is given by Fleming's right hand rule.

Need of a Split ring commutator:



According to Fleming's right hand rule, the direction of induced current changes whenever the direction of motion of the conductor changes. Let's consider an armature rotating clockwise and a conductor at the left is moving upward. When the armature completes a half rotation, the direction of motion of that particular conductor will be reversed to downward. Hence, the direction of current in every armature conductor will be alternating. If you look at the above figure, you will know how the direction of the induced current is alternating in an armature conductor. But with a split ring commutator, connections of the armature conductors also gets reversed when the current reversal occurs. And therefore, we get unidirectional current at the terminals.

<u>EMF equation</u>:As the armature rotates, a voltage is generated in its coils. In the case of a generator, the emf of rotation is called the **Generated emf** or **Armature emf**and is denoted as Er = Eg. In the case of a motor, the emf of rotation is known as **Back emf** or **Counter emf** and represented as Er = Eb.The expression for emf is same for both the operations. I.e., for Generator as well as for Motor.

Derivation of EMF Equation of a DC Machine – Generator and Motor

Let,

- **P** – Number of poles of the machine
- **ϕ** – Flux per pole in Weber.
- **Z** – Total number of armature conductors.
- **N** – Speed of armature in revolution per minute (r.p.m).
- **A** – Number of parallel paths in the armature winding.

In one revolution of the armature, the flux cut by one conductor is given as

$$\text{Flux cut by one conductor} = P\varphi \quad \text{wb} \dots \dots (1)$$

Time taken to complete one revolution is given as

$$t = \frac{60}{N} \quad \text{seconds} \quad \dots \dots (2)$$

Therefore, the average induced e.m.f in one conductor will be

$$e = \frac{P\varphi}{t} \quad \dots \dots (3)$$

Putting the value of (t) from Equation (2) in the equation (3) we will get

$$e = \frac{P\varphi}{60/N} = \frac{P\varphi N}{60} \quad \text{volts} \quad \dots \dots (4)$$

Types Of A DC motar:

Understanding the different types of DC motors will also help you understand how they're used for different applications, and which type may apply to your application.
There are 4 main types of DC motors:

1. Permanent Magnet DC Motors:

The permanent magnet motor uses a permanent magnet to create field flux. This type of DC motor provides great starting torque and has good speed regulation, but torque is limited so they are typically found on low horsepower applications.

2. Series DC Motors:

In a series DC motor, the field is wound with a few turns of a large wire carrying the full armature current. Typically, series DC motors create a large amount of starting torque, but cannot regulate speed and can even be damaged by running with no load. These limitations mean that they are not a good option for variable speed drive applications.

3. Shunt DC Motors:

In shunt DC motors the field is connected in parallel (shunt) with the armature windings. These motors offer great speed regulation due to the fact that the shunt field can be excited separately from the armature windings, which also offers simplified reversing controls.

4. Compound DC Motors:

Compound DC motors, like shunt DC motors, have a separately excited shunt field. Compound DC motors have good starting torque but may experience control problems in variable speed drive applications.

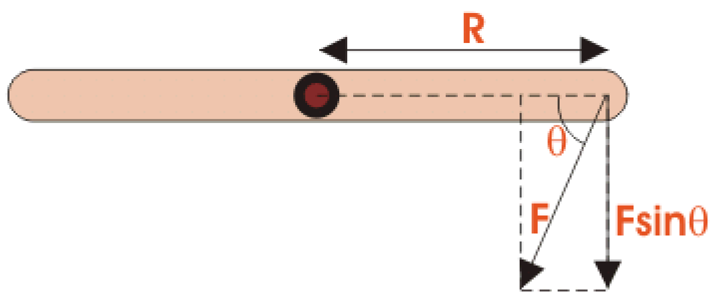
Torque equation:

When a DC machine is loaded either as a motor or as a generator, the rotor conductors carry current. These conductors lie in the magnetic field of the air gap. Thus each conductor experiences a force. The conductors lie near the surface of the rotor at a common radius from its center. Hence torque is produced at the circumference of the rotor and rotor starts rotating. The term torque as best explained by Dr. Huge d Young is the quantitative measure of the tendency of a force to cause a rotational motion, or to bring about a change in rotational motion. It is in fact the moment of a force that produces or changes a rotational motion.

The equation of torque is given by,

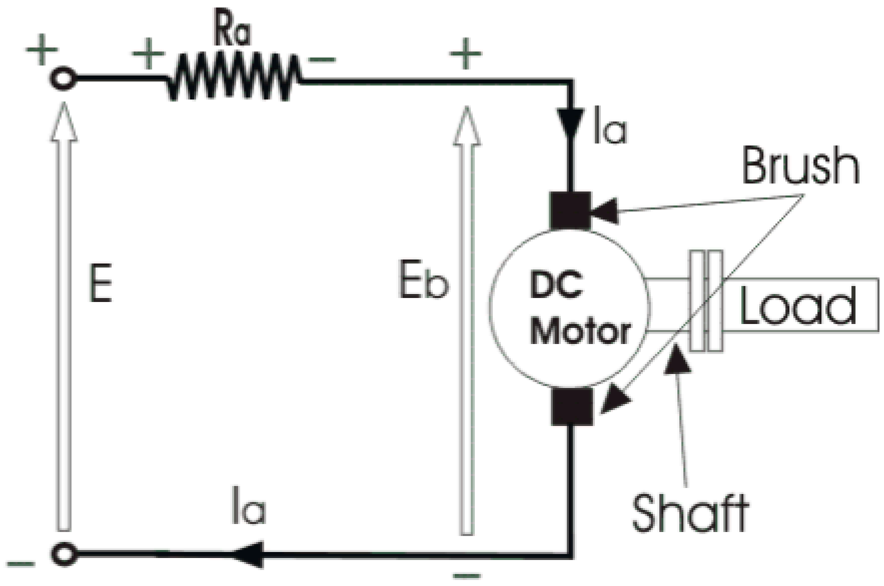
$$\tau = FR\sin\theta \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Where, F is force in linear direction.
R is radius of the object being rotated,
and θ is the angle, the force F is making with R vector



The DC motor as we all know is a rotational machine, and **torque of DC motor** is a very important parameter in this concern, and it's of utmost importance to understand the **torque equation of DC motor** for establishing its running characteristics.

To establish the torque equation, let us first consider the basic circuit diagram of a DC motor, and its voltage equation.



Referring to the diagram beside, we can see, that if E is the supply voltage, E_b is the back emf produced and I_a, R_a are the armature current and armature resistance respectively then the voltage equation is given by,

$$E = E_b + I_aR_a \text{ .... } (2)$$

But keeping in mind that our purpose is to derive the **torque equation of DC motor** we multiply both sides of equation (2) by I_a.

$$Therefore,\ EI_a = E_bI_a + I_a^2R_a \text{ .... } (3)$$

Now $I_a^2.R_a$ is the power loss due to heating of the armature coil, and the true effective mechanical power that is required to produce the desired torque of DC machine is given by,

$$P_m = E_bI_a \text{ .... } (4)$$

The mechanical power P_m is related to the electromagnetic torque T_g as,

$$P_m = T_g\omega \text{ .... } (5)$$

Where, ω is speed in rad/sec.

Now equating equation (4) and (5) we get,

$$E_bI_a = T_g\omega$$

Now for simplifying the torque equation of DC motor we substitute.

$$E_b = \frac{P\varphi ZN}{60A} \text{ .... } (6)$$

Where, P is no of poles,

φ is flux per pole,

Z is no. of conductors,
A is no. of parallel paths,
and N is the speed of the DC motor.

$$Hence,\ w = \frac{2\pi N}{60} \text{ .... } (7)$$

Substituting equation (6) and (7) in equation (4), we get:

$$T_g = \frac{P.Z.\varphi.I_a}{2\pi A}$$

The torque we so obtain, is known as the electromagnetic torque of DC motor, and subtracting the mechanical and rotational losses from it we get the mechanical torque.

Therefore,

$$T_m = T_g - mechanical\ losses$$

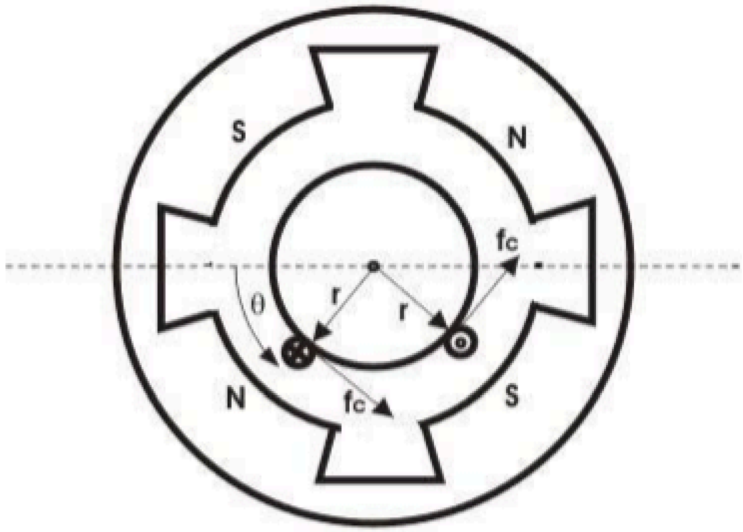
This is the torque equation of DC motor. It can be further simplified as:

$$T_g = k_a \phi I_A$$

$$Where,\ k_a = \frac{P.Z}{2\pi A}$$

Which is constant for a particular machine and therefore the torque of DC motor varies with only flux φ and armature current I_a.

The **Torque equation of a DC motor** can also be explained considering the figure below.



$$Here\ we\ can\ see\ Area\ per\ pole\ A_r = \frac{2\pi.r.L}{P}$$

$$B = \frac{\varphi}{A_r}$$

$$B = \frac{P.\varphi}{2\pi r L}$$

Current/conductor $I_c = I_a$ A Therefore,

force per conductor = $f_c = BLI_a/A$

Now torque $T_c = f_c.\ r = BLI_a.r/A$

$$\therefore\ T_c = \frac{\varphi P.I_a}{2\pi A}$$

Hence, the total torque developed of a DC machine is,

$$T_g = \frac{P.Z.\varphi.I_a}{2\pi.A}$$

This **torque equation of DC motor** can be further simplified as:

$$T_g = k_a \phi I_a$$

$$Where,\ k_a = \frac{P.Z}{2\pi.A}$$

Which is constant for a particular machine and therefore the torque of DC motor varies with only flux φ and armature current I_a.

Three point starter:

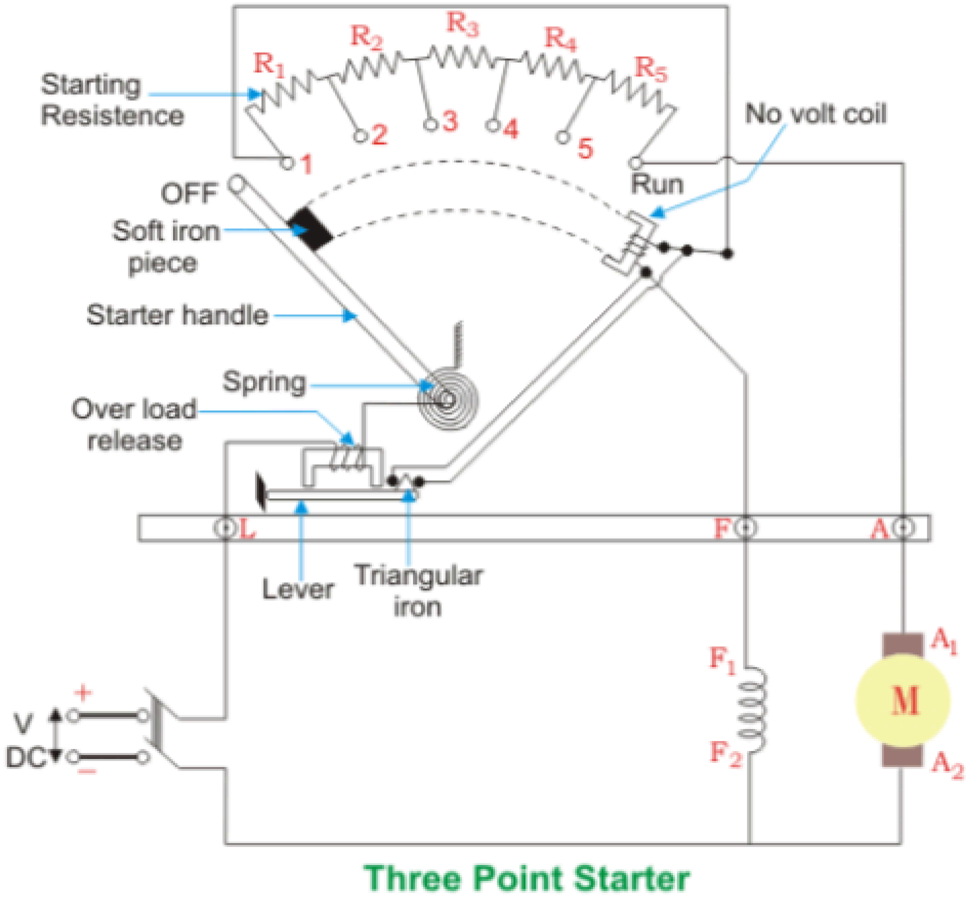
A **3 point starter** is a device that helps in the starting and running of a DC shunt motor or compound wound DC motor (similar to a 4 point starter).
Now the question is why these types of DC motors require the assistance of the starter in the first place? Well, it's due to the presence of back emf (E_b), which plays a critical role in governing the operation of the motor. The back emf develops as the motor armature starts to rotate in presence of the magnetic field, by generating action and counters the supply voltage. Hence the back emf at the starting of the motor is zero, but it develops gradually as the motor gathers speed.
The general motor emf equation is:

$$E = E_b + I_a.R_a$$

Where E=Supply Voltage; E_b=Back EMF; I_a=Armature Current; and R_a=Armature Resistance. Since at starting $E_b = 0$, then $E = I_a.R_a$. Hence we can rearrange for the armature current I_a:

$$\therefore\ I_a = \frac{E}{R_a}$$

We can see from the above equation that the current will be dangerously high at starting (as the armature resistance R_a is small). This is why it's important that we make use of a device like the **3 point starter** to limit the starting current to acceptably low value.
To understand how the starting current is restricted to the desired value, we need to look at the construction and **working of three-point starter**. The electrical symbols in the diagram below show all the essential parts of a three-point starter.



3 Point Starter

Diagram

Construction of 3 Point Starter:

Construction wise a starter is a variable resistance, integrated into the number of sections as shown in the figure beside. The contact points of these sections are called studs and are shown separately as **OFF, 1, 2, 3, 4, 5, RUN**. Other than that there are three main points, referred to as

1. 'L' Line terminal (Connected to positive of supply)
2. 'A' Armature terminal (Connected to the armature winding)
3. 'F' Field terminal (Connected to the field winding)

And from there it gets the name 3 point starter. Now studying the **construction of 3 point starter** in further details reveals that the point 'L' is connected to an electromagnet called overload release (OLR) as shown in the figure. The other end of OLR is connected to the lower end of conducting lever of starter handle where spring is also attached with it, and the starter handle also contains a soft iron piece housed on it. This handle is free to move to the other side RUN against the force of the spring. This spring brings back the handle to its original OFF position under the influence of its own force. Another parallel path is derived from the stud '1', given to another electromagnet called No Volt Coil (NVC) which is further connected to terminal 'F.' The starting resistance at starting is entirely in series with the armature. The OLR and NVC act as the two protecting devices of the starter.

Working of Three Point Starter:

Having studied its construction, let us now go into the **working of the 3 point starter**. To start with the handle is in the OFF position when the supply to the DC motor is switched on. Then handle is slowly moved against the spring force to make contact with stud No. 1. At this point, field winding of the shunt or the compound motor gets supply through the parallel path provided to starting the resistance, through No Voltage Coil. While entire starting resistance comes in series with the armature. The high starting armature current thus gets limited as the current equation at this stage becomes:

$$I_a = \frac{E}{(R_a + R_{st})}$$

As the handle is moved further, it goes on making contact with studs 2, 3, 4, etc., thus gradually cutting off the series resistance from the armature circuit as the motor gathers speed. Finally, when the starter handle is in 'RUN' position, the entire starting resistance is eliminated, and the motor runs with normal speed. This is because back emf is developed consequently with speed to counter the supply voltage and reduce the armature current.

So the external electrical resistance is not required anymore and is removed for optimum operation. The handle is moved manually from OFF to the RUN position with the development of speed. Now the obvious question is once the handle is taken to the RUN position how it is supposed to stay there, as long as the motor is running.

To find the answer to this question let us look into the working of No Voltage Coil.

Speed control methods of DC motor:

Often we want to control the speed of a DC motor on demand. This intentional change of drive speed is known as **speed control of a DC motor**.

Speed control of a DC motor is either done manually by the operator or by means of an automatic control device. This is different to speed regulation – where the speed is trying to be maintained (or 'regulated') against the natural change in speed due to a change in the load on the shaft.

The **speed of a DC motor** (N) is equal to:

$$N = \frac{V - I_a R_a}{k\phi}$$

Therefore speed of the 3 types of DC motors – shunt, series and compound – can be controlled by changing the quantities on the right-hand side of the equation above.

Hence the speed can be varied by changing:

1. The terminal voltage of the armature, V.

2. The external resistance in armature circuit, R_a.
3. The flux per pole, φ.

Terminal voltage and external resistance involve a change that affects the armature circuit, while flux involves a change in the magnetic field. Therefore**speed control of DC motor**can be classified into:

1. Armature Control Methods
2. Field Control Methods

We will discuss how both of these methods control the speed of **DC series motors** and **DC shunt motors**.

Speed Control of DC Series Motor

Speed control methods for a DC series motor can be classified as:

1. Armature Control Methods
2. Field Control Methods

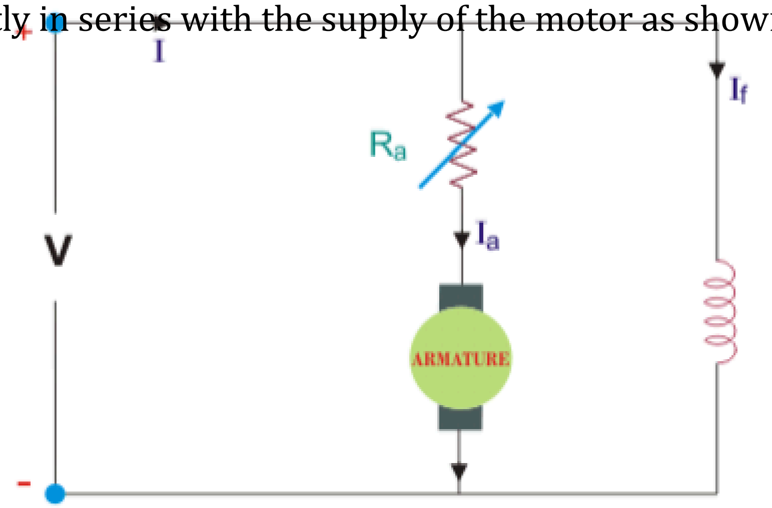
Armature Controlled DC Series Motor

Speed adjustment of a DC series motor by **armature control** may be done by:

1. Armature Resistance Control Method
2. Shunted Armature Control Method
3. Armature Terminal Voltage Control

Armature Resistance Control Method:

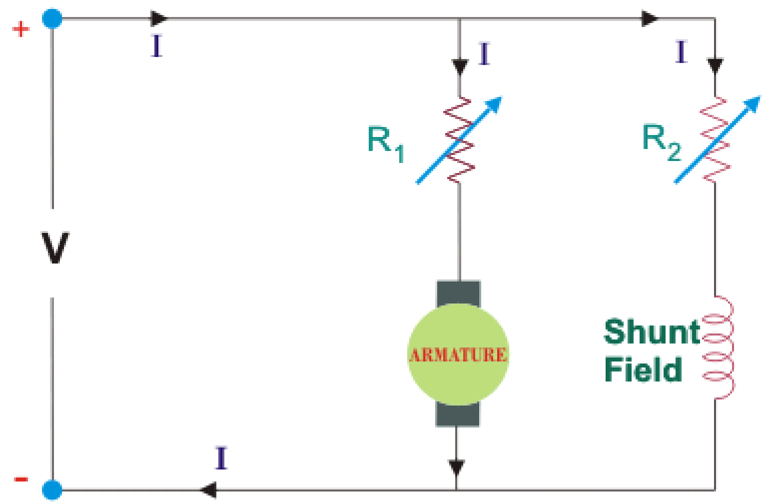
This is the most common method employed. Here the controlling resistance is connected directly in series with the supply of the motor as shown in the fig.



The power loss in the control resistance of DC series motor can be neglected because this control method is utilized for a large portion of time for reducing the speed under light load condition. This method of speed control is most economical for constant torque. This method of speed control is employed for DC series motor driving cranes, hoists, trains etc.

Shunted Armature Control:

The combination of a rheostat shunting the armature and a rheostat in series with the armature is involved in this method of speed control. The voltage applied to the armature is varies by varying series rheostat R_1. The exciting current can be varied by varying the armature shunting resistance R_2. This method of speed control is not economical due to considerable power losses in speed controlling resistances. Here speed control is obtained over wide range but below normal speed.



Armature Terminal Voltage Control:

The speed control of DC series motor can be accomplished by supplying the power to the motor from a separate variable voltage supply. This method involves high cost so it rarely used.

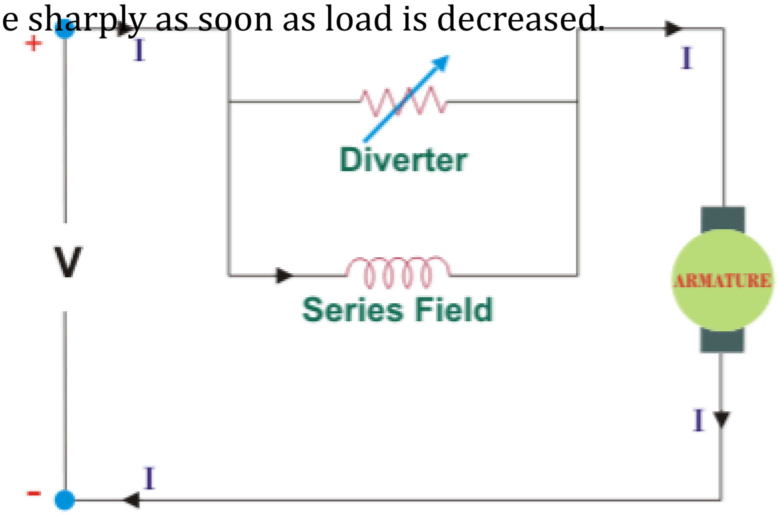
Field Controlled DC Series Motor

Speed adjustment of a DC series motor by **field control** may be done by:

1. Field Diverter Method
2. Tapped Field Control

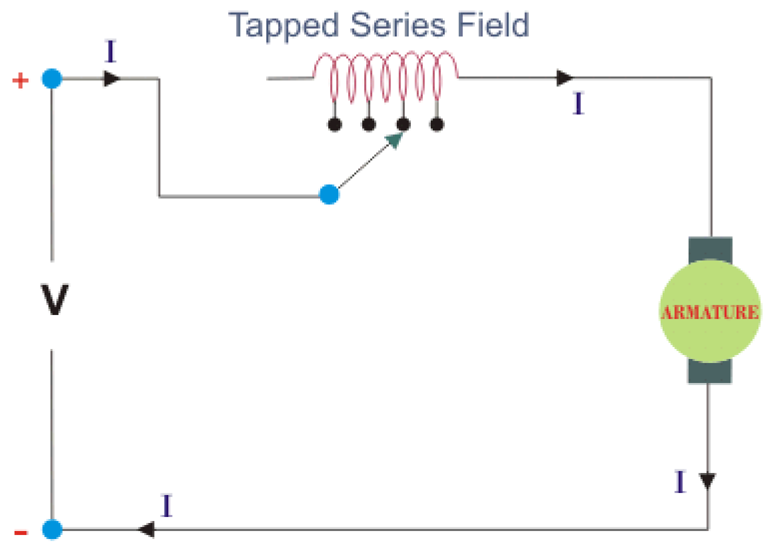
Field Diverter Method:

This method uses a diverter. Here the field flux can be reduced by shunting a portion of motor current around the series field. Lesser the diverter resistance less is the field current, less flux therefore more speed. This method gives speed above normal and the method is used in electric drives in which speed should rise sharply as soon as load is decreased.



Tapped Field Control

This is another method of increasing the speed by reducing the flux and it is done by lowering number of turns of field winding through which current flows. In this method a number of tapping from field winding are brought outside. This method is employed in electric traction.



<u>Speed Control of DC Shunt Motor</u>

The classification of **speed control methods for a DC shunt motor** are similar to those of a DC series motor. These two methods are:

1. Armature Control Methods
2. Field Control Methods

Armature Controlled DC Shunt Motor:

Armature controlled DC shunt motor can be performed in two ways:

1. Armature Resistance Control
2. Armature Voltage Control

Armature Resistance Control:

In armature resistance control a variable resistance is added to the armature circuit. Field is directly connected across the supply so flux is not changed due to variation of series resistance. This is applied for DC shunt motor. This method is used in printing press, cranes, hoists where speeds lower than rated is used for a short period only.

Armature Voltage Control:

This method of speed control needs a variable source of voltage separated from the source supplying the field current. This method avoids disadvantages of poor speed regulation and low efficiency of armature-resistance control methods.

The basic adjustable armature voltage control method of speed d control is accomplished by means of an adjustable voltage generator is called **Ward Leonard System**. This method involves using a motor-generator (M-G) set. This method is best suited for steel rolling mills, paper machines, elevators, mine hoists, etc. This method is known as Ward Leonard System.

Advantages of Armature Controlled DC Shunt Motor:

1. Very fine speed control over whole range in both directions

2. Uniform acceleration is obtained
3. Good speed regulation

4. It has regenerative braking capacity

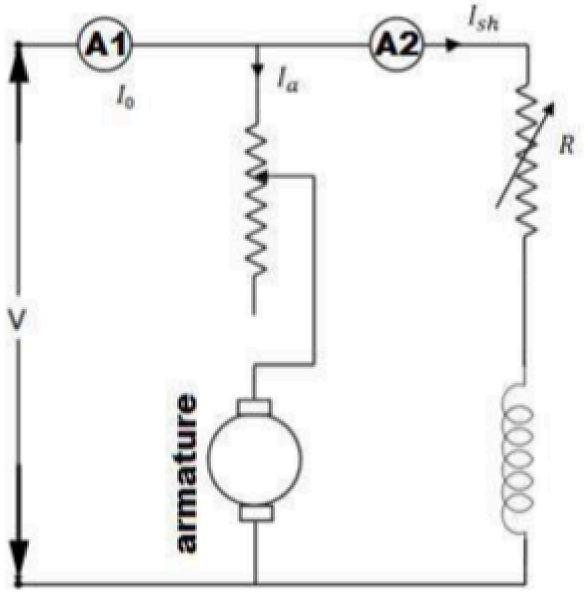
Disadvantages of Armature Controlled DC Shunt Motor:

1. Costly arrangement is needed, floor space required is more
2. Low efficiency at light loads
3. Drive produced more noise.

Swinburne's Test:

This method is an indirect method of testing a DC machine. It is named after Sir James Swinburne. **Swinburne's test** is the most commonly used and simplest method of testing of shunt and compound wound DC machines which have constant flux. In this test the efficiency of the machine at any load is pre-determined. We can run the machine as a motor or as a generator. In this method of testing no load losses are measured separately and eventually we can determine the efficiency.

The circuit connection for **Swinburne's test** is shown in figure below. The speed of the machine is adjusted to the rated speed with the help of the shunt regulator R as shown in figure.



Calculation of Efficiency:

Let, I_0 is the no load current (it can be measured by ammeter A_1)
I_{sh} is the shunt field current (it can be measured by ammeter A_2)
Then, no load armature current =$(I_0 - I_{sh})$

Also let, V is the supply voltage. Therefore, No load power input = VI_0 watts.

In **Swinburne's test** no load power input is only required to supply the losses. The losses occur in the machine mainly are:

- Iron losses in the core
- Friction and windings losses
- Armature copper loss.

Since the no load mechanical output of the machine is zero in Swinburne's test, the no load input power is only used to supply the losses.

The value of armature copper loss = $(I_0 - I_{sh})^2 R_a$
Here, R_a is the armature resistance.
Now, no to get the constant losses we have to subtract the armature copper loss from the no load power input.
Then, $Constant\ losses\ W_C = VI_0 - (I_0 - I_{sh})^2 R_a$
After calculating the no load constant losses now we can determine the efficiency at any load.
Let, I is the load current at which we have to calculate the efficiency of the machine.
Then, armature current (I_a) will be ($I - I_{sh}$), when the machine is motoring.
And $I_a = (I + I_{sh})$, when the machine is generating.

Calculation of Efficiency When the Machine is Motoring on Load

Power input = VI
Armature copper loss, $P_{CU} = I^2 R_a = (I - I_{sh})^2 R_a$
Constant losses, $W_C = VI_0 - (I_0 - I_{sh})^2 R_a$
$Total\ losses = P_{CU} + W_C$
∴ Efficiency of the motor:

$$\eta_m = \frac{output}{input} = \frac{input\ -\ losses}{input} = \frac{VI\ -\ (P_C U + W_C)}{VI}$$

Calculation of Efficiency When the Machine is Generating on Load:

Power input = VI
Armature copper loss, $P_{CU} = I_2 R_a = (I + I_{sh})^2 R_a$
Constant losses, $W_C = VI_0 - (I_0 - I_{sh})^2 R_a$
$Total\ losses = P_{CU} + W_C$
∴ Efficiency of the generator:

$$\eta_g = \frac{output}{input} = \frac{input\ -\ losses}{input} = \frac{VI\ -\ (P_C U\ +\ W_C)}{VI}$$

Advantages of Swinburne's Test:

The main advantages of this test are:

1.
    1. This test is very convenient and economical as it is required very less power from supply to perform the test.
    2. Since constant losses are known, efficiency of **Swinburne's test** can be pre-determined at any load.

Disadvantages of Swinburne's Test:

The main disadvantages of this test are :

1.
    1. Iron loss is neglected though there is change in iron loss from no load to full load due to armature reaction.
    2. We cannot be sure about the satisfactory commutation on loaded condition because the test is done on no-load.

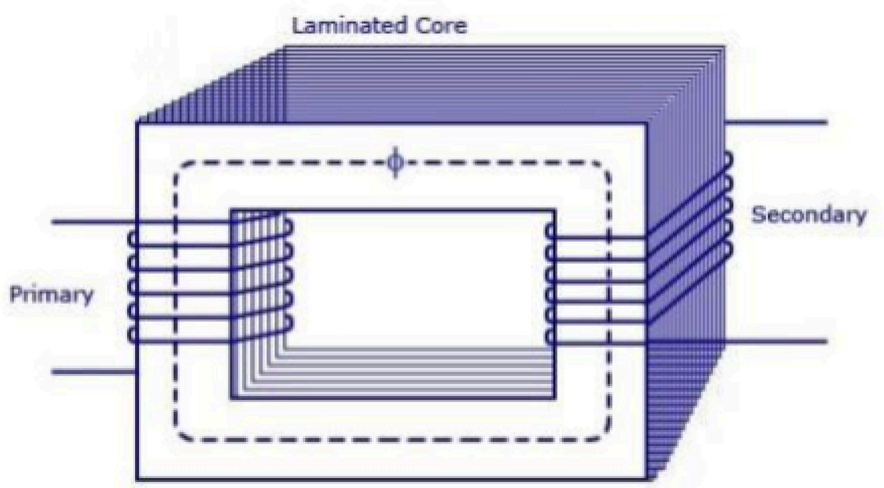
3. We can’t measure the temperature rise when the machine is loaded. Power losses can vary with the temperature.
4. In DC series motors, the Swinburne’s test cannot be done to find its efficiency as it is a no load test.

TRANSFORMERS

Principle of operation and construction of single phase transformers:

A transformer can be defined as a static device which helps in the transformation of electric power in one circuit to electric power of the same frequency in another circuit. The voltage can be raised or lowered in a circuit, but with a proportional increase or decrease in the current ratings.

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



As shown above the transformer has primary and secondary windings. The core laminations are joined in the form of strips in between the strips you can see that there are some narrow gaps right through the cross-section of the core. These staggered joints are said to be

'imbricated'. Both the coils have high mutual inductance. A mutual electro-motive force is induced in the transformer from the alternating flux that is set up in the laminated core, due to the coil that is connected to a source of alternating voltage. Most of the alternating flux developed by this coil is linked with the other coil and thus produces the mutual induced electro-motive force. The so produced electro-motive force can be explained with the help of Faraday's laws of Electromagnetic Induction as

$$e=M*dI/dt$$

If the second coil circuit is closed, a current flows in it and thus electrical energy is transferred magnetically from the first to the second coil.

The alternating current supply is given to the first coil and hence it can be called as the primary winding. The energy is drawn out from the second coil and thus can be called as the secondary winding.

In short, a transformer carries the operations shown below:

Transfer of electric power from one circuit to another.

Transfer of electric power without any change in frequency.

Transfer with the principle of electromagnetic induction.

The two electrical circuits are linked by mutual induction

TRANSFORMER CONSTRUCTION:

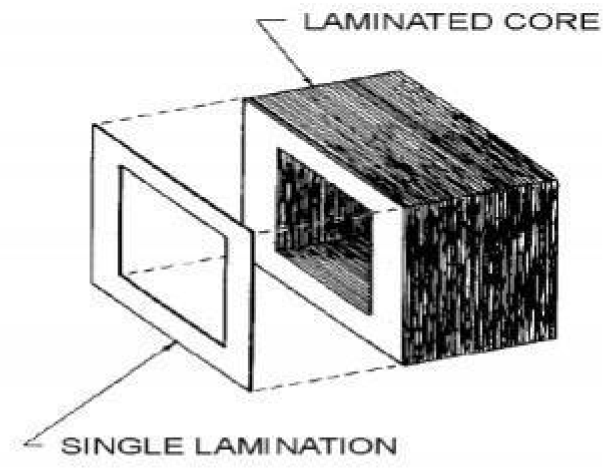
Two coils of wire (called windings) are wound on some type of core material. In some cases the coils of wire are wound on a cylindrical or rectangular cardboard form. In effect, the core material is air and the transformer is called an AIR-CORE TRANSFORMER. Transformers used at low frequencies, such as 60 hertz and 400 hertz, require a core of low-reluctance magnetic material, usually iron. This type of transformer is called an IRON-CORE TRANSFORMER. Most power transformers are of the iron-core type.

The principle parts of a transformer and their functions are:
The CORE, which provides a path for the magnetic lines of flux.
The PRIMARY WINDING, which receives energy from the ac source.

The SECONDARY WINDING, which receives energy from the primary winding and delivers it to the load.

The ENCLOSURE, which protects the above components from dirt, moisture, and mechanical damage.

(i) CORE:



There are two main shapes of cores used in laminated-steel-core transformers. One is the HOLLOWCORE, so named because the core is shaped with a hollow square through the center. This shape of core. Notice that the core is made up of many laminations of steel it shows how the transformer windings are wrapped around both sides of the core.

(ii) WINDINGS:

As stated above, the transformer consists of two coils called WINDINGS which are wrapped around a core. The transformer operates when a source of ac voltage is connected to one of the windings and a load device is connected to the other. The winding that is connected to the source is called the PRIMARY WINDING. The winding that is connected to the load is called the SECONDARY WINDING. The primary is wound in layers directly on a rectangular cardboard form.

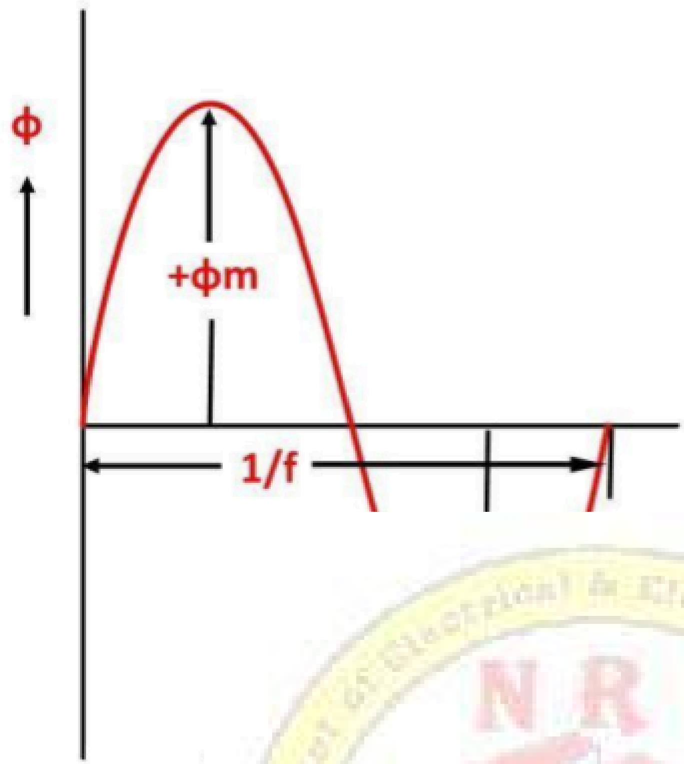
EMF equation:

When a sinusoidal voltage is applied to the primary winding of a transformer, alternating flux ϕ_m sets up in the iron core of the transformer. This sinusoidal flux links with both primary and secondary winding. The function of flux is a sine function. The rate of change of flux with respect to time is derived mathematically.

The derivation of **EMF Equation** of the transformer is shown below. Let

- ϕ_m be the maximum value of flux in Weber
- f be the supply frequency in Hz
- N_1 is the number of turns in the primary winding
- N_2 is the number of turns in the secondary winding

Φ is the flux per turn in Weber



As shown in the above figure that the flux changes from + ϕ_m to – ϕ_m in half a cycle of 1/2f seconds.

By Faraday's Law

Let E_1 is the emf induced in the primary winding

$$E_1 = -\frac{d\psi}{dt}$$

Where $\Psi = N_1\phi$

$$\text{Therefore, } E_1 = -N_1 \frac{d\varphi}{dt} \quad \ldots\ldots\ldots.(2)$$

Since ϕ is due to AC supply $\phi = \phi_m$ Sinwt

$$E_1 = -N_1 \frac{d}{dt}(\varphi_m \, \text{Sinwt})$$

$$E_1 = -N_1 \, w\varphi_m \, \text{Coswt}$$

$$E_1 = N_1 w\varphi_m \, \text{Sin}(wt - \pi/2) \ldots\ldots\ldots.(3)$$

So the induced emf lags flux by 90 degrees.

Maximum valve of emf

$$E_1 max = N_1 w\varphi_m \ldots\ldots\ldots(4)$$

But w = 2πf

$$E_1 max = 2\pi f N_1 \varphi_m \ldots\ldots\ldots(5)$$

Losses:

In any electrical machine, 'loss' can be defined as the difference between input power and output power. An electrical transformer is an static device, hence mechanical losses (like windage or friction losses) are absent in it. A transformer only consists of electrical losses (iron losses and copper losses). Transformer losses are similar to losses in a DC machine, except that transformers do not have mechanical losses.

Losses in transformer are explained below -

(I) Core Losses Or Iron Losses

Eddy current loss and hysteresis loss depend upon the magnetic properties of the material used for the construction of core. Hence these losses are also known as **core losses** or **iron losses**.

- **Hysteresis loss in transformer:**

  Hysteresis loss is due to reversal of magnetization in the transformer core. This loss depends upon the volume and grade of the iron, frequency of magnetic reversals and value of flux density. It can be given by, Steinmetz formula:

  $W_h = \eta B_{max}^{1.6} fV$ (watts)

  where, η = Steinmetz hysteresis constant

  V = volume of the core in m^3

- **Eddy current loss in transformer:**

  In transformer, AC current is supplied to the primary winding which sets up alternating magnetizing flux. When this flux links with secondary winding, it produces induced emf in it. But some part of this flux also gets linked with other conducting parts like steel core or iron body or the transformer, which will result in induced emf in those parts, causing small circulating current in them. This current is called as eddy current. Due to these eddy currents, some energy will be dissipated in the form of heat.

(Ii) Copper Loss In Transformer:

Copper loss is due to ohmic resistance of the transformer windings. Copper loss for the primary winding is $I_1^2R_1$ and for secondary winding is $I_2^2R_2$. Where,

I_1 and I_2 are current in primary and secondary winding respectively, R_1 and R_2 are the resistances of primary and secondary winding respectively. It is clear that Cu loss is proportional to square of the current, and current depends on the load. Hence copper loss in transformer varies with the load.

Efficiency Of Transformer:

Just like any other electrical machine, **efficiency of a transformer** can be defined as the output power divided by the input power. That is efficiency = output / input .

Transformers are the most highly efficient electrical devices. Most of the transformers have full load efficiency between 95% to 98.5% . As a transformer being highly efficient, output and input are having nearly same value, and hence it is impractical to measure the efficiency of transformer by using output / input. A better method to find efficiency of a transformer is using, efficiency = (input - losses) / input = 1 - (losses / input).

Condition For Maximum Efficiency

Let,

Copper loss = I12R1

Iron loss = Wi

$$\text{efficiency} = 1 - \frac{\text{losses}}{\text{input}} = 1 - \frac{I_1^2 R_1 + W_i}{V_1 I_1 \cos\Phi_1}$$

$$\eta = 1 - \frac{I_1 R_1}{V_1 \cos\Phi_1} - \frac{W_i}{V_1 I_1 \cos\Phi_1}$$

differentiating above equation with respect to I_1

$$\frac{d\eta}{dI_1} = 0 - \frac{R_1}{V_1 \cos\Phi_1} + \frac{W_i}{V_1 I_1^2 \cos\Phi_1}$$

η will be maximum at $\frac{d\eta}{dI_1} = 0$

Hence efficiency η will be maximum at

$$\frac{R_1}{V_1 \cos\Phi_1} = \frac{W_i}{V_1 I_1^2 \cos\Phi_1}$$

$$\frac{I_1^2 R_1}{V_1 I_1^2 \cos\Phi_1} = \frac{W_i}{V_1 I_1^2 \cos\Phi_1}$$

$$I_1^2 R_1 = W_i$$

Hence, **efficiency of a transformer** will be maximum when copper loss and iron losses are equal.
That is Copper loss = Iron loss.

<u>All Day Efficiency Of Transformer:</u>

As we have seen above, ordinary or commercial efficiency of a transformer can be given as

$$\text{ordinary efficiency} = \frac{\text{output (in watts)}}{\text{input (in watts)}}$$

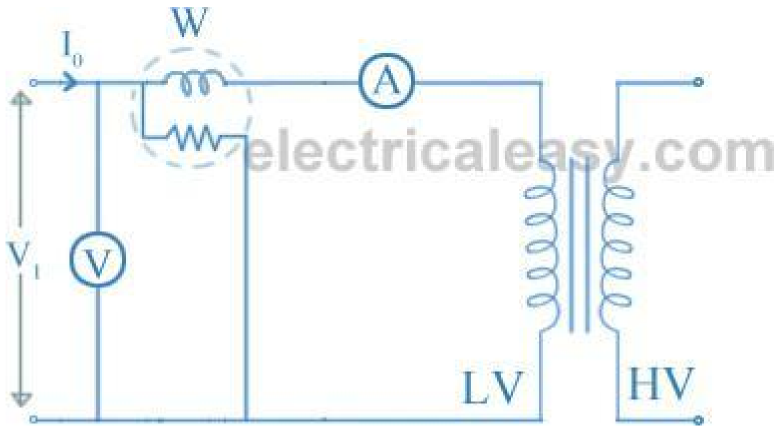
But in some types of transformers, their performance can not be judged by this efficiency. For example, distribution transformers have their primaries energized all the time. But, their secondaries supply little load all no-load most of the time during day (as residential use of electricity is observed mostly during evening till midnight).
That is, when secondaries of transformer are not supplying any load (or supplying only little load), then only core losses of transformer are considerable and copper losses are absent (or very little). Copper losses are considerable only when transformers are loaded. Thus, for such transformers copper losses are relatively less important. The performance of such transformers is compared on the basis of energy consumed in one day.

$$\text{All day efficiency} = \frac{\text{output (in kWh)}}{\text{input (in kWh)}} \quad \text{(for 24 hours)}$$

<u>OC & SC tests:</u>These two transformer tests are performed to find the parameters of equivalent circuit of transformer and losses of the transformer. **Open circuit test and short circuit test on transformer** are very economical and convenient because they are performed without actually loading of the transformer.

<u>Open Circuit Or No Load Test On Transformer:</u>

Open circuit test or no load test on a transformer is performed to determine 'no load loss (core loss)' and 'no load current I_0'. The circuit diagram for open circuit test **is shown in the figure below.**



Usually high voltage (HV) winding is kept open and the low voltage (LV) winding is connected to its normal supply. A wattmeter (W), ammeter (A) and voltmeter (V) are connected to the LV winding as shown in the figure. Now, applied voltage is slowly increased from zero to normal rated value of the LV side with the help of a variac. When the applied voltage reaches to the rated value of the LV winding, readings from all the three instruments are taken. The ammeter reading gives the no load current I_0. As I_0 itself is very small, the voltage drops due to this current can be neglected.
The input power is indicated by the wattmeter (W). And as the other side of transformer is open circuited, there is no output power. Hence, this input power only consists of core losses and copper losses. As described above, no-load current is so small that these copper losses can be neglected. Hence, now the input power is almost equal to the core losses. Thus, the wattmeter reading gives the core losses of the transformer.
Sometimes, a high resistance voltmeter is connected across the HV winding. Though, a voltmeter is connected, HV winding can be treated as open circuit as the current through the voltmeter is negligibly small. This helps in to find voltage transformation ratio (K).

The two components of no load current can be given as,

$I_\mu = I_0 \sin\Phi_0$ and $I_w = I_0 \cos\Phi_0$.
$\cos\Phi_0$ (no load power factor) = $W / (V_1 I_0)$. (W = wattmeter reading)

From this, shunt parameters of equivalent circuit parameters of equivalent circuit of transformer(X_0 and R_0) can be calculated as

$X_0 = V_1/I_\mu$ and $R_0 = V_1/I_w$.

(These values are referring to LV side of the transformer.)
Hence, it is seen that **open circuit test** gives core losses of transformer and

shunt parameters of the equivalent circuit.

Short Circuit Or Impedance Test On Transformer:

The connection diagram for short circuit test **or impedance test on transformer is as shown in the figure below. The LV side of transformer is short circuited and wattmeter (W), voltmere (V) and ammeter (A) are connected on the HV side of the transformer. Voltage is applied to the HV side and increased from the zero until the ammeter reading equals the rated current. All the readings are taken at this rated current.**

The ammeter reading gives primary equivalent of full load current (I_{sc}).
The voltage applied for full load current is very small as compared to rated voltage. Hence, core loss due to small applied voltage can be neglected. Thus, the wattmeter reading can be taken as copper loss in the transformer.
Therefore, $W = I_{sc}^2 R_{eq}$ (where R_{eq} is the equivalent resistance of transformer)
$Z_{eq} = V_{sc}/I_{sc}$.
Therefore, equivalent reactance of transformer can be calculated from the formula $Z_{eq}^2 = R_{eq}^2 + X_{eq}^2$.
These, values are referred to the HV side of the transformer.
Hence, it is seen that the short circuit test gives copper losses of transformer and approximate equivalent resistance and reactance ofthe transformer.

Efficiency and regulation:

Say an electrical power transformer is open circuited, meaning that the load is not connected to the secondary terminals. In this situation, the secondary terminal voltage of the transformer will be its secondary induced emf E_2. Whenever a full load is connected to the secondary terminals of the transformer, rated current I_2 flows through the secondary circuit and voltage drop comes into picture. At this situation, primary winding will also draw equivalent full load current from source. The voltage drop in the secondary is $I_2 Z_2$ where Z_2 is the secondary impedance of transformer.

Now if at this loading condition, any one measures the voltage between secondary terminals, he or she will get voltage V_2 across load terminals which is obviously less than no load secondary voltage E_2 and this is because of I_2Z_2 voltage drop in the transformer.

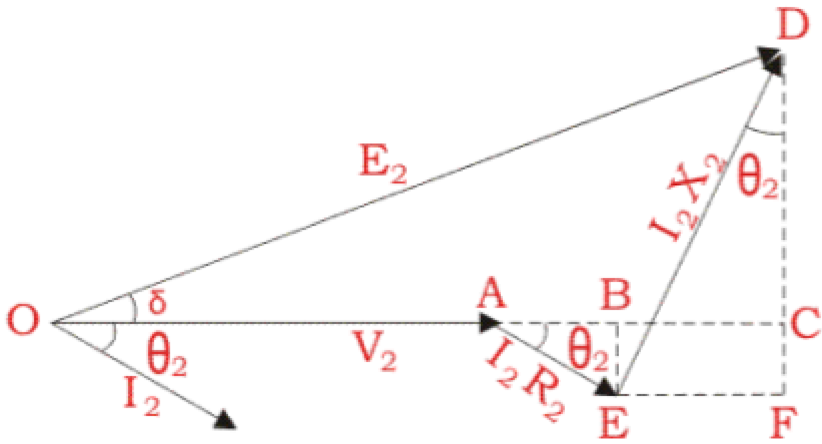
Expression of Voltage Regulation of Transformer:

*The equation for the **voltage regulation of transformer**, represented in percentage, is*

$$Voltage\ regulation(\%) = \frac{E_2 - V_2}{V_2} \times 100\%$$

Voltage Regulation of Transformer for Lagging Power Factor:

Now we will derive the expression of voltage regulation in detail. Say lagging power factor of the load is $\cos\theta_2$, that means angle between secondary current and voltage is θ_2.



Voltage Regulation at Lagging Power Factor

Here, from the above diagram,

$$OC = OA + AB + BC$$

$$Here,\ OA = V_2$$

$$Here,\ AB = AE\cos\theta_2 = I_2R_2\cos\theta_2$$

$$and,\ BC = DE\sin\theta_2 = I_2X_2\sin\theta_2$$

Angle between OC and OD may be very small, so it can be neglected and OD is considered nearly equal to OC i.e.

$$E_2 = OC = OA + AB + BC$$

$$E_2 = OC = V_2 + I_2R_2\cos\theta_2 + I_2X_2\sin\theta_2$$

Voltage regulation of transformer at lagging power factor,

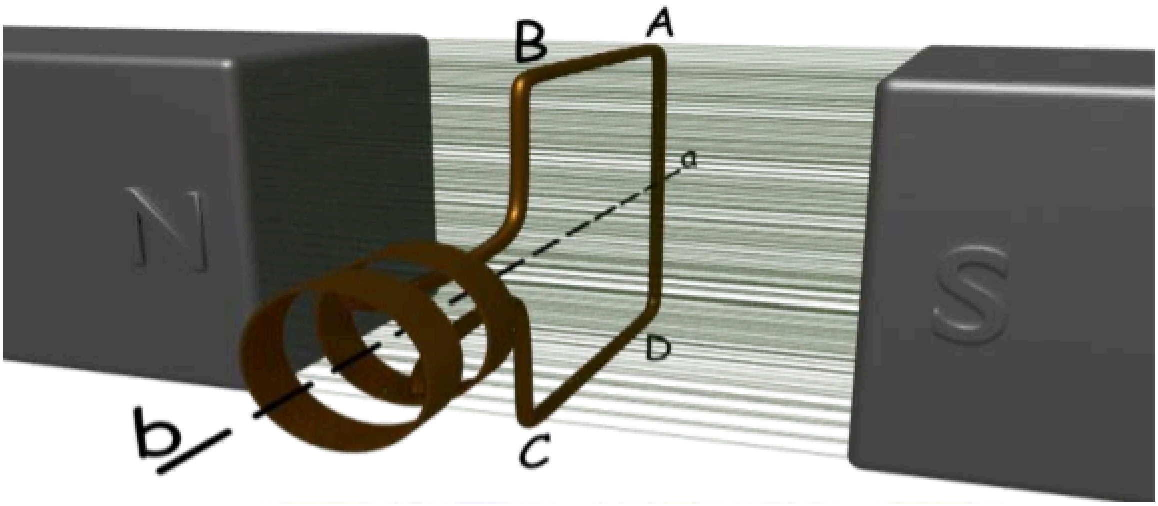
$$Voltage\ regulation\ (\%) = \frac{E_2 - V_2}{V_2} \times 100(\%)$$

$$= \frac{I_2R_2\cos\theta_2 + I_2X_2\sin\theta_2}{V_2} \times 100(\%)$$

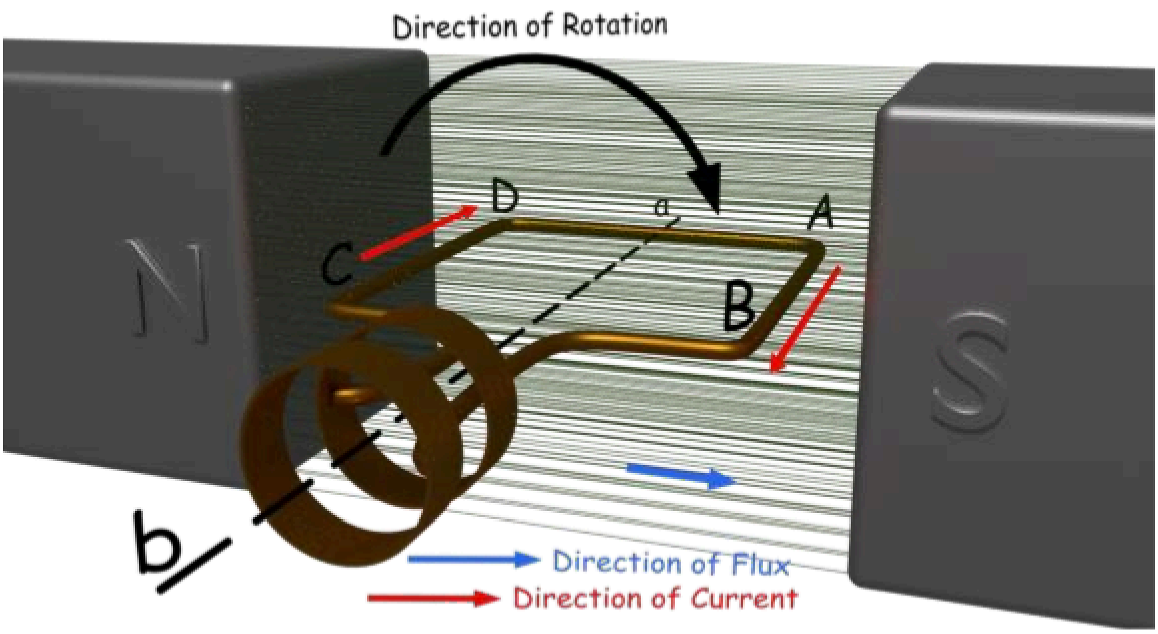
UNIT - IV
AC ROTATING MACHINES

Principle of operation and construction of alternators:

The **working principle of an alternator** is very simple. It is just like the basic principle of DC generator. It also depends upon Faraday's law of electromagnetic induction which says the current is induced in the conductor inside a magnetic field when there is a relative motion between that conductor and the magnetic field.



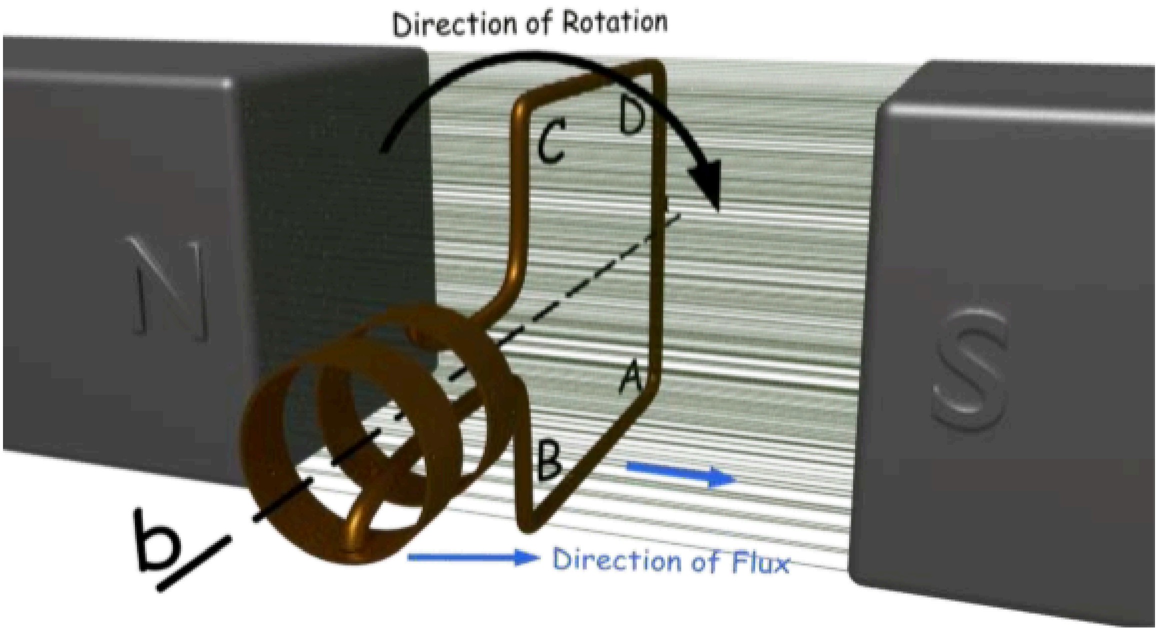
For understanding **working of alternator** let us think about a single rectangular turn placed in between two opposite magnetic poles as shown above.



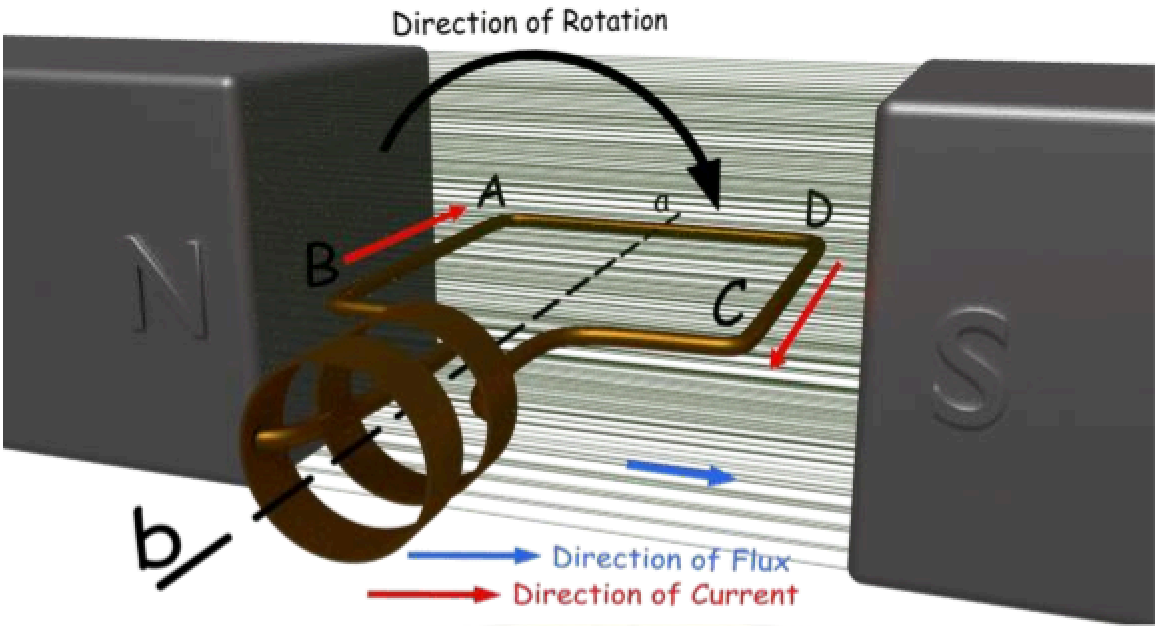
Say this single turn loop ABCD can rotate against axis a-b. Suppose this loop starts rotating clockwise. After 90^o rotation the side AB or conductor AB of the loop comes in front of S-pole and conductor CD comes in front of N-pole. At this position the tangential motion of the conductor AB is just perpendicular to the magnetic flux lines from N to S pole. Hence, the rate of flux cutting by the conductor AB is maximum here and for that flux cutting there will be an induced current in the conductor AB and the direction of the induced current can be determined by Fleming's right-hand rule. As per this rule the direction of this current will be from A to B. At the same time conductor CD comes under N pole and here also if we apply Fleming right-hand rule we will get the direction of induced current and it will be from C to D.

Now after clockwise rotation of another 90^o the turn ABCD comes at the vertical position as shown below. At this position tangential motion of conductor AB and CD is just parallel to the magnetic flux lines, hence there will be no flux cutting that is no current in the conductor.

While the turn ABCD comes from a horizontal position to a vertical position, the angle between flux lines and direction of motion of conductor, reduces from 90^o to 0^o and consequently the induced current in the turn is reduced to zero from its maximum value.



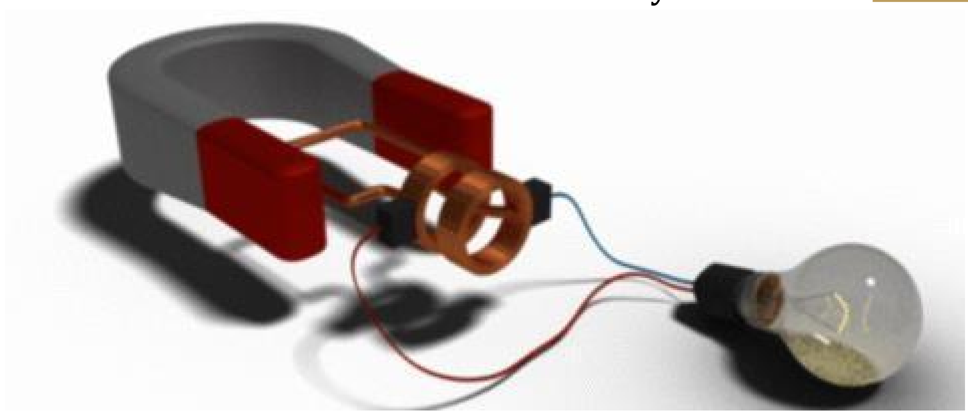
After another clockwise rotation of 90^o the turn again comes to horizontal position, and here conductor AB comes under N-pole and CD comes under S-pole, and here if we again apply Fleming right-hand rule, we will see that induced current in conductor AB, is from point B to A and induced current in the conductor CD is from D to C.



As at this position the turn comes at a horizontal position from its vertical position, the current in the conductors comes to its maximum value from zero. That means current is circulating in the close turn from point B to A, from A to D, from D to C and from C to B, provided the loop is closed although it is not shown here. That means the current is in reverse of that of the previous horizontal position when the current was circulating as A → B → C → D → A. While the turn further proceeds to its vertical position the current is again reduced to zero. So if the turn continues to rotate the current in turn continually alternate its direction. During every full revolution of the turn, the current in turn gradually reaches to its maximum value then reduces to zero and then again it comes to its maximum value but in opposite direction and again it comes to zero. In this way, the current completes one full sine wave cycle during each 360^o revolution of the turn. So, we have seen how alternating current is produced in a turn is rotated inside a magnetic field. From this, we will now come to the actual

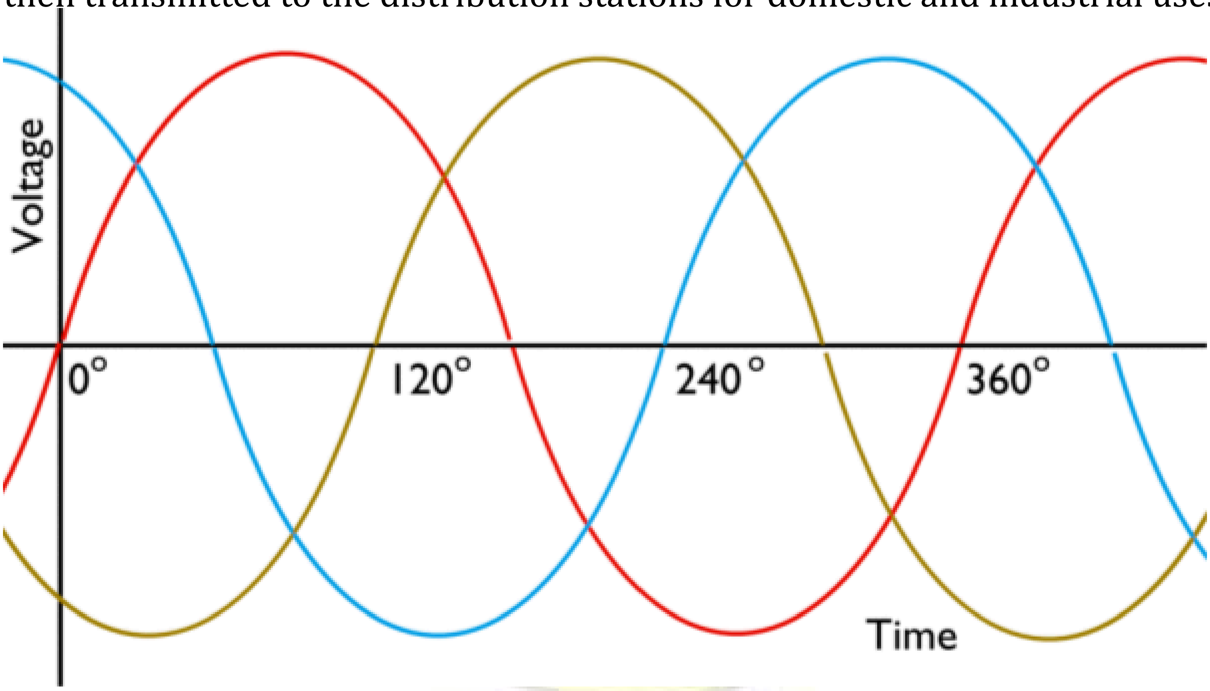
working principle of an alternator:

Now we place one stationary brush on each slip ring. If we connect two terminals of an external load with these two brushes, we will get an alternating current in the load. This is our elementary model of an alternator.



Having understood the very basic principle of an alternator, let us now have an insight into its basic operational principle of a practical alternator. During the

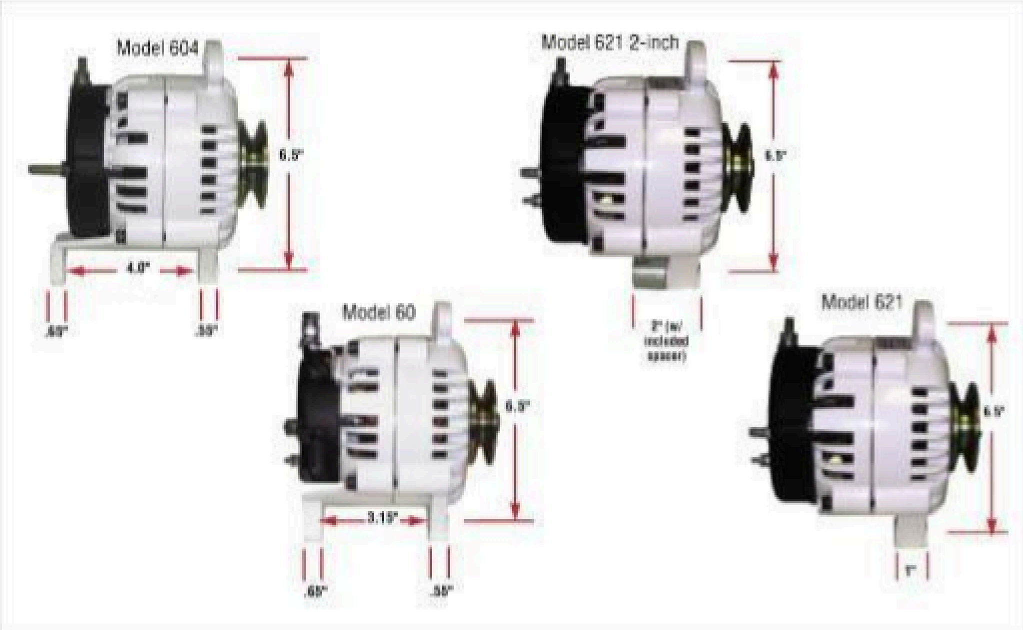
discussion of the basic working principle of an alternator, we have considered that the magnetic field is stationary and conductors (armature) is rotating. But generally in practical construction of alternator, armature conductors are stationary and field magnets rotate between them. The rotor of an alternator or a synchronous generator is mechanically coupled to the shaft or the turbine blades, which is made to rotate at synchronous speed N_s under some mechanical force results in magnetic flux cutting of the stationary armature conductors housed on the stator.
As a direct consequence of this flux cutting an induced emf and current starts to flow through the armature conductors which first flow in one direction for the first half cycle and then in the other direction for the second half cycle for each winding with a definite time lag of 120^o due to the space displaced arrangement of 120^o between them as shown in the figure below. This particular phenomenon results in three-phase power flow out of the alternator which is then transmitted to the distribution stations for domestic and industrial uses.



Types of alternators:

Alternators or **synchronous generators** can be classified in many ways depending upon their applications and designs.
The **five different types of alternators** include:

- **Automotive alternators** – used in modern automobiles.
- **Diesel-electric locomotive alternators** – used in diesel electric multiple units.
- **Marine alternators** – used in marine applications.
- **Brushless alternators** – used in electrical power generation plants as the main source of power.
- **Radio alternators** – used for low band radio frequency transmission.



We can categorize these AC generators (alternators) in many ways, but the two main categories depending on their design are:

1. Salient Pole Type
2. Smooth Cylindrical Type

Salient Pole Type:

We use it 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 get characterized by their large diameters and short axial lengths. These generators look like a big wheel. These are mainly used for low-speed turbine such as in hydel power plant.

Smooth Cylindrical Type:

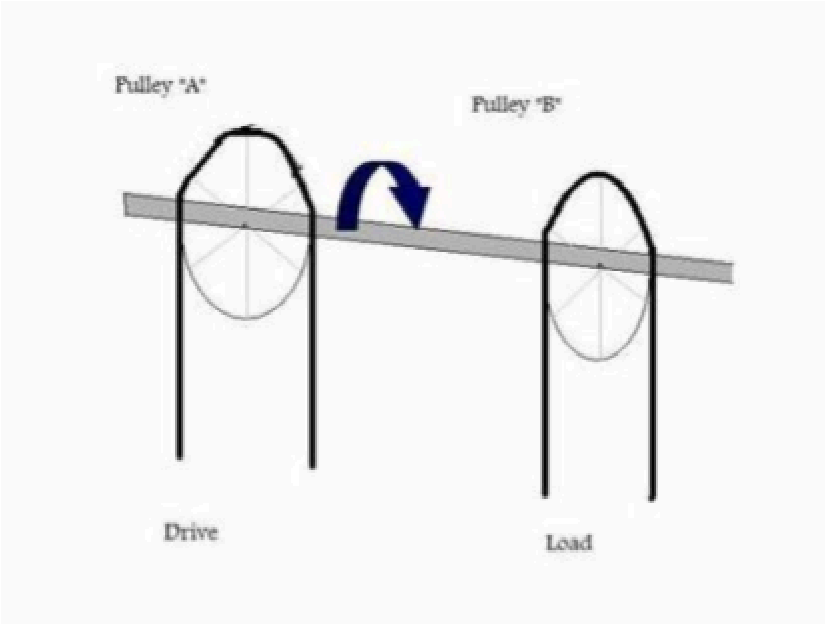
We use it for a steam turbine driven alternator. The rotor of this generator rotates at very high speed. The rotor consists of a smooth solid forged steel cylinder having certain numbers of slots milled out at intervals along the outer periphery for accommodating field coils.

These rotors are designed mostly for 2 poles or 4 poles turbo generator running at 36000 rpm or 1800 rpm respectively.

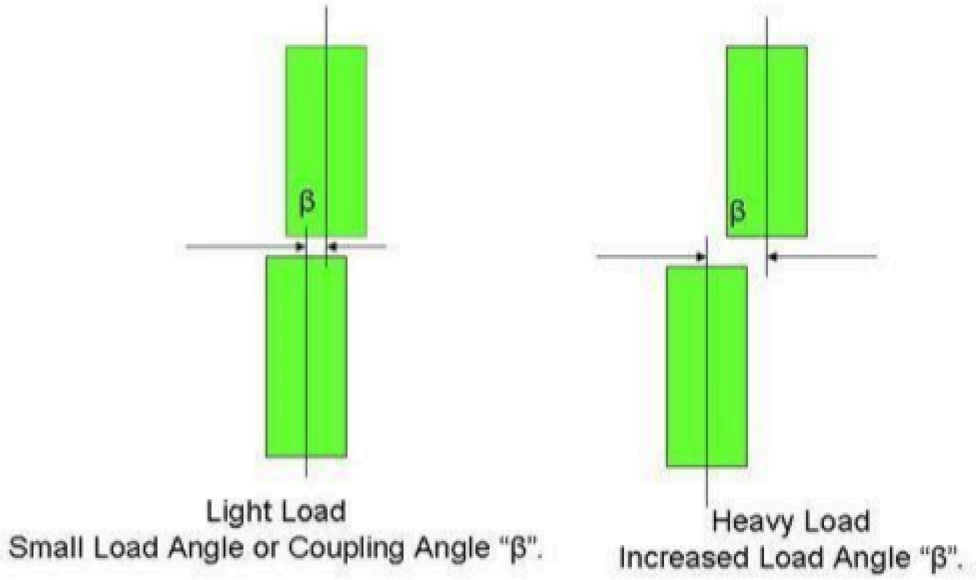
Principle of operation of synchronous motor:

.When the motor is supplied with a.c. power supply, the stator poles get energised. This in turn attracts (opposite) the rotor poles, thus both the stator and rotor poles get magnetically interlocked. It is this interlock which makes the rotor to rotate at the same synchronous speed with the stator poles. The synchronous speed of rotation is given by the expression Ns=120f/P.

When the load on the motor is increased gradually, the rotor even though runs at same speed, tends to progressively fall back in phase by some angle, “β", called the Load Angle or the Coupling Angle. This Load angle is dependent on the amount of load that the motor is designed to handle. In other words, we can interpret as the torque developed by the motor depends on the load angle, “β".



The electrical working of a Synchronous Motor can be compared to the transmission of power by a mechanical shaft. In the figure are shown two pulleys, “A" & “B". Pulley “A" and the pulley “B" are assumed to be keyed on the same shaft. Pulley “A" transfers the power from the drive through the shaft, in turn making the pulley “B" to rotate, thus transferring power to the load.



<u>The two pulleys which are keyed to the same shaft can be compared to the interlock between the stator & rotor poles.</u>

If the load increases, the pulley “B" transfers the increase in load to the shaft, which is exhibited by the twisting of the shaft.

Thus the twist of the shaft can be compared to the rotor falling back in phase with the stator.

The twist angle can be compared to the load angle “β". Also when the load increases, the twisting force and the twist angle increases, thus the load angle “β" also increases.

If the load on the pulley “B" is increased to such an extent that it makes the shaft to twist and break, then the transmission of power through the shaft stops as the shaft is broken. This can be compared with the rotor going out of synchronism with the stator poles.

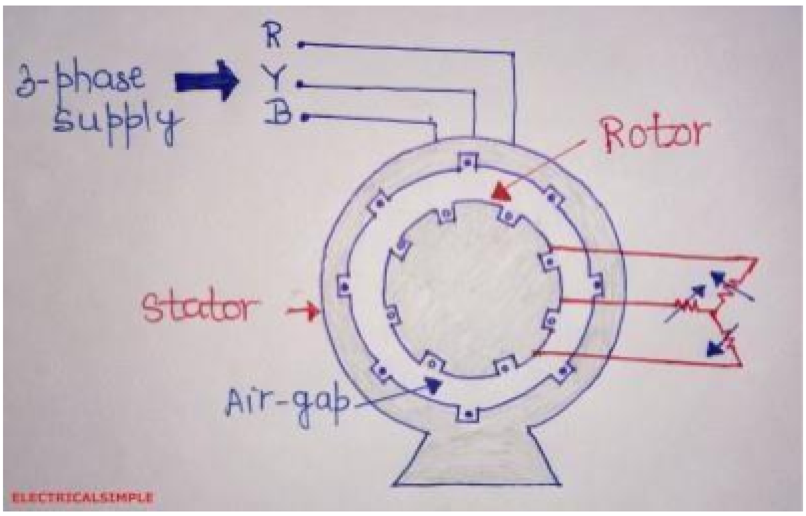
Thus Synchronous motors can run either at synchronous speed or they stop running.

Starting procedure:

All the Synchronous Motors are equipped with “Squirrel Cage winding", consisting of Cu (copper) bars, short-circuited at both ends. These windings also serve the purpose of self-starting of the Synchronous motor. During starting, it readily starts and acts as induction motors. For starting a Synchronous motor, the line voltage is applied to the stator terminals with the field terminals (rotor) left unexcited. It starts as an induction motor, and when it reaches a speed of about 95% of its synchronous speed, a weak d.c excitation is given to the rotor, thus making the rotor to align in synchronism with the stator.(at this moment the stator & rotor poles get interlocked with each other & hence pull the motor into synchronism.

Principle of operation of 3-Phase induction motor:

Consider the simplified view of a 3 phase induction motor shown below.

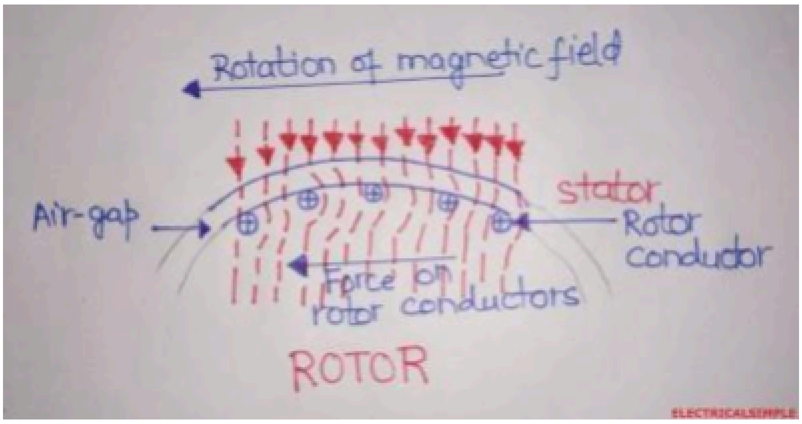


The stator hosts a three phase winding distributed symmetrically on its inner periphery. This stator winding is energised from a three phase supply.

The rotor also hosts a 3 phase winding on its periphery. But, the rotor winding is not energised from any source and is short- circuited on itself.

Three phase Induction motor working principle:

(1) When the 3 phase stator winding is energised from a 3 phase supply, a rotating magnetic field is produced which rotates around the stator at synchronous speed.



- The rotating magnetic field cuts the rotor conductors, which as yet, are stationary. Due to this flux cutting, emfs are induced in the rotor conductors. As rotor circuit is short circuited, therefore, currents start flowing in it.

- Now, as per Lenz's law , "the direction of induced current will be such that it opposes the very cause that produced it " .

(4) Here, the cause of emf induction is the relative motion between the rotating field and the stationary rotor conductors. Hence, to reduce this relative motion, the rotor starts rotating in the same direction as that of the stator field and tries to catch it but, can never catch it due to friction and windage and therefore emf induction continues and motor keeps rotating.

Thus, ***principle of 3 phase induction motor*** also explains why rotor rotates in same direction as the rotating field and why *induction motor is self starting*.

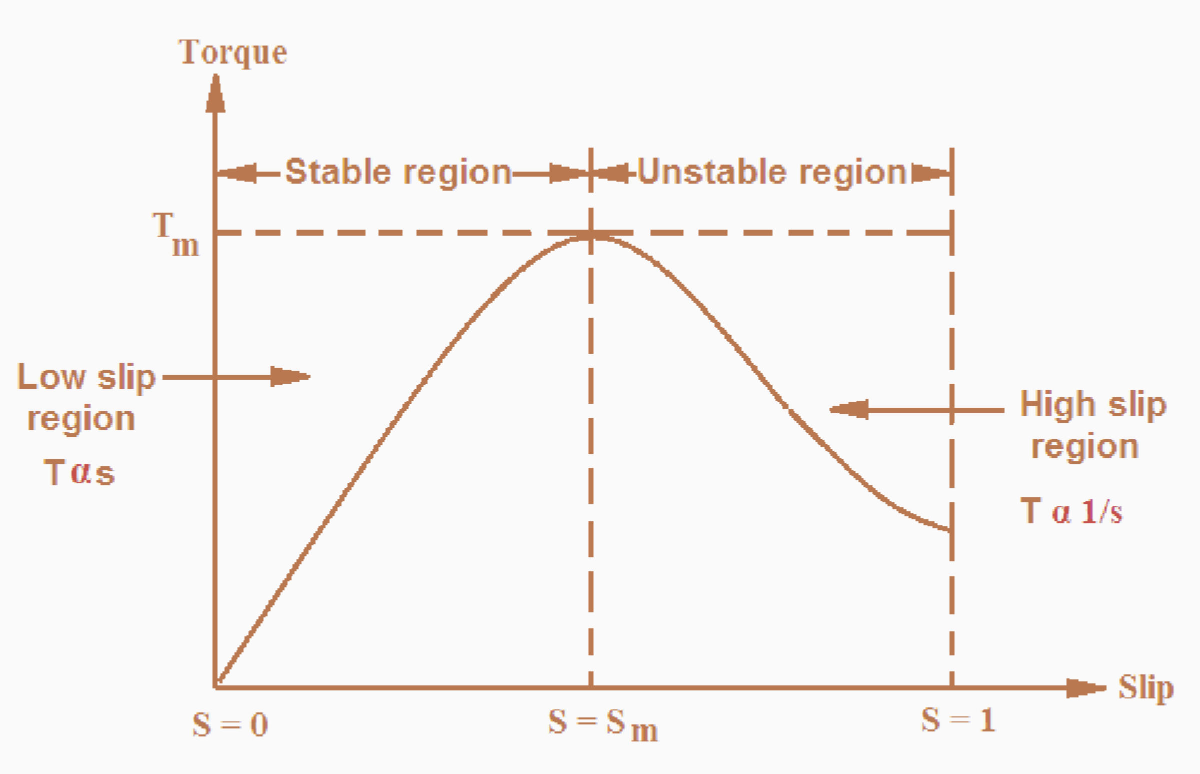
When rotor winding is short-circuited with no resistance in series, it is called a ***squirrel cage induction motor*** and when rotor winding is shorted through a resistance in series, it is called slip ring induction motor

Slip-torque characteristics:

Thus, **at low values of slip, torque is approximately proportional to slip *s* and the torque slip characteristics of induction motor is a straight line as shown in the figure.**

The region (from $s = 0$ to $s = s_m$) is called the stable region of operation and operating point of the motor should be in this region.

In the stable region, the value of slip is small. Hence this region is also called as the low slip region.



Torque Slip characteristics of Induction motor

- As the slip increases torque increases and attains its maximum value when $s = R_2/X_2$. This maximum value of torque is also known as break down or pull out torque.
- When a further increase in slip occurs due to increase in load beyond the point maximum torque

i.e. when slip is high, the value of term $(sX_2)^2$ is very large in comparison to R_2^2.

Therefore, R_2^2 is neglected as compare to $(sX_2)^2$ and torque is given by the expression:

$T = ksE_2^2R_2 / (sX_2)^2$

or $T = kE_2^2R_2 / (sX_2^2)$

In the above expression, all quantities are constant except s.

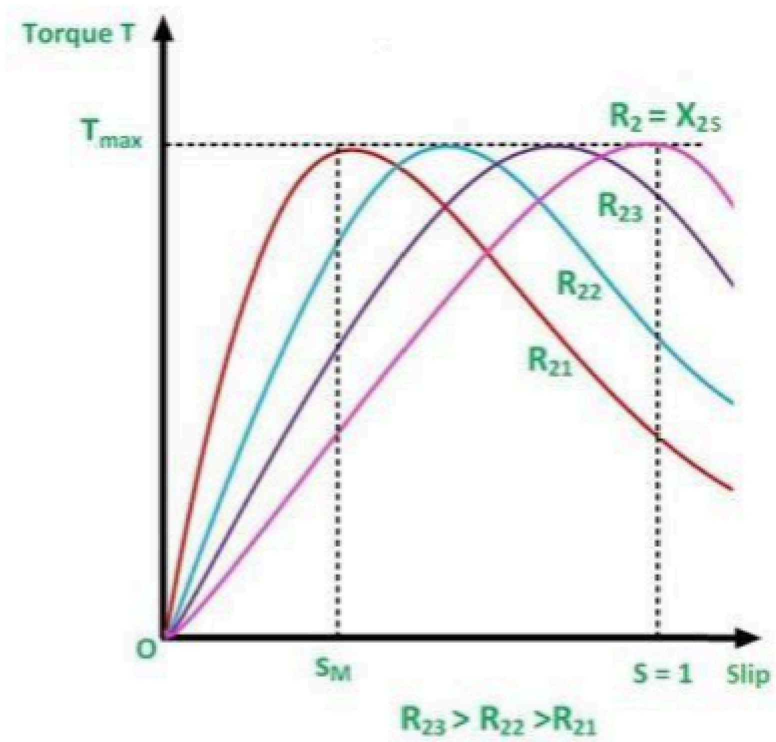
Therefore, T α 1/s

Thus at higher values of slip (i.e. the slip beyond that corresponding to maximum torque) torque is approximately inversely proportional to slip, s and the torque slip characteristics of induction motor is rectangular hyperbola as shown in the figure.

The region (extending from s = s_m to s = 1) is called unstable region. In this region with the increase in load, slip increases but torque decreases.

The result is that the motor could not pick up the load and slows down and eventually stops. In the unstable region, the value of slip is large so this region is also called as the high-slip region.

Effect of Rotor Resistance on Torque Slip Characteristics:



To see the effect of rotor resistance on *torque slip characteristics of induction motor*, consider a slip ring induction motorin which additional resistance in the rotor circuit can be introduced through slip rings. The rotor reactance at stand still X_2remains constant.

The maximum value of the torque developed by an induction motor is independent of rotor resistance R_2.

Therefore, the effect of change in rotor resistance is the change in slip at which this maximum torque takes place; greater the rotor resistance, greater the value of slip at which the maximum torque occurs since
$s = R_2/X_2$

The torque *slip characteristics of induction motor* (three phase) are shown in the figure for various values or rotor resistance R_2 keeping rotor reactance X_2 constant. The maximum value of the torque can be obtained even at the start by adding that much resistance in the rotor circuit so that R_2 becomes equal to X_2.

When $R_2 = X_2$; $s = R_2/X_2 = 1$ i.e. at start torque will be maximum.

Efficiency:

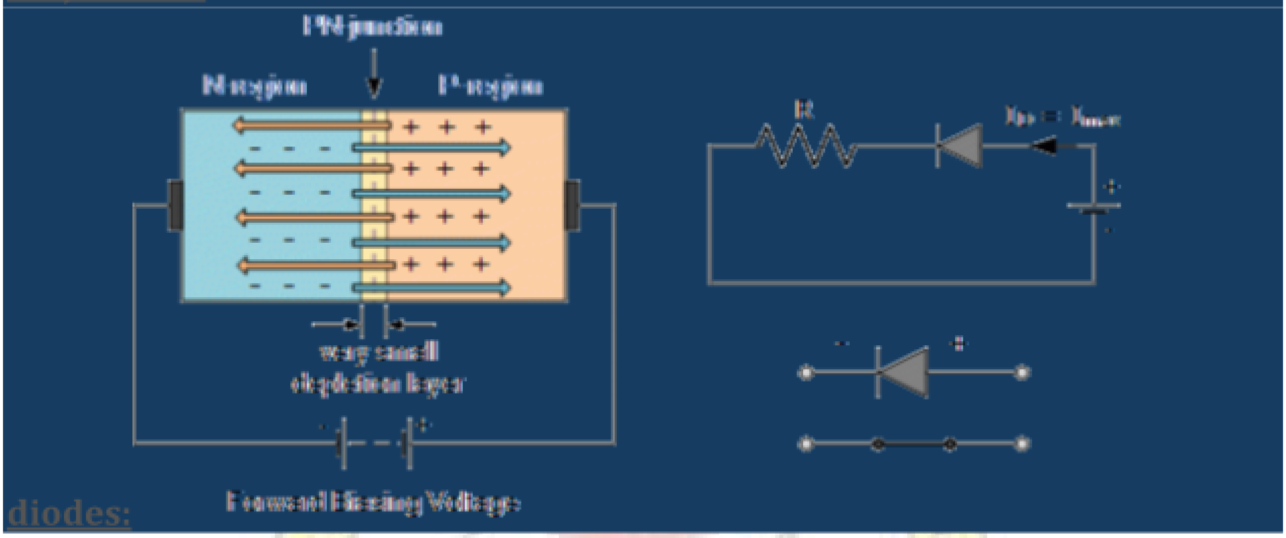
It may sound paradoxical, but there are certain situations in the production process where braking gains time. Machine shutdown processes cost time and money. Setting the system to a slower speed actually can increase efficiency. Functionally safe rotary encoders combined with drive converters reliably achieve this objective.

The printing rollers on **printing machines** must be cleaned at regular intervals. The **cleaning process** can proceed more efficiently if the system does not have to be shut down but instead can continue operating at a **slower speed**. The system operator can prevent downtime and improve efficiency as a result. Functionally safe **rotary encoders** from Pepperl+Fuchs combined with the safety module for Lenze **drive converters** achieve this objective.

UNIT IV RECTIFIERS & LINEAR ICS:

PN Junction Diode

PN junction diodes:



A PN-junction diode is formed when a p-type semiconductor is fused to an n-type semiconductor creating a potential barrier voltage across the diode junction

The effect described in the previous tutorial is achieved without any external voltage being applied to the actual PN junction resulting in the junction being in a state of equilibrium.

However, if we were to make electrical connections at the ends of both the N-type and the P-type materials and then connect them to a battery source, an additional energy source now exists to overcome the potential barrier.

The effect of adding this additional energy source results in the free electrons being able to cross the depletion region from one side to the other. The behaviour of the PN junction with regards to the potential barrier's width produces an asymmetrical conducting two terminal device, better known as the **PN Junction Diode**.

A *PN Junction Diode* is one of the simplest semiconductor devices around, and which has the characteristic of passing current in only one direction only. However, unlike a resistor, a diode does not behave linearly with respect to the applied voltage as the diode has an exponential current-voltage (I-V)

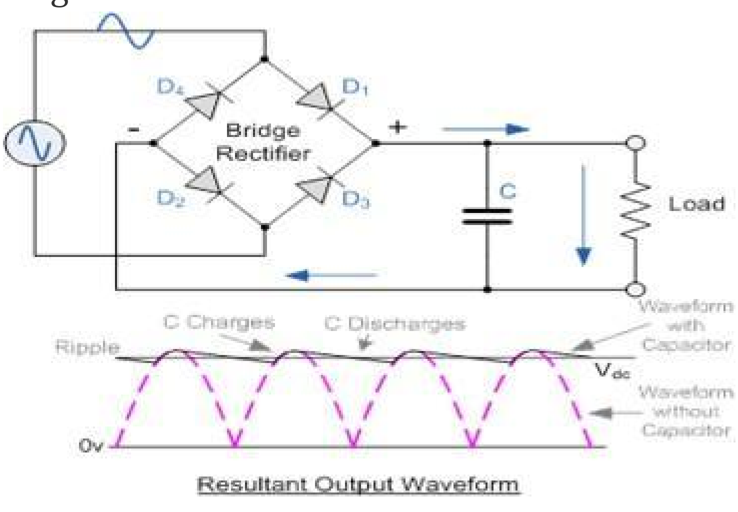
relationship and therefore we can not described its operation by simply using an equation such as Ohm’s law.
If a suitable positive voltage (forward bias) is applied between the two ends of the PN junction, it can supply free electrons and holes with the extra energy

they require to cross the junction as the width of the depletion layer around the PN junction is decreased.
By applying a negative voltage (reverse bias) results in the free charges being pulled away from the junction resulting in the depletion layer width being increased. This has the effect of increasing or decreasing the effective resistance of the junction itself allowing or blocking current flow through the diode.
Then the depletion layer widens with an increase in the application of a reverse voltage and narrows with an increase in the application of a forward voltage. This is due to the differences in the electrical properties on the two sides of the PN junction resulting in physical changes taking place. One of the results produces rectification as seen in the PN junction diodes static I-V (current-voltage) characteristics.

Diode applications(Half wave and bridge rectifiers):

Diode bridge rectifier:

Rectifier circuits are classified into two major groups i.e., single phase and three phases. In both cases they are again classified into three main categories those are uncontrolled, half controlled and fully controlled. If we use diode to convert this voltage we can call that as uncontrolled, instead if we use power electronic components like SCRS we can call as controlled rectifiers. We can control half wave or full wave according to the application dependency.
The main difference between conventional rectifier and bridge rectifier is that it produces almost double the output voltage as a full wave center-tapped transformer rectifier using the same secondary voltage. The advantage of using this circuit is that no center-tapped transformer is required. In center tapped rectifier each diode uses only one-half of the transformer secondary voltage, so the DC output is comparatively small, also it is difficult to locate the center-tap on secondary winding of the transformer and the diodes used must have high Peak-inverse voltage.



Bridge Rectifier Circuit and the output waveform

During the positive half cycle of the supply, diodes D1 and D2 conduct in series while diodes D3 and D4 are reverse biased and the current flows through the load During the negative half cycle of the supply, diodes D3 and D4 conduct in series, but diodes D1 and D2switch “OFF” as they are now reverse biased. The current flowing through the load is the same direction as before.

The smoothing capacitor converts the full-wave rippled output of the rectifier into a smooth DC output voltage. Generally for DC power supply circuits the smoothing capacitor is an Aluminum Electrolytic type that has a capacitance value of 100uF or more with repeated DC voltage pulses from the rectifier charging up the capacitor to peak voltage. However, there are two important parameters to consider when choosing a suitable smoothing capacitor and these are its *Working Voltage,* which must be higher than the no-load output value of the rectifier and its *Capacitance Value,* which determines the amount of ripple that will appear superimposed on top of the DC voltage.

5 Advantages of bridge rectifier:

- The rectification efficiency of full-wave rectifier is double of that of a half-wave rectifier.
- Higher output voltage, higher output power and higher Transformer Utilization Factor in case of full-wave rectifier.
- The ripple voltage is low and of higher frequency in case of full-wave rectifier so simple filtering circuit is required
- No center tap is required in the transformer secondary so in case of a bridge rectifier the transformer required is simpler. If stepping up or stepping down of voltage is not required, transformer can be eliminated even.
- For a given power output, power transformer of smaller size can be used in case of the bridge rectifier because current in both primary and secondary windings of the supply transformer flow for the entire ac cycle

2 Disadvantages of Bridge Rectifier:

- It requires four diodes.
- The use of two extra diodes cause an additional voltage drop thereby reducing the output voltage.

Characteristics of operation amplifiers (OP-AMP):

Operational amplifiers are the basic building blocks of Analogue electronic circuits. They are linear devices with all properties of a DC amplifier. We can use external resistors or capacitors to the Op Amp is many different ways to make them different forms of amplifies such as Inverting amplifier, Non inverting amplifier, Voltage follower, Comparator, Differential amplifier, Summing amplifier, Integrator etc. OPAMPs may be single, dual, quad etc. OPAMPs like CA3130, CA3140, TL0 71, LM311 etc have excellent performance with very low input current and voltage. The ideal Op Amp has three important terminals in addition to other terminals. The input terminals are Inverting input and Non inverting input. The third terminal is the output which can sink and source current and voltage. The output signal is the amplifiers gain multiplied by the value of the input signal.

5 Ideal characters of an Op Amp:

1. Open Loop gain:

Open loop gain is the gain of the Op Amp without a positive or negative feedback. An ideal OP Amp should have an infinite open loop gain but typically it range between 20,000 and 2, 00000.

2. Input impedance:

It is the ratio of the input voltage to input current. It should be infinite without any leakage of current from the supply to the inputs. But there will be a few Pico ampere current leakages in most Op Amps.

3. Output impedance:

The ideal Op Amp should have zero output impedance without any internal resistance. So that it can supply full current to the load connected to the output.

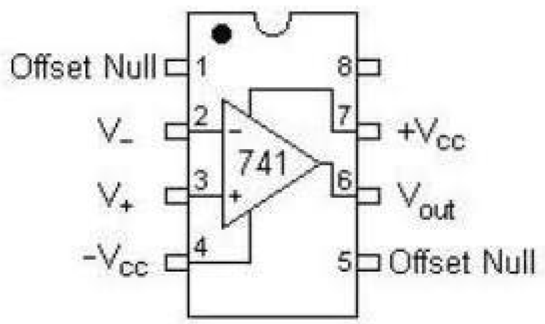
4.Band width:

The ideal Op Amp should have an infinite frequency response so that it can amplify any frequency from DC signals to the highest AC frequencies. But most Op Amps have limited bandwidth.

X5. Offset:

The output of the Op Amp should be zero when the voltage difference between the inputs is zero. But in most Op Amps, the output will not be zero when off but there will be a minute voltage from it.

OPAMP Pin Configuration:



In a typical Op Amp there will be 8 pins. These are

Pin1 – Offset Null

Pin2 – Inverting input INV

Pin3 – Non inverting input Non-INV

Pin4 – Ground- Negative supply

Pin5 – Offset Null

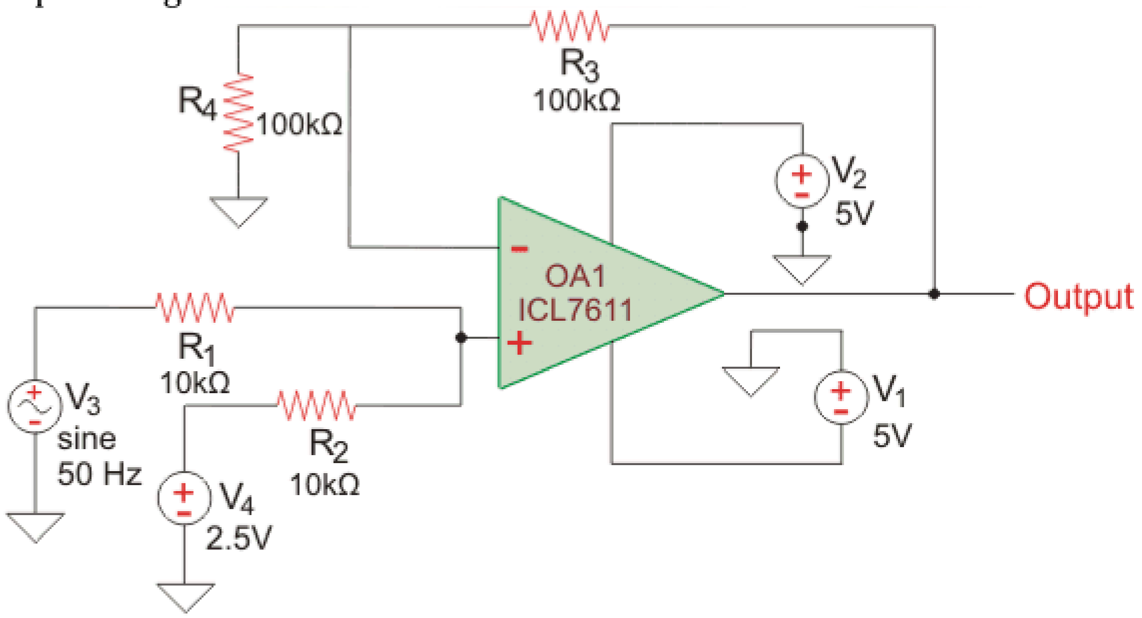
Pin6 – Output

Pin7 – Positive supply

Pin8 – Strobe

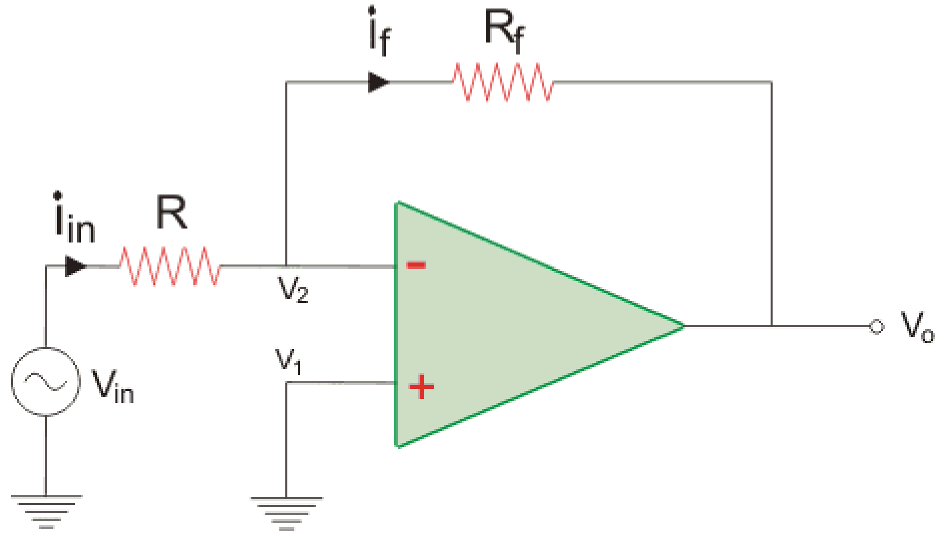
application of OP-AMPs (inverting, non-inverting, integrator and differentiator):

Op-Amp is used for direct coupling procedure and so DC voltage level at the emitter terminal increases from phase to phase. This rapidly increasing DC level is likely to shift the operating point of the upcoming stages. Thus to move down the increasing voltage swing, this phase shifter is applied.The phase shifter performs by adding a DC voltage level to the output of fall stage to pass the output to a ground level.



Op Amp as Scale Changer:

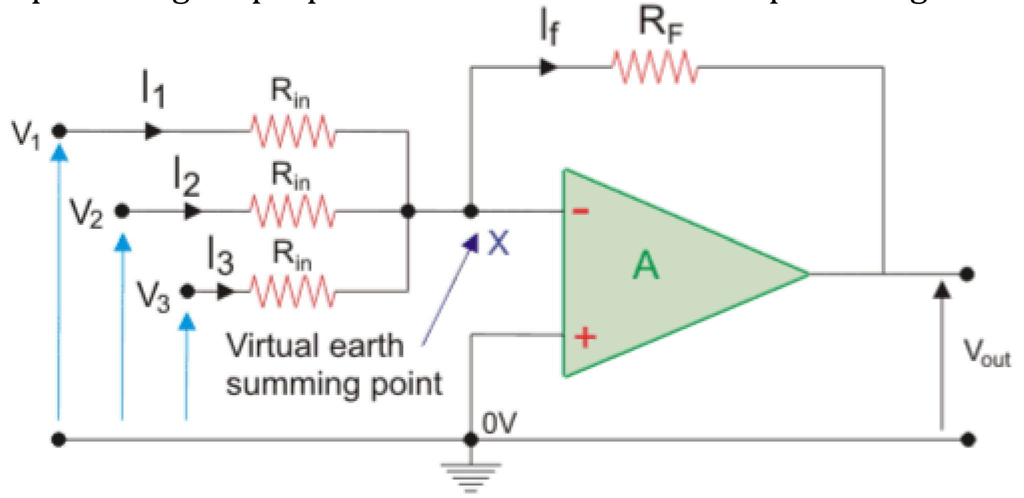
Op-Amp functions as a scale changer through small signals with constant-gain in both inverting and non-inverting amplifiers.



Non-inverting terminal is grounded whereas R_1 links the input signal v_1 to the inverting input. A feedback resistor R_f is then connected from output to the inverting input. The closed loop gain of the inverting amplifier works based on the ratio of the two external resistors R_1 and R_f and Op-Amp acts as a negative scaler when it multiplies the input by a negative constant factor.
While in need for an output that is equal to input for getting multiplied by a positive constant the positive scaler circuit is used by applying negative feedback.

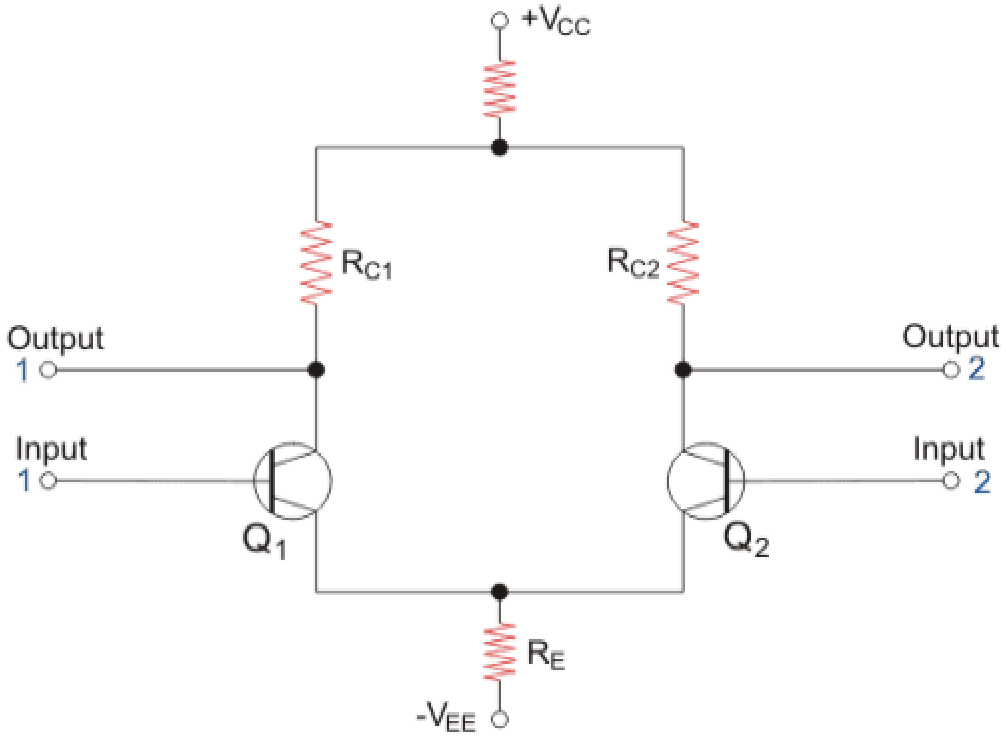
Op Amp Applications as Adder or Summing Amplifier:

Op-amp can be used to sum the input voltage of two or more sources into a single output voltage. Below is a circuit diagram depicting the application of an op-amp as an adder or summing amplifier. The input voltages are applied to the inverting terminal of the op-amp. The inverting terminal is grounded. The output voltage is proportional to the sum of the input voltages.



Op Amp Applications as a Differential Amplifier:

Differential Amplifier is a useful blend of both the inverting amplifier and non-inverting amplifier. It is mostly used to amplify the diversity amid two input signals.

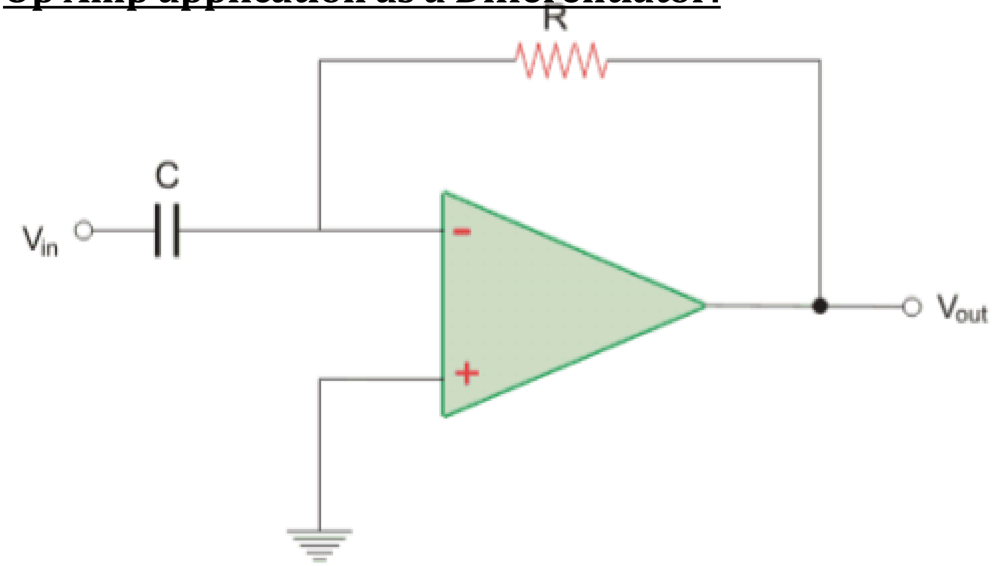


Major applications of Differential Amplifiers are

- Signal Amplification
- Input stage emitter coupled logic
- Switch
- Controlling of Motors and Servo Motors

Example: it is useful while eliminating the noise in ambience as through differential amplifier, you can eliminate the connected protected cable or twisted pair cable mostly used to eradicate the transitory noise.

Op Amp application as a Differentiator:



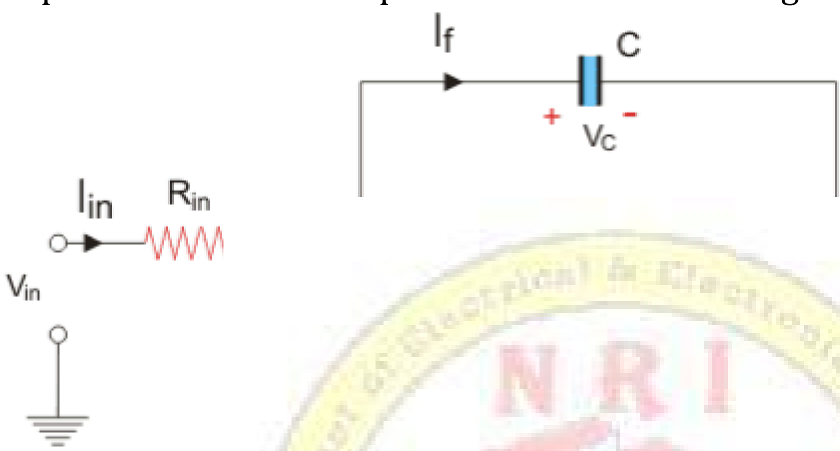
Op-amp can be used as a differentiator where the output is the first derivative of the input signal. The following equation gives the relation between the input signal and the output signal.

$$V_{OUT} = -R_F C \frac{dV_{IN}}{dt}$$

As you can see the output voltage is a first derivative of the input voltage. We are not going into how the equation is derived but only learning about the use of an op amp as a differentiator.

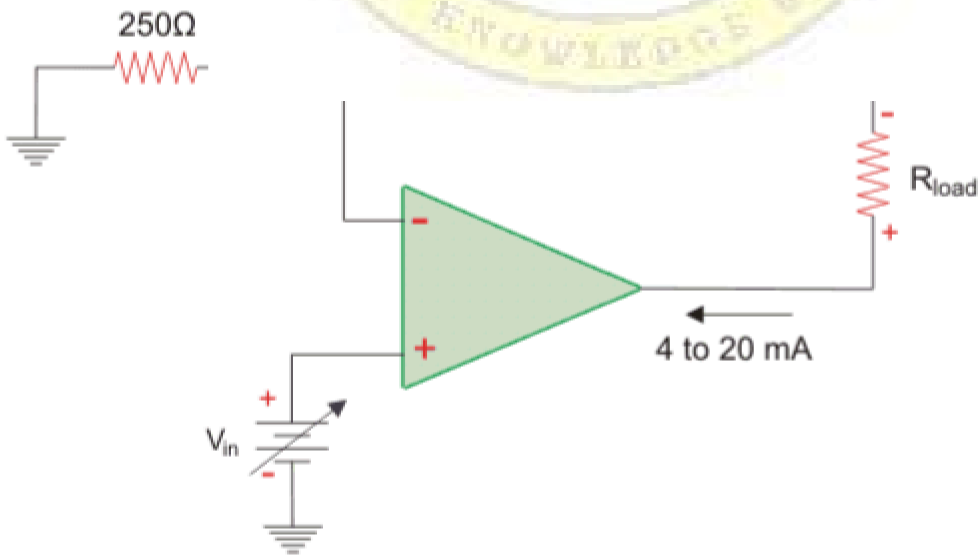
Op Amp Applications as Integrator:

Op-amp is used as an integrator also. The integrator op-amp produces an output that is proportional to the amplitude of the input signal as well as the duration of the input signal. Instead of a resistor in the feedback loop, we have a capacitor. It is able to perform the mathematical operation of integration as the output varies with the input and duration of the signal.

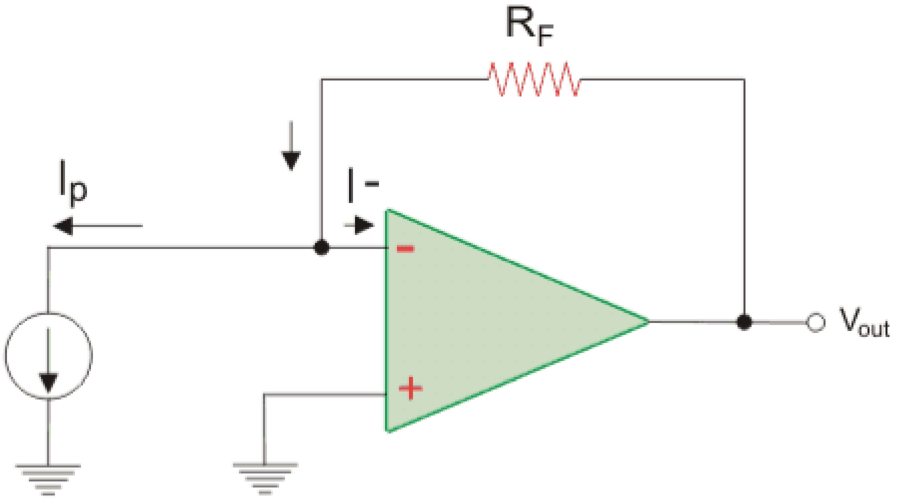


Op Amp Applications as Voltage to Current Converter:

An op-amp with a negative feedback is generally used for voltage to current conversions. Below you can see the circuit diagram. We are not going into the details here, just we will discuss the circuit given below. The voltage is applied to the non-inverting terminal and the output is feedback to the inverting terminal. It is also grounded using a resistor.



Op Amp Applications as Current to Voltage Converter:



Op-amp can be used as a current to voltage converter using a very simple circuit as shown above. All we need is a feedback resistance connected to the output of the op-amp. The current source is fed into the inverting terminal and the non-inverting terminal is grounded. Here the output voltage is proportional to the input current. As an ideal op-amp has infinite resistance, the current cannot flow through the op-amp. The current flows through the feedback resistance and the voltage across it depends on the current source.

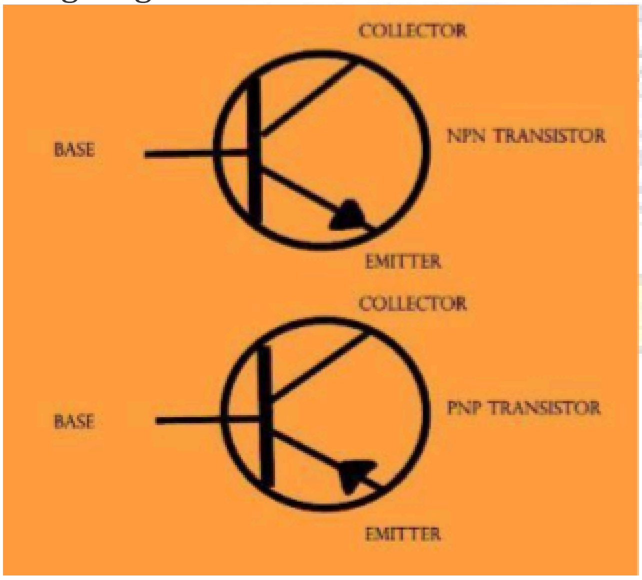
$$V_{out} = -R_f I_{in}$$

UNIT V
TRANSISTORS

PNP and NPN junction transistor:

The transistors PNP and NPN are BJTs and it is a basic electrical component, used in various electrical and electronic circuits to build the projects. The operation of the PNP and NPN transistors mainly utilizes holes and electrons. These transistors can be used as amplifiers, switches and oscillators. In PNP transistor, the majority charge carriers are holes, where in NPN the majority charge carriers are electrons. Except, FETs have only one sort of charge carrier. The major difference between NPN and PNP transistor is, an NPN transistor gets the power when the flow of current runs through the base terminal of the transistor.

In NPN transistor, the flow of current runs from the collector terminal to the emitter terminal. A PNP transistor switches ON, when there is no flow of current at the base terminal of the transistor. In PNP transistor, the flow of current runs from the emitter terminal to the collector terminal. As a result, a PNP transistor switch ON by a low signal, where NPN transistor switches ON by a high signal.

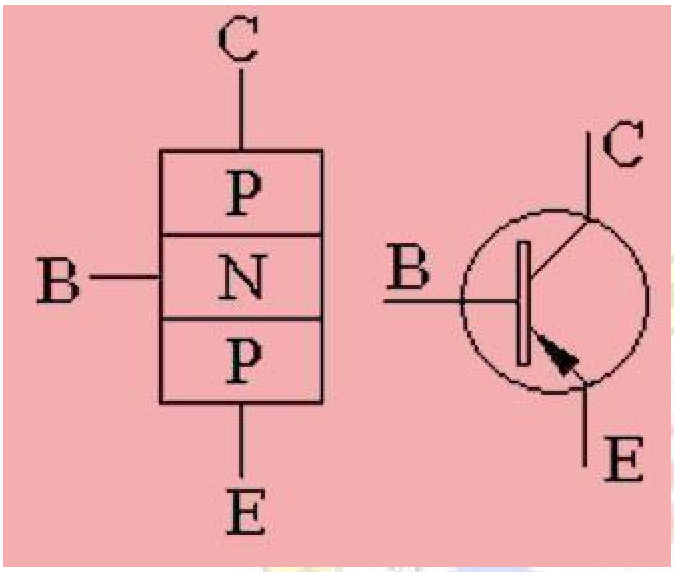


Difference between NPN and PNP Transistor:

The main difference between NPN and PNP transistors includes what are PNP and NPN transistors, construction, working and its applications.

What is a PNP Transistor?

The term 'PNP' stands for positive, negative, positive and also known as sourcing. The PNP transistor is a BJT; in this transistor the letter 'P' specifies the polarity of the voltage necessary for the emitter terminal. The second letter 'N' specifies the polarity of the base terminal. In this kind of transistor, the majority charge carriers are holes. Mainly, this transistor works as the same as the NPN transistor.

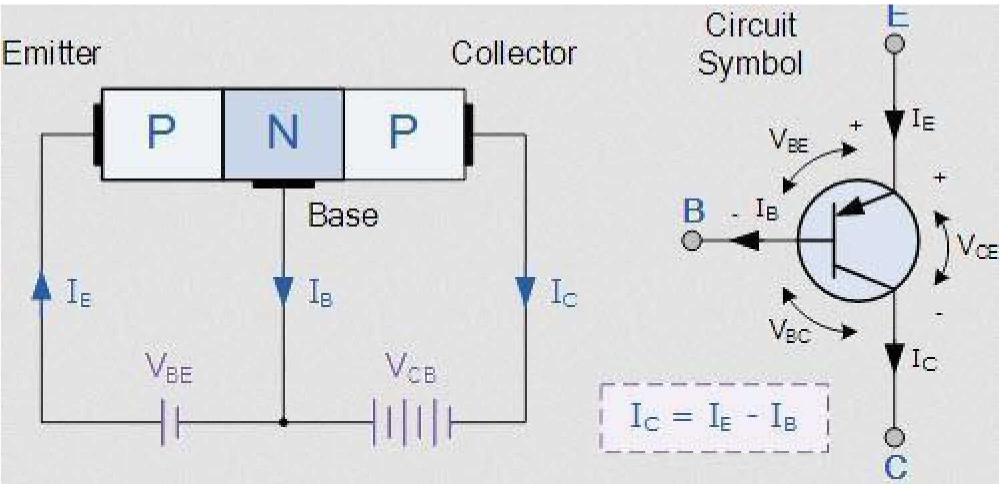


PNP Transistor

The required materials used to build the emitter (E), base (B) and collector(C) terminals in this transistor are diverse from those used in the NPN transistor. The BC terminals of this transistor are constantly reversed biased, then the –Ve voltage should be used for the collector terminal. Consequently, the base-terminal of the PNP transistor must be –Ve with respect to the emitter-terminal, and the collector terminal must be –Ve than the base terminal

PNP Transistor Construction:

The PNP transistor construction is shown below. The main characteristics of both the transistors are similar except that the biasing of the current & voltage directions are inverted for any one of the achievable 3-configurations namely common base, common emitter and common collector.



PNP <u>Transistor Construction:</u>

The voltage between the VBE (base and emitter terminal) is –Ve at the base terminal & +Ve at the emitter terminal. Since for this transistor, the base terminal constantly biased -Ve with respect to the emitter terminal. Also, the VBE is positive with respect to the collector VCE.

The voltage sources connected to this transistor is shown in the above figure. The emitter terminal is connected to the 'Vcc' with the load resistor ' RL'. This resistor stops the current flow through the device, which is allied to the collector terminal.

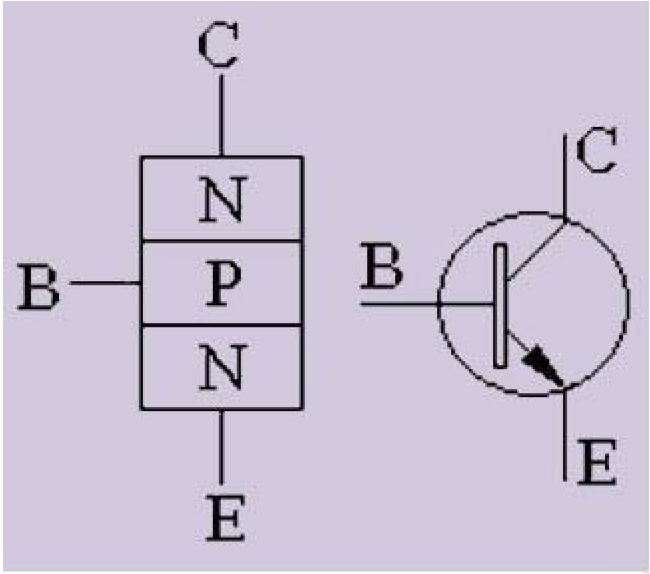
X

The base voltage 'VB' is connected to the 'RB' base resistor, which is biased negative with respect to the emitter terminal. To root the base current to flow through a PNP transistor, the base terminal of the transistor should be more negative than the base terminal by approximately 0.7volts (or) a Si device.

The **primary difference between PNP and NPN transistor** is the correct biasing of the transistor joints. The directions of current and the voltage polarities are constantly reverse to each other.

What is an NPN Transistor?

The term 'NPN' stands for negative, positive, negative and also known as sinking. **The NPN transistor is a BJT**, in this transistor, the initial letter 'N' specifies a negatively charged coating of the material. Where, 'P' specifies a completely charged layer. The two transistors have a positive layer, which are situated in the middle of two negative layers. Generally, NPN transistor is used in various electrical circuits for switching and strengthens the signals that exceed through them.



NPN Transistor

The NPN transistor includes three terminals like base, emitter and collector. These three terminals can be used to connect the transistor to the circuit board. When the current flows through this transistor, the base terminal of the transistor gets the electrical signal. The collector terminal creates a **stronger electric current**, and the emitter terminal exceeds this stronger current on to the circuit. In PNP transistor, the current runs through the collector to the emitter terminal.

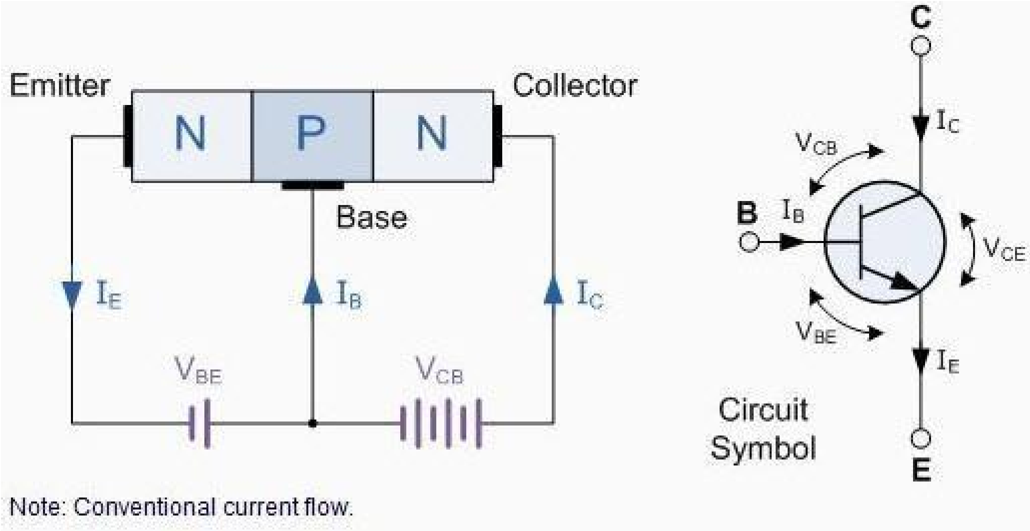
Usually, NPN transistor is used because it is so simple to generate. For an NPN transistor to function properly, it requires to be created from a semiconductor object, which holds some current. But not the max amount as extremely conductive materials such as metal. Silicon is one of the most normally used in semiconductors. These transistors are the simple transistors to build out of silicon.

The NPN transistor is used on a computer circuit board to translate the information into binary code, and this procedure is proficient through a plethora of tiny switches flipping On& OFF on the boards. A powerful electric signal twists the switch on, while a lack of a signal makes the switch off.

Construction of NPN Transistor:

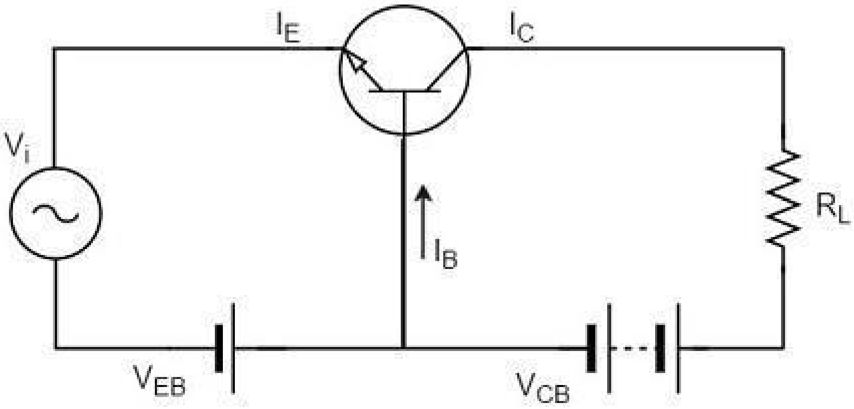
The construction of this transistor is shown below. The voltage at the transistor's base is +Ve and –Ve at the transistors emitter terminal. The base terminal of the transistor is positive at all times with respect to the emitter, and also collector voltage supply is +Ve with respect to the transistor's emitter terminal. In this transistor, the collector terminal is linked to the VCC through the RL

<u>Transistor Construction:</u>



This resistor restricts the current flow through the highest base current. In NPN transistor, the electrons flow through the base represents transistor action. The main characteristic of this transistor action is the connection between the i/p and o/p circuits. Because, the amplifying properties of transistor come from the resultant control that the base utilizes upon the collector to emitter current. The NPN transistor is a current activated device. When the transistor is turned ON, the huge current IC supplies between the collector & emitter terminals in the transistor. But, this only occurs when a tiny biasing current 'Ib' flows through the transistor's base terminal. It is a bipolar transistor; the current is the relation of two currents (Ic/Ib), named the DC current gain of the device. It is specified with "hfe" or these days beta. The beta value can be huge up to 200 for typical transistors. When the NPN transistor is used in an active region, then base current 'Ib' offers the i/p and collector current 'IC' gives the o/p. The current gain of the NPN transistor from the C to the Eis called alpha (Ic/Ie), and it is a purpose of the transistor itself. As the Ie (emitter current) is the sum of a tiny base current and huge collector current. The worth of the alpha is very close to unity, and for a typical low power signal transistor the value ranges from about 0.950- 0.999.

transistor as an amplifier: A transistor acts as an amplifier by raising the strength of a weak signal. The DC bias voltage applied to the emitter base junction, makes it remain in forward biased condition. This forward bias is maintained regardless of the polarity of the signal. The below figure shows how a transistor looks like when connected as an amplifier.



The low resistance in input circuit, lets any small change in input signal to result in an appreciable change in the output. The emitter current caused by the input signal contributes the collector current, which when flows through the load resistor R_L, results in a large voltage drop across it. Thus a small input voltage results in a large output voltage, which shows that the transistor works as an amplifier.

Example:

Let there be a change of 0.1v in the input voltage being applied, which further produces a change of 1mA in the emitter current. This emitter current will obviously produce a change in collector current, which would also be 1mA.

A load resistance of 5kΩ placed in the collector would produce a voltage of

5 kΩ × 1 mA = 5V

Hence it is observed that a change of 0.1v in the input gives a change of 5v in the output, which means the voltage level of the signal is amplified.

Performance of Amplifier

As the common emitter mode of connection is mostly adopted, let us first understand a few important terms with reference to this mode of connection.

Input Resistance:

As the input circuit is forward biased, the input resistance will be low. The input resistance is the opposition offered by the base-emitter junction to the signal flow.

By definition, it is the ratio of small change in base-emitter voltage (ΔV_{BE}) to the resulting change in base current (ΔI_B) at constant collector-emitter voltage.

Input resistance, Ri=ΔVBEΔIBRi=ΔVBEΔIB

Where R_i = input resistance, V_{BE} = base-emitter voltage, and I_B = base current.

Output Resistance:

The output resistance of a transistor amplifier is very high. The collector current changes very slightly with the change in collector-emitter voltage.

By definition, it is the ratio of change in collector-emitter voltage (ΔV_{CE}) to the resulting change in collector current (ΔI_C) at constant base current.

Output resistance = $Ro=\Delta VCE\Delta ICRo=\Delta VCE\Delta IC$
Where R_o = Output resistance, V_{CE} = Collector-emitter voltage, and I_C = Collector-emitter voltage.

Effective Collector Load:

The load is connected at the collector of a transistor and for a single-stage amplifier, the output voltage is taken from the collector of the transistor and for a multi-stage amplifier, the same is collected from a cascaded stages of transistor circuit.

By definition, it is the total load as seen by the a.c. collector current. In case of single stage amplifiers, the effective collector load is a parallel combination of R_C and R_o.

Effective Collector Load, $RAC=RC//RoRAC=RC//Ro$

$=RC\times RoRC+Ro=RAC=RC\times RoRC+Ro=RAC$

Hence for a single stage amplifier, effective load is equal to collector load R_C.

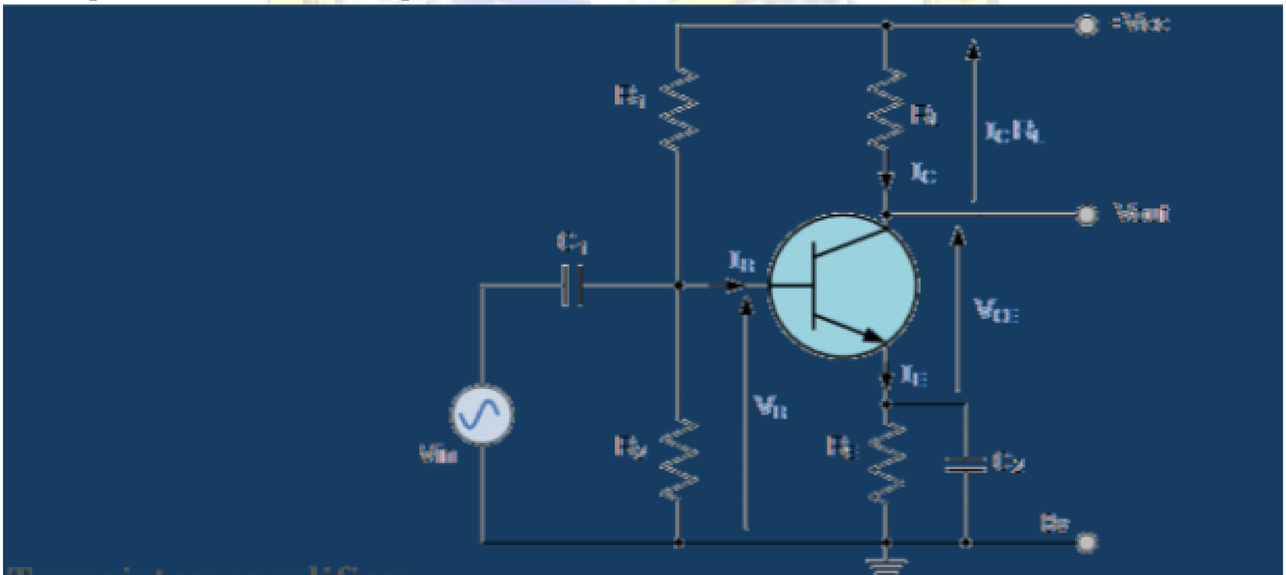
In a multi-stage amplifier (i.e. having more than one amplification stage), the input resistance R_i of the next stage also comes into picture.

Effective collector load becomes parallel combination of R_C, R_o and R_i i.e,

Effective Collector Load, $RAC=RC//Ro//RiRAC=RC//Ro//Ri$

$RC//Ri=RCRiRC+RiRC//Ri=RCRiRC+Ri$

As input resistance R_i is quite small, therefore effective load is reduced.



Transistor amplifier:

The most common amplifier configuration for an NPN transistor is that of the Common Emitter Amplifier circuit

In the previous introduction to the amplifier tutorial, we saw that a family of curves known commonly as the **Output Characteristic Curves**, relate the transistors Collector Current (Ic), to its Collector Voltage (Vce) for different values of the transistors Base Current (Ib).

All types of transistor amplifiers operate using AC signal inputs which alternate between a positive value and a negative value so some way of “presetting” the amplifier circuit to operate between these two maximum or peak values is required. This is achieved using a process known as **Biasing**. Biasing is very important in amplifier design as it establishes the correct operating point of the transistor amplifier ready to receive signals, thereby reducing any distortion to the output signal.

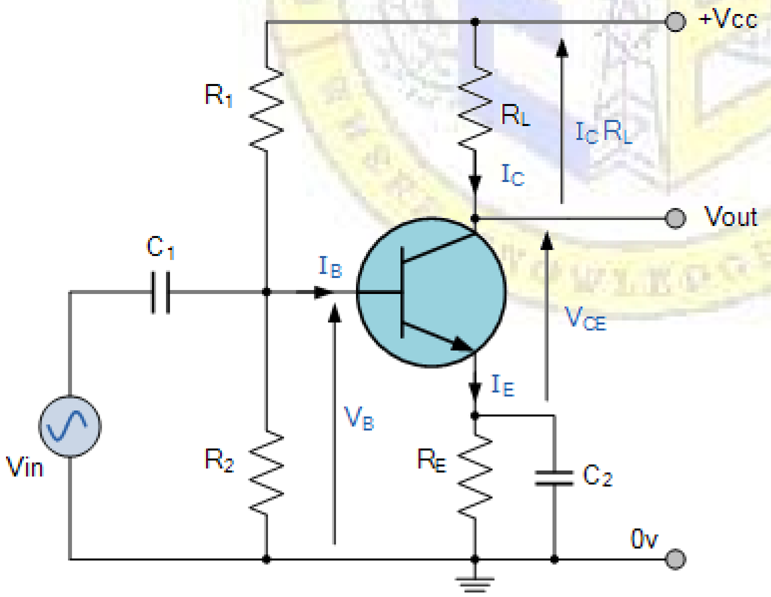
We also saw that a static or DC load line can be drawn onto these output characteristics curves to show all the possible operating points of the transistor from fully "ON" to fully "OFF", and to which the quiescent operating point or **Q-point** of the amplifier can be found.

The aim of any small signal amplifier is to amplify all of the input signal with the minimum amount of distortion possible to the output signal, in other words, the output signal must be an exact reproduction of the input signal but only bigger (amplified).

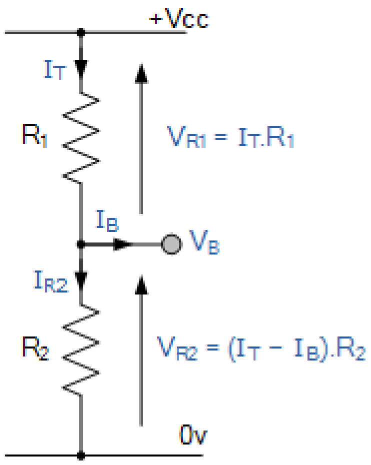
To obtain low distortion when used as an amplifier the operating quiescent point needs to be correctly selected. This is in fact the DC operating point of the amplifier and its position may be established at any point along the load line by a suitable biasing arrangement.

The best possible position for this Q-point is as close to the center position of the load line as reasonably possible, thereby producing a Class A type amplifier operation, ie. Vce = 1/2Vcc. Consider the **Common Emitter Amplifier** circuit shown below.

The Common Emitter Amplifier Circuit:



The single stage common emitter amplifier circuit shown above uses what is commonly called "Voltage Divider Biasing". This type of biasing arrangement uses two resistors as a potential divider network across the supply with their center point supplying the required Base bias voltage to the transistor. Voltage divider biasing is commonly used in the design of bipolar transistor amplifier circuits.



This method of biasing the transistor greatly reduces the effects of varying Beta, (β) by holding the Base bias at a constant steady voltage level allowing for best stability. The quiescent Base voltage (Vb) is determined by the potential divider network formed by the two resistors, R1, R2 and the power supply voltage Vcc as shown with the current flowing through both resistors.

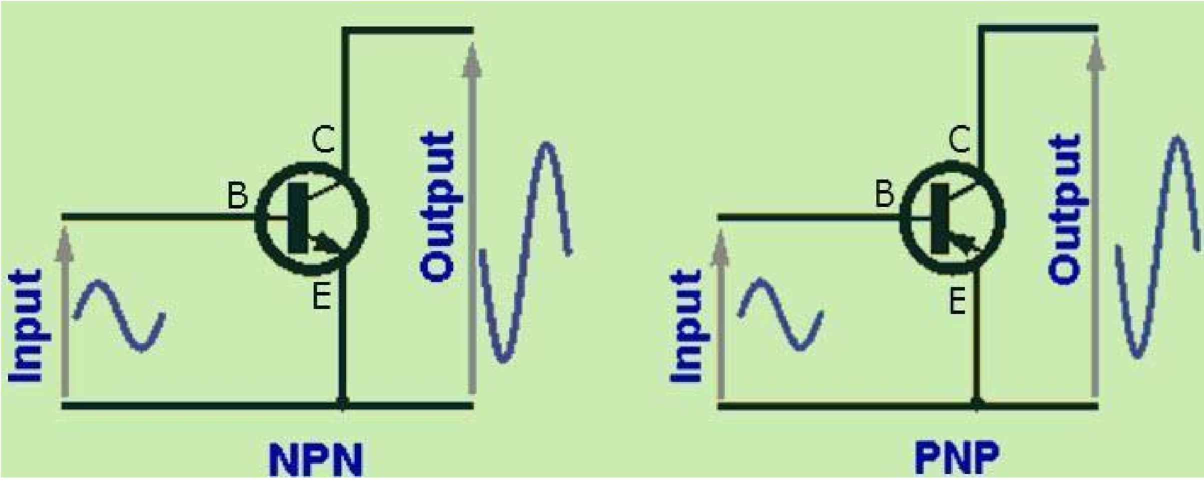
Then the total resistance R_T will be equal to R1 + R2 giving the current as i = Vcc/R_T. The voltage level generated at the junction of resistors R1 and R2 holds the Base voltage (Vb) constant at a value below the supply voltage.
Then the potential divider network used in the common emitter amplifier circuit divides the supply voltage in proportion to the resistance.

Frequency response of CE amplifier:

The Amplifier is an electronic circuit that is used to increase the strength of a weak input signal in terms of voltage, current, or power. The process of increasing the strength of a weak signal is known as Amplification. One most important constraint during the amplification is that only the magnitude of the signal should increase and there should be no changes in original signal shape. The transistor (BJT, FET) is a major component in an amplifier system. When a transistor is used as an amplifier, the first step is to choose an appropriate configuration, in which device is to be used. Then, the transistor should be biased to get the desired Q-point. The signal is applied to the amplifier input and output gain is achieved. In this article, we will discuss common emitter amplifier analysis.

Common Emitter Amplifier Configuration:

In Common Emitter Amplifier Configuration, the Emitter of a BJT is common to both the input and output signal as shown below. The arrangement is the same for a PNP transistor, but bias will be opposite w.r.t NPN transistor.

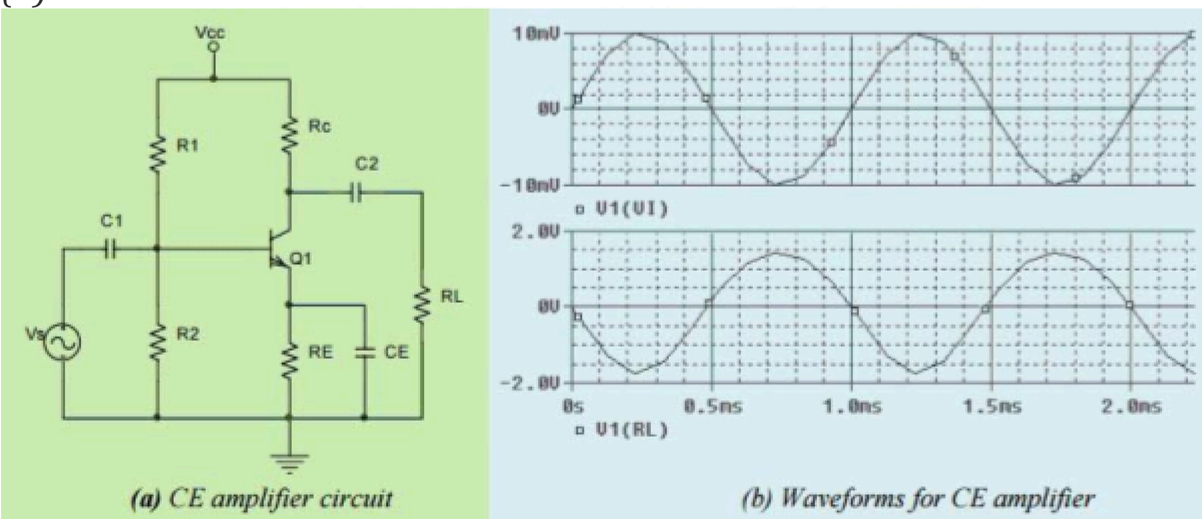


NPN and PNP CE Configuration Amplifier

Operation of Common Emitter Amplifier:

When a signal is applied across the emitter-base junction, the forward bias across this junction increases during the upper half cycle. This leads to increase the flow of electrons from the emitter to a collector through the base, hence increases the collector current. The increasing collector current makes more voltage drops across the collector load resistor RC.

The negative half cycle decreases the forward bias voltage across the emitter-base junction. The decreasing collector-base voltage decreases the collector current in the whole collector resistor Rc. Thus, the amplified load resistor appears across the collector resistor. The common emitter amplifier circuit is shown below figure (a).



CE Amplifier

From the voltage waveforms for the CE circuit shown in Fig. (b) It is seen that there is an 180-degree phase shift between the input and output waveforms.

<u>Frequency response of CE amplifier:</u>

The common emitter configuration is widely used as a basic amplifier as it has both voltage and current amplification.

Resistors R1 and R2 form a voltage divider across the base of the transistor. The function of this network is to provide necessary bias condition and ensure that emitter-base junction is operating in the proper region.
In order to operate transistor as an amplifier, biasing is done in such a way that the operating point is in the active region. For an amplifier the Q-point is placed so that the load line is bisected. Therefore, in practical design V_{CE} is always set to $V_{CC}/2$. This will confirm that the Q-point always swings within the active region. This limitation can be explained by maximum signal handling capacity. For the maximum input signal, output is produced without any distortion and clipping.

<u>The Bypass Capacitor:</u>

The emitter resistor R_E is required to obtain the DC quiescent point stability. However the inclusion of R_E in the circuit causes a decrease in amplification at higher frequencies. In order to avoid such a condition, it is bypassed by a capacitor so that it acts as a short circuit for AC and contributes stability for DC quiescent condition. Hence capacitor is connected in parallel with emitter resistance.

$$X_{CE} << R_E$$

$$\frac{1}{2\pi f C_E} << R_E, \quad C_E >> \frac{1}{2\pi f R_E}$$

The Input/ Output Coupling (or Blocking) Capacitor: An amplifier amplifies the given AC signal. In order to have noiseless transmission of a signal (without DC), it is necessary to block DC i.e. the direct current should not enter the amplifier or load. This is usually accomplished by inserting a coupling capacitor between two stages.

$XC_C <<(R_i h_{ie})$

$$\frac{1}{2\pi f C_C} << R_i h_{ie}$$

$$C_C >> \frac{1}{2\pi f (R_i h_{ie})}$$

C_C - Output Coupling Capacitor

C_B - Input Coupling Capacitor

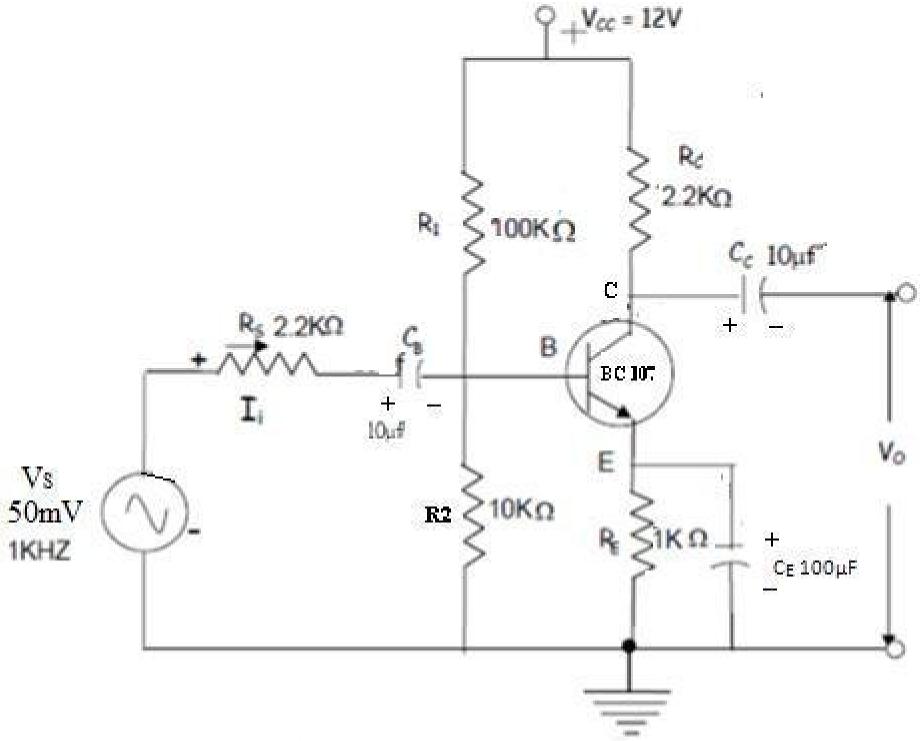
<u>Frequency response of Common Emitter Amplifier:</u>

Emitter bypass capacitors are used to short circuit the emitter resistor and thus increases the gain at high frequency. The coupling and bypass capacitors cause the fall of the signal in the low frequency response of the amplifier because their impedance becomes large at low frequencies. The stray capacitances are effectively open circuits.
In the mid frequency range large capacitors are effectively short circuits and the stray capacitors are open circuits, so that no capacitance appears in the mid frequency range. Hence the mid band frequency gain is maximum.
At the high frequencies, the bypass and coupling capacitors are replaced by short circuits. The stray capacitors and the transistor determine the response.

Characteristics of CE Amplifier:

1. Large current gain.
2. Large voltage gain.
3. Large power gain.
4. Current and voltage phase shift of 180^0.
5. Moderated output resistance.

Circuit Diagram:

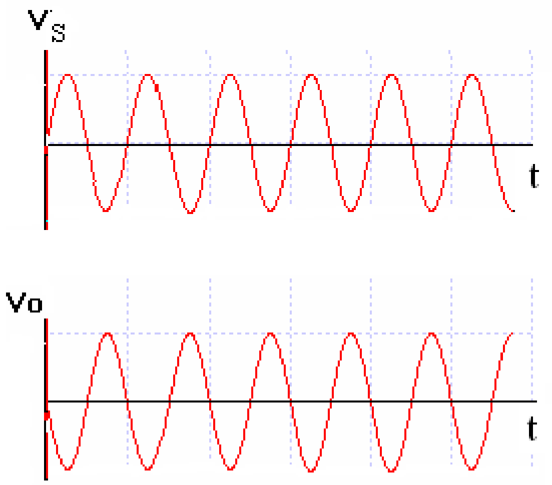


Procedure:

1. Connect the circuit as shown in the circuit diagram.
2. Set source voltage Vs = 50mV (say) at 1 KHz frequency using the function generator. Observe the phase difference between input and output by giving these two signals to the dual channels of CRO.
3. Keeping input voltage constant, vary the frequency from 50 Hz to 1 MHz in regular steps and note down the corresponding output voltage. Calculate gain in dB as shown in the tabular column.
4. Plot the graph: gain (dB) verses Frequency on a semi log graph sheet.
5. Calculate the 3-dB bandwidth from the frequency response.

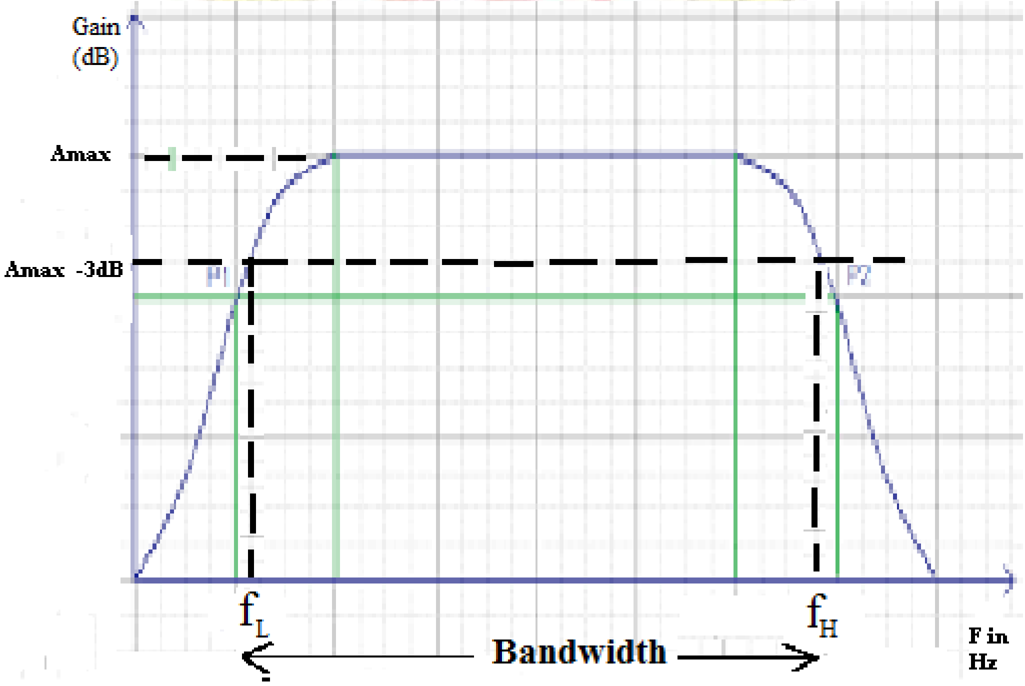
Expected waveform:

(a) The Input & Output Waveforms at 1 KHz



(b) **Frequency Response Curve:**

In the usual application, mid band frequency range are defined as those frequencies at which the response has fallen to 3dB below the maximum gain (|A| max). These are shown as f_L and f_H and are called as the 3dB frequencies (Lower and Upper Cut-Off Frequencies respectively). The difference between higher cut-off and lower cut-off frequency is referred to as bandwidth (f_H - f_L).

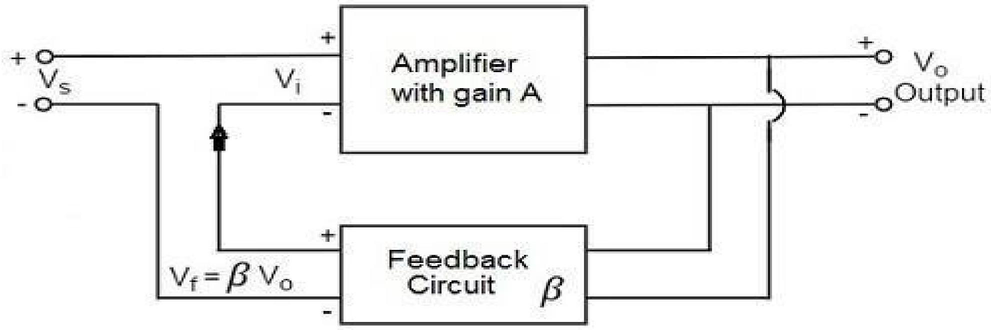


Concepts of feedback amplifier: An amplifier circuit simply increases the signal strength. But while amplifying, it just increases the strength of its input signal whether it contains information or some noise along with information. This noise or some disturbance is introduced in the amplifiers because of their strong tendency to introduce **hum** due to sudden temperature changes or stray electric and magnetic fields. Therefore, every high gain amplifier tends to give noise along with signal in its output, which is very undesirable.

The noise level in the amplifier circuits can be considerably reduced by using **negative feedback** done by injecting a fraction of output in phase opposition to the input signal.

Principle of Feedback Amplifier

A feedback amplifier generally consists of two parts. They are the **amplifier**and the **feedback circuit**. The feedback circuit usually consists of resistors. The concept of feedback amplifier can be understood from the following figure.



From the above figure, the gain of the amplifier is represented as A. the gain of the amplifier is the ratio of output voltage V_o to the input voltage V_i. the feedback network extracts a voltage $V_f = \beta\ V_o$ from the output V_o of the amplifier. This voltage is added for positive feedback and subtracted for negative feedback, from the signal voltage V_s. Now,

$Vi=Vs+Vf=Vs+\beta VoVi=Vs+Vf=Vs+\beta Vo$

$Vi=Vs-Vf=Vs-\beta VoVi=Vs-Vf=Vs-\beta Vo$

The quantity $\beta = V_f/V_o$ is called as feedback ratio or feedback fraction.

Let us consider the case of negative feedback. The output V_o must be equal to the input voltage ($V_s - \beta V_o$) multiplied by the gain A of the amplifier.

Hence,

$(Vs-\beta Vo$

)
A
=
V
o
(
V
s
−
β

Therefore,

V
o
)
A
=
V
o
O
r

AVs−AβVo=VoAVs−AβVo=Vo

O

r
AVs=Vo(
1+Aβ)A
Vs=Vo(1
+Aβ)

VoVs=A1+AβVoVs=A1+Aβ

Let A_f be the overall gain (gain with the feedback) of the amplifier. This is defined as the ratio of output voltage V_o to the applied signal voltage V_s, i.e.,
Af=OutputvoltageInputsignalvoltage=VoVsAf=OutputvoltageInputsignalvoltage=VoVs

So, from the above two equations, we can understand that,
The equation of gain of the feedback amplifier, with negative feedback is given by Af=A1+AβAf=A1+Aβ
The equation of gain of the feedback amplifier, with positive feedback is given by Af=A1−AβAf=A1−Aβ
These are the standard equations to calculate the gain of feedback amplifiers.

Types of Feedbacks

The process of injecting a fraction of output energy of some device back to the input is known as **Feedback**. It has been found that feedback is very useful in reducing noise and making the amplifier operation stable.
Depending upon whether the feedback signal **aids** or **opposes** the input signal, there are two types of feedbacks used.

Positive Feedback:

The feedback in which the feedback energy i.e., either voltage or current is in phase with the input signal and thus aids it is called as **Positive feedback**.
Both the input signal and feedback signal introduces a phase shift of 180^o thus making a 360^o resultant phase shift around the loop, to be finally in phase with the input signal.
Though the positive feedback **increases the gain** of the amplifier, it has the disadvantages such as

- Increasing distortion
- Instability

It is because of these disadvantages the positive feedback is not recommended for the amplifiers. If the positive feedback is sufficiently large, it leads to oscillations, by which oscillator circuits are formed. This concept will be discussed in OSCILLATORS tutorial.

Negative Feedback:

The feedback in which the feedback energy i.e., either voltage or current is out of phase with the input and thus opposes it, is called as **negative feedback**.
In negative feedback, the amplifier introduces a phase shift of 180^o into the circuit while the feedback network is so designed that it produces no phase shift or zero phase shift. Thus the resultant feedback voltage V_f is 180^o out of phase with the input signal V_{in}.
Though the **gain** of negative feedback amplifier is **reduced**, there are many advantages of negative feedback such as

- Stability of gain is improved
- Reduction in distortion
- Reduction in noise

- Increase in input impedance

- Decrease in output impedance
- Increase in the range of uniform application

It is because of these advantages negative feedback is frequently employed in amplifiers.