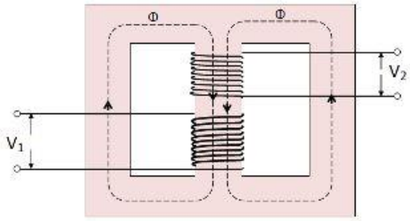
Electrical transformer is a static electrical machine which transforms electrical power from one circuit to another circuit, without changing the frequency. Transformer can increase or decrease the voltage with corresponding decrease or increase in current.

Working principle of transformer
The basic principle behind working of a transformer is the phenomenon of mutual induction between two windings linked by common magnetic flux. The figure at right shows the simplest form of a transformer. Basically a transformer consists of two inductive coils; primary winding and secondary winding. The coils are electrically separated but magnetically linked to each other. When, primary winding is connected to a source of alternating voltage, alternating magnetic flux is produced around the winding. The core provides magnetic path for the flux, to get linked with the secondary winding. Most of the flux gets linked with the secondary winding which is called as 'useful flux' or main 'flux', and the flux which does not get linked with secondary winding is called as 'leakage flux'. As the flux produced is alternating (the direction of it is continuously changing), EMF gets induced in the secondary winding according to Faraday's law of electromagnetic induction. This emf is called 'mutually induced emf', and the frequency of mutually induced emf is same as that of supplied emf. If the secondary winding is closed circuit, then mutually induced current flows through it, and hence the electrical energy is transferred from one circuit (primary) to another circuit

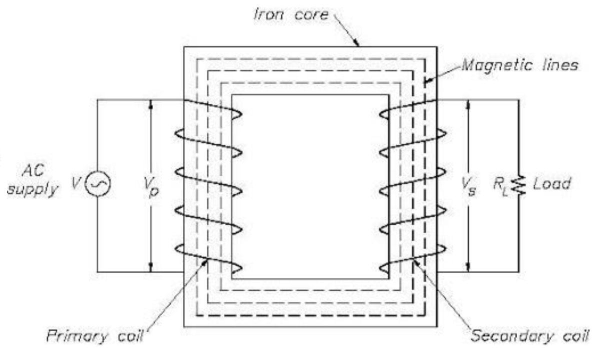
Basic construction of transformer
On the basis of construction, transformers can be classified into two types as; (i) Core type transformer and (ii) Shell type transformer, which are described below.

(i) Core type transformer
In core type transformer, windings are cylindrical former wound, mounted on the core limbs as shown in the figure above. The cylindrical coils have different layers and each layer is insulated from each other. Materials like paper, cloth or mica can be used for insulation. Low voltage windings are placed nearer to the core, as they are easier to insulate.

(ii) Shell type transformer
The coils are former wound and mounted in layers stacked with insulation between them. A shell type transformer may have simple rectangular form (as shown in above fig), or it may have a distributed form.



Shell Type



<u>EMF equation of the Transformer</u>

let,

N_1 = Number of turns in primary winding

N_2 = Number of turns in secondary winding

Φ_m = Maximum flux in the core (in Wb) = (B_m x A)

f = frequency of the AC supply (in Hz)

As, shown in the fig., the flux rises sinusoidally to its maximum value Φ_m from 0. It reaches to the maximum value in one quarter of the cycle i.e in T/4 sec (where, T is time period of the sin wave of the supply = 1/f).

Therefore, average rate of change of flux = $\frac{d\phi}{dt} = \frac{\phi_m}{\frac{T}{4}}$

Therefore, average rate of change of flux = 4f Φ_m .... (Wb/s).

Now, Induced emf per turn = rate of change of flux per turn

Therefore, average emf per turn = 4f Φ_m .... (Volts).

Now, we know, Form factor = RMS value / average value

Therefore, RMS value of emf per turn = Form factor X average emf per turn.

As, the flux Φ varies sinusoidally, form factor of a sine wave is 1.11

Therefore, RMS value of emf per turn = 1.11 x 4f Φ_m = 4.44f Φ_m.

RMS value of induced emf in whole primary winding (E_1) = RMS value of emf per turn X Number of turns in primary winding

$E_1 = 4.44f\, N_1\, \Phi_m$ .... Eq 1

Similarly, RMS induced emf in secondary winding (E_2) can be given as

$E_2 = 4.44f\, N_2\, \Phi_m$. .... Eq 2

from the above equations 1 and 2,

$$\frac{E_1}{N_1} = \frac{E_2}{N_2} = 4.44f\,\Phi m$$

This is called the emf equation of transformer

Voltage Transformation Ratio (K)

As derived above,

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

Where, K = constant .This constant K is known as **voltage transformation ratio**.
If $N_2 > N_1$, i.e. $K > 1$, then the transformer is called step-up transformer. If $N_2 < N_1$, i.e. $K < 1$, then the transformer is called step-down transformer.

Transformer on No Load Condition (phasor diagram)

When the transformer is operating at no load, the secondary winding is open-circuited, which means there is no load on the secondary side of the transformer and, therefore, current in the secondary will be zero.
While primary winding carries a small current I_0 called no-load current which is **2 to 10% of the rated current**.
This current is responsible for supplying the iron losses (hysteresis and eddy current losses) in the core and a very small amount of copper losses in the primary winding. The angle of lag depends upon the losses in the transformer. The power factor is very low and varies from **0.1 to 0.15**.

The no-load current consists of two components:

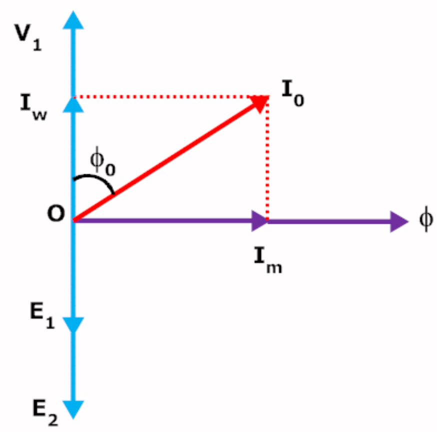
- **Reactive or magnetizing component I_m**
  It is in quadrature with the applied voltage V_1. It produces flux in the core and does not consume any power

- **Active or power component I_w or working component**
  It is in phase with the applied voltage V_1. It supplies the iron losses and a small amount of primary copper loss

The following steps are given below to draw the phasor diagram:

1. The function of the magnetizing component is to produce the magnetizing flux, and thus, it will be in phase with the flux.
2. Induced emf in the primary and the secondary winding lags the flux ϕ by 90 degrees.
3. The primary copper loss is neglected, and secondary current losses are zero as $I_2 = 0$.
   Therefore, the current I_0 lags behind the voltage vector V_1 by an angle ϕ_0 called the no-load power factor angle and is shown in the phasor diagram above.

4. The applied voltage V_1 is drawn equal and opposite to the induced emf E_1 because the difference between the two, at no load, is negligible.
5. Active component I_w is drawn in phase with the applied voltage V_1.
6. The phasor sum of magnetizing current I_m and the working current I_w gives the no-load current I_0.



Phasor diagram of practical transformer on no load

Working component $I_w = I_0 \cos\varphi_0$

No load current $I_0 = \sqrt{I_w^2 + I_m^2}$

Magnetizing component $I_m = I_0 \sin\varphi_0$

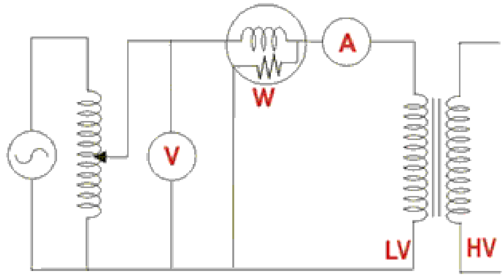
Power factor $\cos\varphi_0 = \frac{I_w}{I_0}$

No load power input $P_0 = V_1 I_0 \cos\varphi_0$

Testing of transformer

Open circuit or No load test;

- 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.



Open Circuit Test on Transformer

- 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.

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

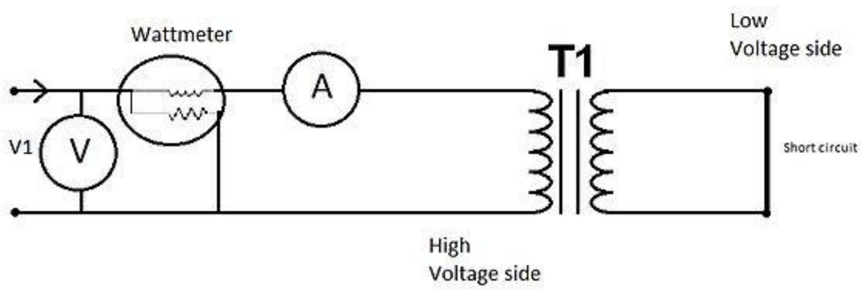
$I_m = I_0\sin\Phi_0$ and $I_w = I_0\cos\Phi_0$.
$\cos\Phi_0$ (no load power factor) = $W / (V_1 I_0)$. ... (W = wattmeter reading)

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

$X_0 = V_1/I_m$ and $R_0 = V_1/I_w$.

Short circuit test

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), voltmeter (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

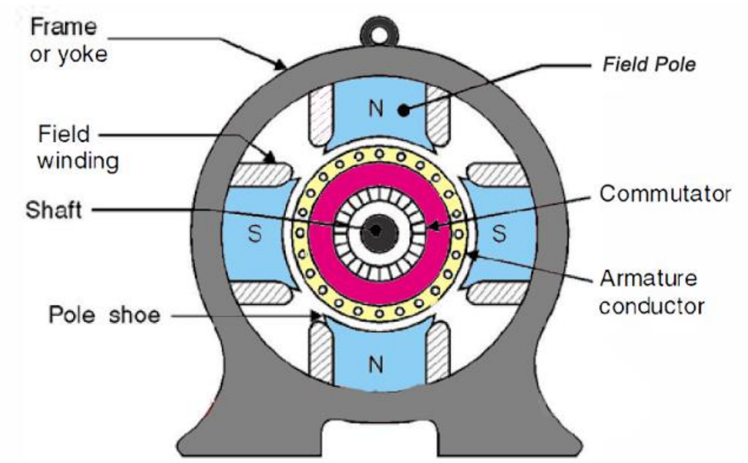
$Z_{eq}^2 = R_{eq}^2 + X_{eq}^2$.
These, values are referred to the HV side of the transformer.
Hence, it is seen that the short circuit test gives copper losses of transformer and approximate equivalent resistance and reactance of the transformer.

Dc machines:

The construction of dc motor and generator is nearly same.
A DC Machine is an electro-mechanical energy conversion device. There are two types of DC machines; one is DC generator, and another one is known as DC motor. A DC generator converts mechanical power (ωT) into DC electrical power (EI), whereas, a DC motor converts d.c electrical power into mechanical power.

Construction of dc generator

The construction of DC machine can be done using some of the essential parts like Yoke, Pole core & pole shoes, Pole coil & field coil, Armature core, Armature winding otherwise conductor, commutator, brushes & bearings. Some of the parts of the DC machine are discussed below.



Yoke

Another name of a yoke is the frame. The main function of the yoke in the machine is to offer mechanical support intended for poles and protects the entire machine from the moisture, dust, etc. The materials used in the yoke are designed with cast iron, cast steel otherwise rolled steel.

Pole and Pole Core

The pole of the DC machine is an electromagnet and the field winding is winding among pole. Whenever field winding is energized then the pole gives magnetic flux. The materials used for this are cast steel, cast iron otherwise pole core. It can be built with the annealed steel laminations for reducing the power drop because of the eddy currents.

Pole Shoe

Pole shoe in DC machine is an extensive part as well as enlarge the region of the pole. Because of this region, flux can be spread out within the air-gap as well as extra flux can be passed through the air space toward armature. The materials used to build pole shoe is cast iron otherwise cast steed, and also used annealed steel lamination to reduce the loss of power because of eddy currents.

Field Windings

In this, the windings are wounded in the region of pole core & named as field coil. Whenever current is supplied through field winding then it electromagnetic the poles which generate required flux. The material used for field windings is copper.

Armature Core

Armature core includes the huge number of slots within its edge. Armature conductor is located in these slots. It provides the low-reluctance path toward the flux generated with field winding. The materials used in this core are permeability low-reluctance materials like iron otherwise cast. The lamination is used to decrease the loss because of the eddy current.

Armature Winding

The armature winding can be formed by interconnecting the armature conductor. Whenever an armature winding is turned with the help of prime mover then the voltage, as well as magnetic flux, gets induced within it. This winding is allied to an exterior circuit. The materials used for this winding are conducting material like copper.

Commutator

The main function of the commutator in the DC machine is to collect the current from the armature conductor as well as supplies the current to the load using brushes. And also provides uni-directional torque for DC-motor. The commutator can be built with a huge number of segments in the edge form of hard drawn copper. The Segments in the commutator are protected from thin mica layer.

Brushes

Brushes in the DC machine gather the current from commutator and supplies it to exterior load. Brushes wear with time to inspect frequently. The materials used in brushes are graphite otherwise carbon which is in rectangular form.

Emf equation of dc generator:

Consider a DC generator with the following parameters,

P = number of field poles
Ø = flux produced per pole in Wb (Weber)
Z = total no. of armature conductors
A = no. of parallel paths in armature
N = rotational speed of armature in revolutions per min. (rpm)

Now,
Average emf generated per conductor is given by $d\Phi/dt$ Volts ... eq. 1

Flux cut by one conductor in one revolution $= d\Phi = P\Phi$
Number of revolutions per second (speed in RPS) $= N/60$
Therefore, time for one revolution $= dt = 60/N$ Seconds
From eq. 1, emf generated per conductor $= d\Phi/dt = P\Phi N/60$
Above equation gives the emf generated in one conductor of the generator. The conductors are connected in series per parallel path, and the emf across the generator terminals is equal to the generated emf across any parallel path.
Therefore, $\mathbf{E_g = P\Phi NZ / 60A}$
For simplex lap winding, number of parallel paths is equal to the number of poles (i.e. A=P),
Therefore, for simplex lap wound dc generator, $\mathbf{E_g = P\Phi NZ / 60P}$
For wave wound A=2 hence, $E_g = P\Phi NZ / 120$

Torque equation of dc motor

Torque acting on a body is quantitatively defined as the product of force acting on the body and perpendicular distance of the line of action of force from the axis of rotation.
Total torque = torque on one conductor × total number of conductors
Let in a dc motor
r=average armature radius
L=effective length of each conductor
Z=total number of armature conductors
A=number of parallel paths
I_a =armature current
I=current through each conductor= I_a / A
B=average flux density
Φ=flux per pole
P=number of poles a=cross-sectional area of flux path per pole at radius r = (2πrL / P)
Force on each conductor = BIL
Torque due to one conductor = BILr

As,

$$I=\frac{I_a}{A} \quad \text{and} \quad B=\frac{\Phi}{a}=\frac{\Phi}{\left(\frac{2\pi rL}{P}\right)}$$

∴ Total armature torque, T_a = (Torque due to one conductor) × (total number of armature conductors)

$$= BILr \times Z$$

$$= \frac{\Phi}{\left(\frac{2\pi rL}{P}\right)}\left(\frac{I_a}{A}\right) Lr\,Z$$

$$= \frac{P\Phi I_a Z}{2\pi A}$$

or

$$T_a = 0.159\Phi I_a Z\left(\frac{P}{A}\right)$$

Classification of DC generators(methods of excitation)

when the current is passing through the winding then it is called "**Excitation**".

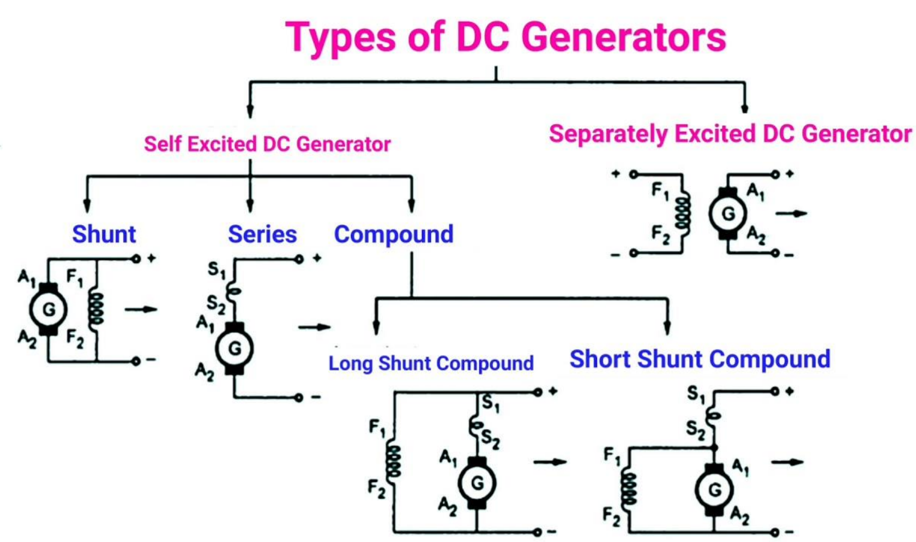
Types of **Excitation:**
(1)seperately excited generator.
(2)self excited generator.

Self Generator is classified into 3 types.
1.shunt generator.
2.series generator.
3.compound generator.

Compoud Generator is again classified into 2 types.
1.short shunt generator.
2.long shunt generator.

METHODS OF EXCITATION

- Separately excited machine: field flux is produced by an external source.
- Self excited machine: The field flux is produced by connecting the field winding with the armature.
- A self excited machine requires residual magnetism for operation.



Construction of Induction Motor

The three phase induction motor is a preferable type of motor. It is mostly used in industrial drives because it is very reasonable and vigorous, economical and reliable

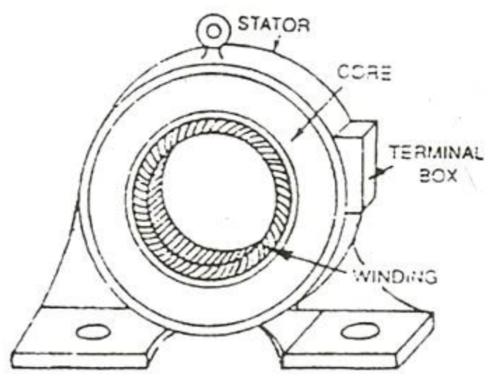
A three phase **Induction motor** mainly consists of two parts called as the **Stator** and the **Rotor**. The stator is the stationary part of the induction motor, and the rotor is the rotating par

Construction of Stator

The stator is built up of high-grade alloy steel laminations to reduce eddy current losses. It has three main parts, namely outer frame, the stator core and a stator winding.

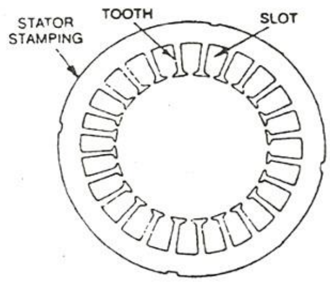
Outer frame

It is the outer body of the motor. Its main function is to support the stator core and to protect the inner parts of the machine. For small machines, the outer frame is casted, but for the large machine, it is fabricated. The figure below shows the stator construction.



Stator Core

The stator core is built of high-grade silicon steel stampings. Its main function is to carry the alternating magnetic field which produces hysteresis and eddy current losses. The stampings are fixed to the stator frame. Each stamping are insulated from the other with a thin varnish layer. The thickness of the stamping usually varies from 0.3 to 0.5 mm. Slots are punched on the inner side of the stampings as shown in the figure below.

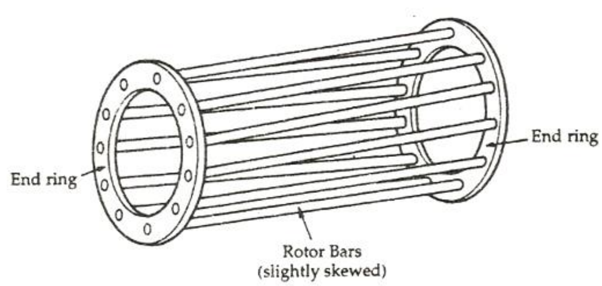


Construction of Rotor

The rotor is also built of thin laminations of the same material as the stator. The laminated cylindrical core is mounted directly on the shaft. These laminations are slotted on the outer side to receive the conductors. There are two types of rotor.

Squirrel Cage Rotor

A squirrel cage rotor consists of a laminated cylindrical core. The circular slots at the outer periphery are semi-closed. Each slot contains uninsulated bar conductor of aluminium or copper. At the end of the rotor the conductors the short-circuited by a heavy ring of copper or aluminium. The diagram of the cage rotor is shown below.



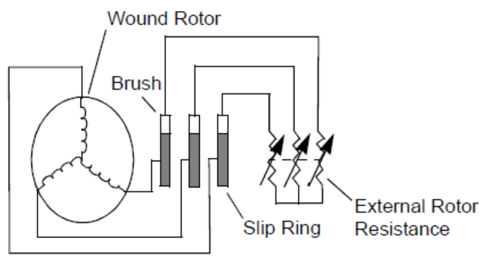
Advantages squirrel cage rotor

- The cage rotor is cheaper, and the construction is robust.
- The absence of the brushes reduces the risk of sparking.
- Its Maintenance is less.
- The power factor is higher

Phase Wound Rotor

The Phase wound rotor is also called as Slip Ring Rotor. It consists of a cylindrical core which is laminated. The outer periphery of the rotor has a semi-closed slot which carries a 3 phase insulated windings. The rotor windings are connected in star.

The **slip ring induction motor** is shown in the figure below.



Important definition

synchronous speed:

The synchronous speed is the speed of the revolution of the magnetic field in the stator winding of the motor. It is the speed at which the electromotive force is produced by the alternating machine

$N_S = \frac{120f}{P}$

f = frequency of electrical power supply (Hz, cycles/sec, 1/s)

p = number of poles

slip::

The slip in an induction motor is the difference between the main flux speed and their rotor speed. The symbol S represents the slip. It is expressed by the percentage of synchronous speed. Mathematically, it is written as

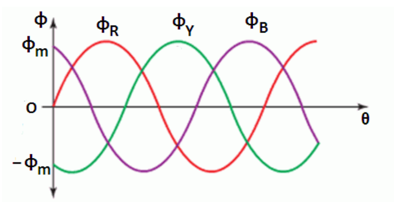
$$\%S = \frac{N_s - N}{N_s} \times 100$$

Rotating Magnetic Field

The induction motor rotates due to the rotating magnetic field in 3 phase induction motor**,** which is produced by the stator winding in the air gap between in the stator and the rotor. The stator has a three phase stationary winding which can be either star connected or delta connected.

Whenever the AC supply is connected to the stator windings, line currents I_R, I_Y, and I_B start flowing. These line currents have phase difference of 120^o with respect to each other. Due to each line current, a sinusoidal flux is produced in the air gap. These fluxes have the same frequency as that of the line currents, and they also have the same phase difference of 120^o with respect to each other.

Let the flux produced by the line currents I_R, I_B, I_Y be φ_R, φ_B, φ_Y respectively.



Fluxes produced by line currents

Mathematically, they are represented as follows:

$\varphi_R = \varphi_m \sin \omega t = \varphi_m \sin \theta$
$\varphi_B = \varphi_m \sin (\omega t - 120^o) = \varphi_m \sin (\theta - 120^o)$
$\varphi_Y = \varphi_m \sin (\omega t - 240^o) = \varphi_m \sin (\theta - 240^o)$

The effective or total flux (ϕ_T) in the air gap is equal to the phasor sum of the three components of fluxes ϕ_R, ϕ_Y and, ϕ_B.

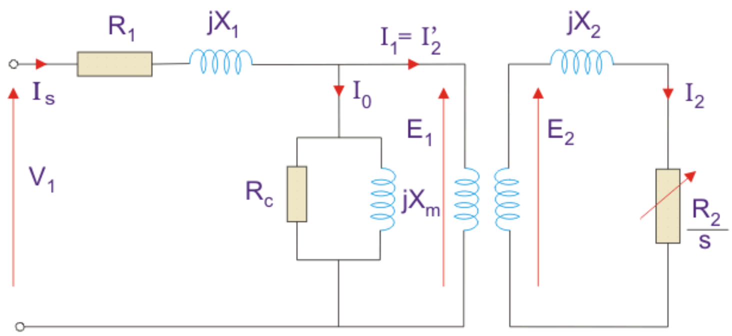
Therefore, $\phi_T = \phi_R + \phi_Y + \phi_B$

<u>Equivalent circuit</u>

The equivalent circuit of any machine shows the various parameter of the machine such as its Ohmic losses and also other losses.

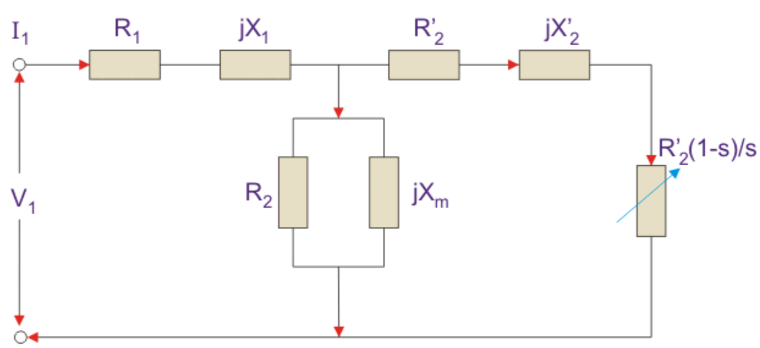
The losses are modeled just by inductor and resistor. The copper losses are occurred in the windings so the winding resistance is taken into account. Also, the winding has inductance for which there is a voltage drop due to inductive reactance and also a term called power factor comes into the picture. There are two types of equivalent circuits in case of a three-phase induction motor

Exact Equivalent Circuit



Here

R_1 is the winding resistance of the stator.
X_1 is the inductance of the stator winding.
R_c is the core loss component.
X_M is the magnetizing reactance of the winding.
R_2/s is the power of the rotor, which includes output mechanical power and copper loss of rotor.
If we draw the circuit with referred to the stator then the circuit will look like-



Here all the other parameters are same except-
R_2' is the rotor winding resistance with referred to stator winding.
X_2' is the rotor winding inductance with referred to stator winding.
$R_2 (1 – s) / s$ is the resistance which shows the power which is converted to mechanical power output or useful power. The power dissipated in that resistor is the useful power output or shaft power.

Torque Speed Characteristic of an Induction Motor

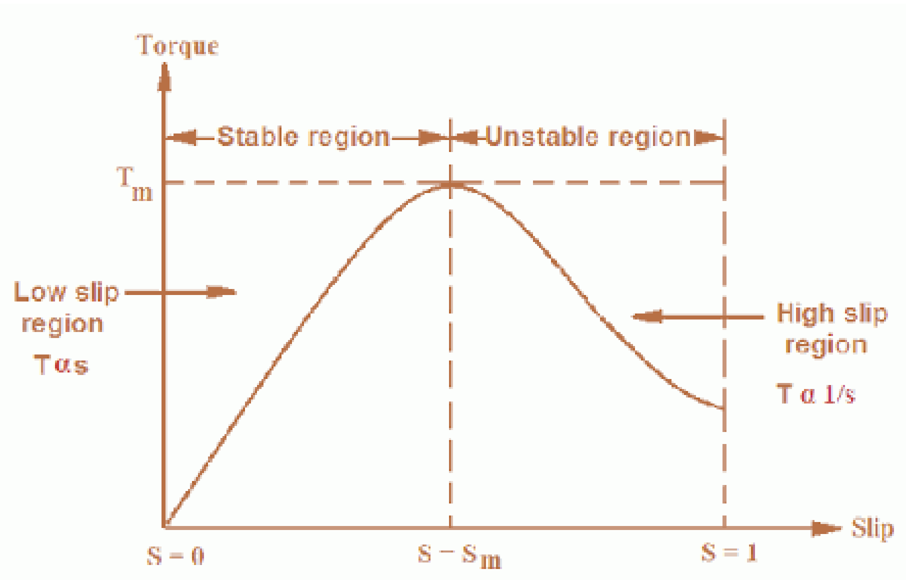
Torque Speed Characteristic is the curve plotted between the torque and the speed of the induction motor. As we have already discussed the torque of the induction motor in the topic Torque Equation of an Induction motor. The equation of the torque is given as shown below.

$$\tau = \frac{k\, s\, R_2 E_{20}^2}{R_2^2 + (sX_{20})^2} \ldots\ldots\ldots\ldots (1)$$

At the maximum torque, the speed of the rotor is expressed by the equation shown below.

$$N_M = N_S\,(1 - s_M) \ldots\ldots\ldots (2)$$

The maximum torque is independent of the rotor resistance. But the exact location of the maximum torque τ_{max} is dependent on it. Greater, the value of the R_2, the greater is the value of the slip at which maximum torque occurs. As the rotor resistance increases, the pullout speeds of the motor decreases. In this condition, the maximum torque remains constant.



Torque Slip characteristics of Induction motor