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MODULE-1

POLY PHASE INDUCTION MOTOR

Introduction

- An **induction motor** or **asynchronous motor** is an AC electric motor in which the electric current in the rotor needed to produce torque is obtained by electromagnetic induction from the magnetic field of the stator winding.
- Three-phase squirrel-cage induction motors are widely used as industrial drives because they are rugged, reliable and economical.
- The induction motor is maintenance free. It has high overloading capacity.
- Single-phase induction motors are used extensively for smaller loads, for household appliances like ceiling fans. Although traditionally used in fixed-speed applications, induction motors are increasingly being used with variable-frequency drives (VFDs) in variable-speed applications like in cranes, lifts, cement plants, ceramic plants, food processing industries etc.
- VFDs offer energy savings opportunities for existing and prospective induction motors in variable-torque centrifugal fan, pump and compressor load applications.

Classification of AC motors

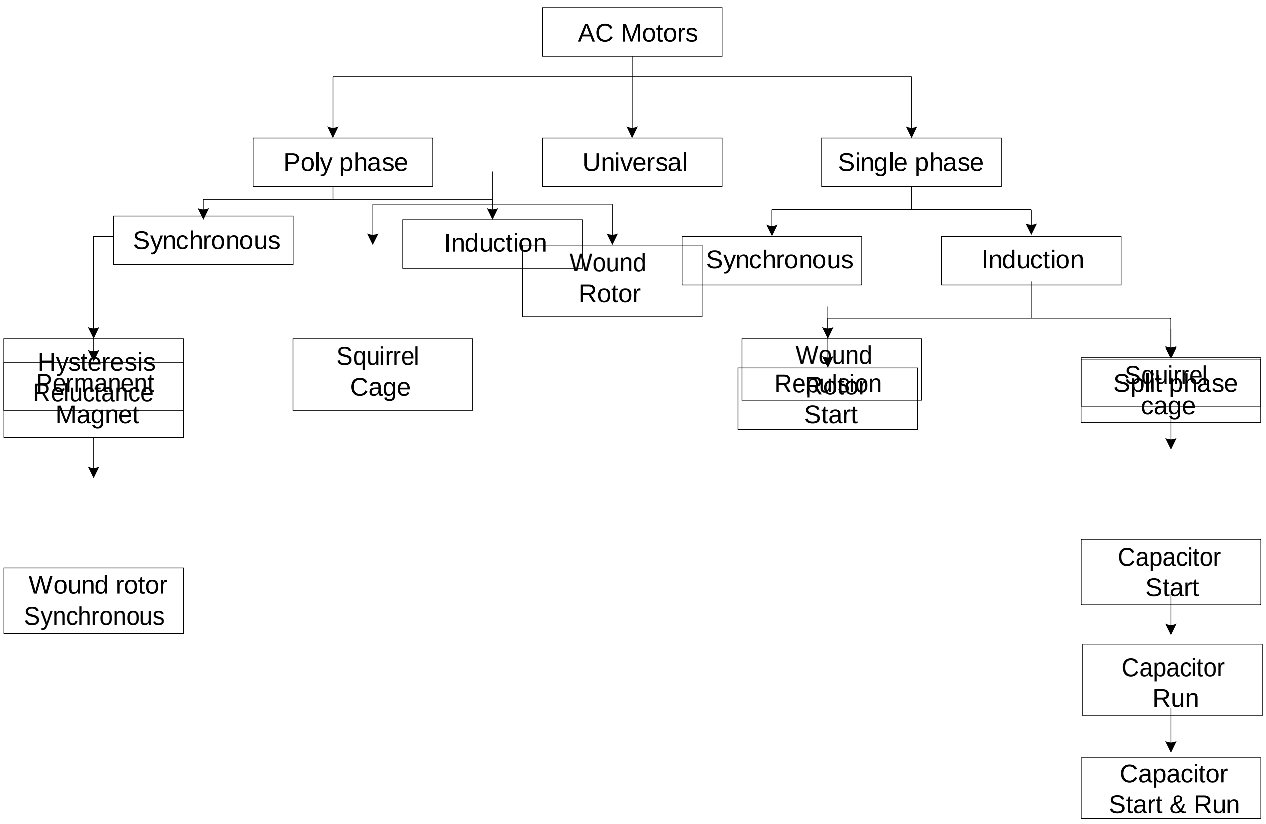

Figure 1.1 Classification of AC motors

Construction of Induction Motor

- A three phase Induction motor mainly consists of two parts called as the Stator and Rotor.

(a) Stator

- It is the stationary part of the induction motor.
- The stator is built up of high-grade alloy steel laminations to reduce eddy current losses.
- It has three main parts, outer frame, 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.

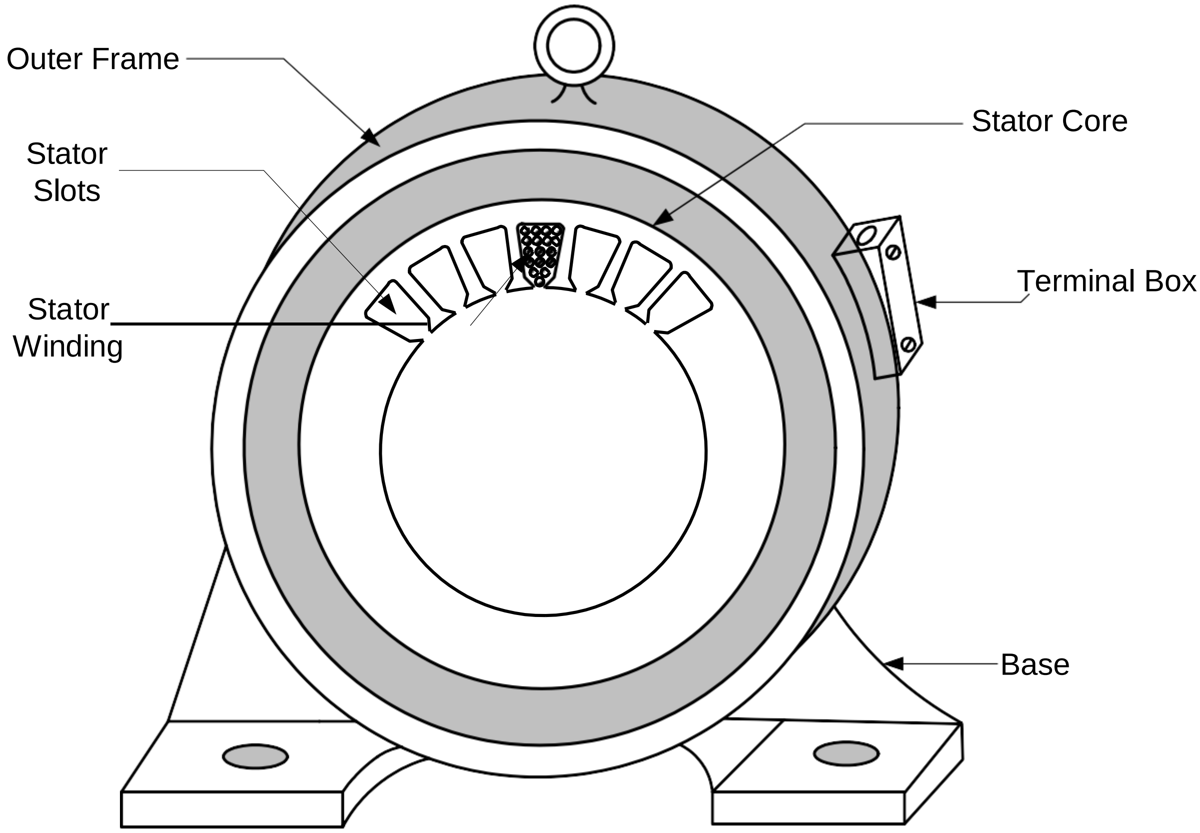

Figure 1.2Outer frame of an induction motor

- ***Stator Core***

- The core of the stator carries three phase windings which are usually supplied from a three-phase supply system.
- 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

○ ***Stator windings***

- The stator windings are housed in stator slots with double layer winding.
- These windings are distributed and are mostly short pitched.
- The short-pitched and distributed windings are effective to limit the magnitudes of the harmonics in the airgap flux. Sometimes, integral slot windings are also used.
- When rotor rotates at that time the air gap reluctance is different at different point. So, this pulsating reluctance produces pulsating exciting current, irregular torque, noise etc, to reduce this effect large number of stator slots are selected.
- But by using large number of slots results increase the manufacturing cost. So, that the number of rotor slots and stator slots are selected different and rotor slots keep skew to get uniform reluctance in the air gap.
- The air gap should be selected as small as possible to reduce magnetizing current required to set up air gap flux.
- Anyway, the stator of the motor is wound for a definite number of poles, depending on the speed of the motor.
- If the number of poles is greater, the speed of the motor will be less and if the number of poles is less than the speed will be high.
- The windings may be connected in start or delta.
- As the relationship between the speed and the pole of the motor is given as

$$N_S \propto \frac{1}{P} or\ N_S = \frac{120f}{P}$$

(b) 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 aluminum or copper.
- At the end of the rotor the conductors the short-circuited by a heavy ring of copper or aluminum.
- Now a days this type of motors are widely used in domestic as well as commercial purposes.
- This type of motors required low maintanance compare to wound rotor type motors.

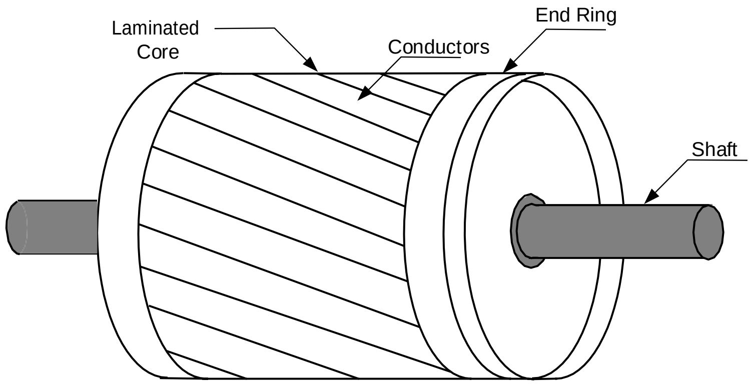

Figure 1.3 Squirrel cage rotor

- ***Wound rotor (Slip ring rotor)***

- A wound rotor is built with a polyphase distributed winding similar tothat of stator winding and wound with the same number of poles as, the stator.
- The terminals of the rotor winding are connected to insulated slip rings mounted on the shaft.
- Carbon brushes bearing on these rings make the rotor terminals available external to the motor,
- Wound-rotor induction machines are relatively uncommon, being found only in a limited number of specialized applications.
- This type of motors are widely used where *high starting torque* is required.
- The cost and size of this type motor is more and large respectively.

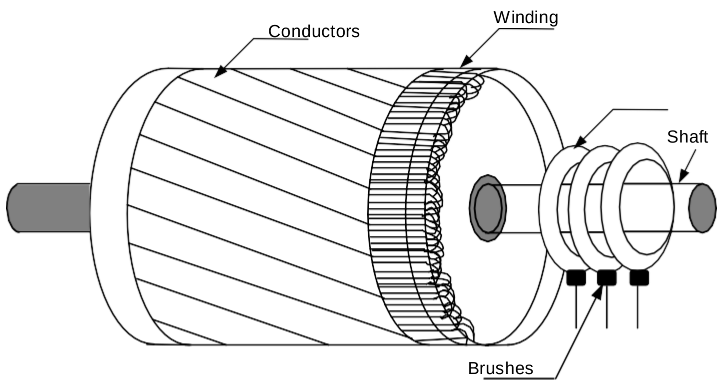

Figure 1.4 Wound rotor

Production of RMF (Rotating Magnetic Field)

- When stationary three phase winding coils are supplied by an alternating 3-phase supply then uniform Rotating Magnetic Field (or Flux) [RMF] of constant value is produced.
- The principle of a three phase, two pole stator having three identical winding coils are placed by 120^0 electrical (Space) degree apart. The flux (Sinusoidal) due to three phase windings is shown in below *Figure 1.5 (b)*
- The directions of the positive fluxes are shown individually below at different positions.

- Let us say that the maximum value of the flux due to any one of the three phases be $\emptyset_m$. The resultant flux $\emptyset_r$, at any instant is given by the resultant sum of the individual fluxes $\emptyset_1$, $\emptyset_2$ and $\emptyset_3$ due to three phases
- We have consider the 1/6th time period apart corresponding to points marked 0, 1, 2 and 3 in *Figure 1.5(a).*

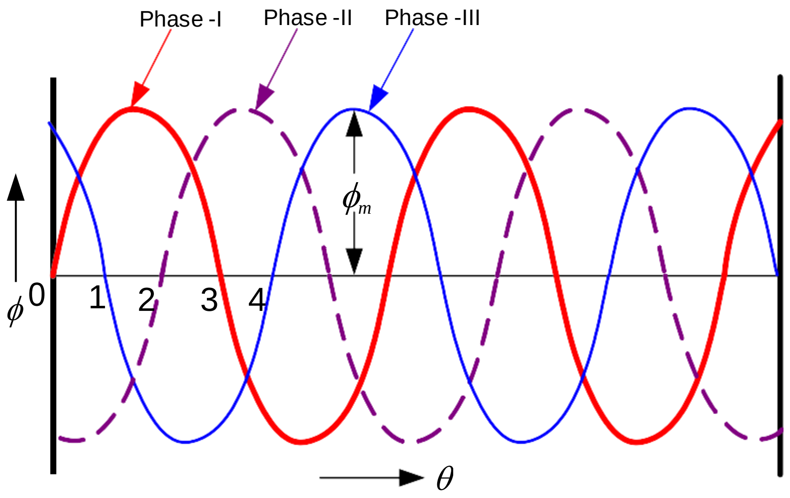

Figure 1.5 (a) Phasor representation

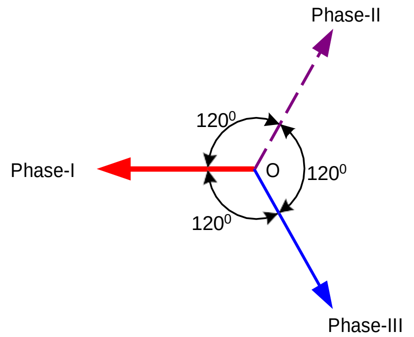

Figure 1.5 (b)

When $\theta = 0^0$ (At point 0)

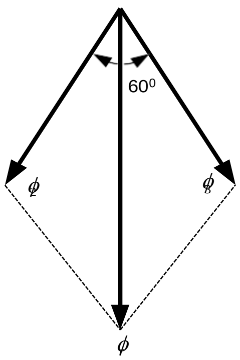

Figure 1.6

$\emptyset_1 = 0$

$$\emptyset_2 = -\frac{\sqrt{3}}{2}\emptyset_m$$

$$\emptyset_3 = \frac{\sqrt{3}}{2}\emptyset_m$$

When $\theta = 60^0$ (At point 1)

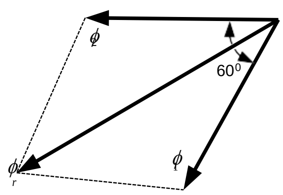

Figure 1.7

$$\emptyset_1 = \frac{\sqrt{3}}{2}\emptyset_m$$

$$\emptyset_2 = -\frac{\sqrt{3}}{2}\emptyset_m$$

$$\emptyset_3 = 0$$

When $\theta = 120^0$ (At point 2)

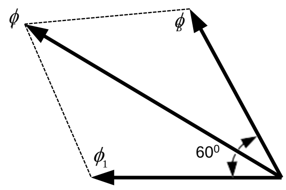

Figure 1.8

$$\emptyset_1 = \frac{\sqrt{3}}{2}\emptyset_m$$

$$\emptyset_2 = 0$$

$$\emptyset_3 = -\frac{\sqrt{3}}{2}\emptyset_m$$

When $\theta = 180^0$ (At point 3)

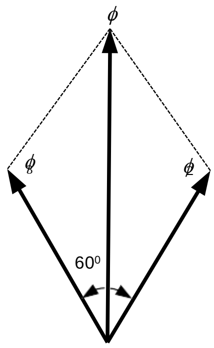

Figure 1.9

$$\emptyset_1 = 0$$

$$\emptyset_2 = \frac{\sqrt{3}}{2}\emptyset_m$$

$$\emptyset_3 = -\frac{\sqrt{3}}{2}\emptyset_m$$

When $\theta = 0^0$ (At point 0)

Resultant flux,

$$\phi_r = \sqrt{\phi_2^2 + \phi_3^2 - 2\phi_2\phi_3\cos\theta}$$

$$= \sqrt{\left(-\frac{\sqrt{3}}{2}\phi_m\right)^2 + \left(\frac{\sqrt{3}}{2}\phi_m\right)^2 - 2\left(-\frac{\sqrt{3}}{2}\phi_m\right)\left(\frac{\sqrt{3}}{2}\phi_m\right)\cos 60^0}$$

$$= \sqrt{\left[\frac{3}{4} + \frac{3}{4} + \frac{3}{2}\left(\frac{1}{2}\right)\right]\phi_m^2}$$

$$= \sqrt{\left[\frac{3+3+3}{4}\right]\phi_m^2}$$

$$= \sqrt{\left[\frac{9}{4}\right]\phi_m^2}$$

$$= \frac{3}{2}\phi_m$$

When $\theta = 60^0$ (At point 1)

Resultant flux,

$$\phi_r = \sqrt{\phi_1^2 + \phi_2^2 - 2\phi_1\phi_2\cos\theta}$$

$$= \sqrt{\left(\frac{\sqrt{3}}{2}\phi_m\right)^2 + \left(-\frac{\sqrt{3}}{2}\phi_m\right)^2 - 2\left(\frac{\sqrt{3}}{2}\phi_m\right)\left(-\frac{\sqrt{3}}{2}\phi_m\right)\cos 60^0}$$

$$= \sqrt{\left[\frac{3}{4} + \frac{3}{4} + \frac{3}{2}\left(\frac{1}{2}\right)\right]\phi_m^2}$$

$$= \sqrt{\left[\frac{3+3+3}{4}\right]\phi_m^2}$$

$$= \sqrt{\left[\frac{9}{4}\right]\phi_m^2}$$

$$= \frac{3}{2}\phi_m$$

When θ = 120⁰ (At point 2)

Resultant flux,

$$\phi_r = \sqrt{\phi_1^2 + \phi_3^2 - 2\phi_1\phi_3\cos\theta}$$

$$= \sqrt{\left(\frac{\sqrt{3}}{2}\phi_m\right)^2 + \left(-\frac{\sqrt{3}}{2}\phi_m\right)^2 - 2\left(\frac{\sqrt{3}}{2}\phi_m\right)\left(-\frac{\sqrt{3}}{2}\phi_m\right)\cos 60^0}$$

$$= \sqrt{\left[\frac{3}{4} + \frac{3}{4} + \frac{3}{2}\left(\frac{1}{2}\right)\right]\phi_m^2}$$

$$= \sqrt{\left[\frac{3+3+3}{4}\right]\phi_m^2}$$

$$= \sqrt{\left[\frac{9}{4}\right]\phi_m^2}$$

$$= \frac{3}{2}\phi_m$$

When θ = 180⁰ (At point 3)

Resultant flux,

$$\phi_r = \sqrt{\phi_2^2 + \phi_3^2 - 2\phi_1\phi_3\cos\theta}$$

$$= \sqrt{\left(\frac{\sqrt{3}}{2}\phi_m\right)^2 + \left(-\frac{\sqrt{3}}{2}\phi_m\right)^2 - 2\left(\frac{\sqrt{3}}{2}\phi_m\right)\left(-\frac{\sqrt{3}}{2}\phi_m\right)\cos 60^0}$$

$$= \sqrt{\left[\frac{3}{4} + \frac{3}{4} + \frac{3}{2}\left(\frac{1}{2}\right)\right]\phi_m^2}$$

$$= \sqrt{\left[\frac{3+3+3}{4}\right]\phi_m^2}$$

$$= \sqrt{\left[\frac{9}{4}\right]\phi_m^2}$$

$$= \frac{3}{2}\phi_m$$

Working Principle

- For simplicity, consider one conductor on the stationary rotor as shown in *Figure 1.10(a).*
- This conductor be subject to the rotating magnetic field produced when a three phase supply is connected to the three phase winding of the stator.
- Consider the rotation of the magnetic field be clockwise.
- A magnetic field moving clockwise has the effect as a conductor moving anticlockwise in a stationary field.
- According to Faraday's law of electromagnetic induction, emf will be produced in the conductor.

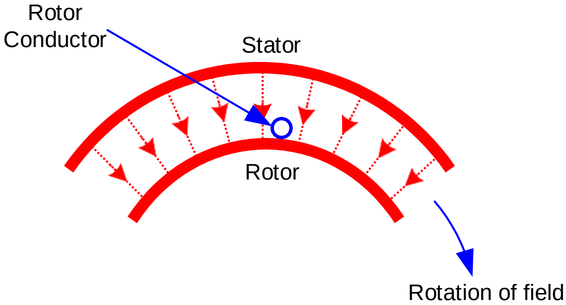

Figure 1.10(a)

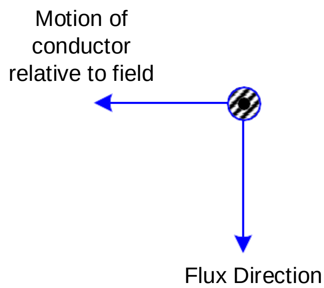

Figure 1.10 (b)

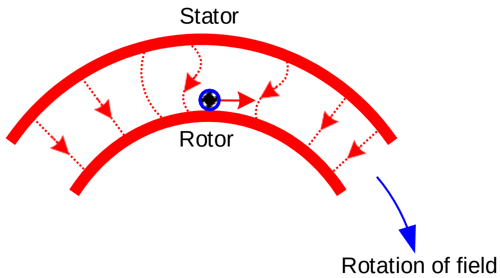

Figure 1.10 (c)

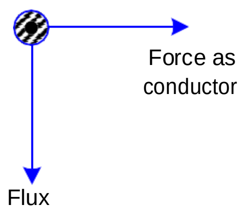

Figure 1.10(d)

- By completing the rotor circuit either using end rings or external resistances the induced emf causes current to flow in the conductor.
- By using right hand rule we can determine the direction of induced current in the conductor.
- By using right hand rule the direction of the induced current is outwards (shown as dot) in *Figure 1.10 (b).*
- The current in the rotor conductor produces its own magnetic field as shown in*Figure 1.10 (c).*
- We know that when a current carrying conductor put in a magnetic field a force is produced. This force is produced on the rotor conductor.
- The direction of this force can be calculated by using left-hand rule as shown in *Figure 1.10(d).*
- It is seen that the force acting on the conductor is in the same direction as the direction of the rotating magnetic field.
- The rotor conductor is in a slot on the circumference of the rotor, the force acts in a tangential direction to the rotor and develops a torque in a rotor.
- Similarly, torque produces in all the rotor conductors.
- Since, the rotor is free to move then it rotates in the same direction as the rotating magnetic field. Thus, three phase induction motor is self-starting motor.

Performance parameters of poly phase induction motor

Following parameters are considered as performance parameters:

(a) Slip

- An induction motor never run at synchronous speed.
- Let us consider for moment that is rotor of induction motor is rotating at synchronous speed.
- Under this condition, the rotor conductors could not cut the flux, so there is no production of generated voltage, current and torque.
- Therefore, rotor speed is slightly less than the synchronous speed. There is no relative speed between field flux and rotor speed.
- The difference between the synchronous speed and actual speed of rotor is known as Slip or Slip speed.

If N_S= Synchronous speed in r.p.m.

N= Actual speed of rotor in r.p.m.

$$Slip\ speed\ ,\ s = N_s - N$$

$$So\ that\ Slip,\ \ s = \frac{N_s - N}{N}$$

$$Percentage\ slip = \frac{N_s - N}{N} \times 100$$

- The slip at full load varies value about 5 percent for small motors to about 2 percent for large motors.

(b) Frequency of Rotor Voltage and Current

- The frequency of current and voltage in the stator is same as the supply frequency given by,

$$f = \frac{PN_s}{120}$$

- The frequency in the rotor winding is variable and depends on the difference between the synchronous speed and rotor speed.
- The rotor frequency is given by,

$$f_r = \frac{P(N_s - N)}{120}$$

$$Also,\ \frac{f_r}{f} = \frac{N_s - N}{N_s}$$

$$s = \frac{N_s - N}{N_s}$$

$$\therefore\ f_r = sf$$

Rotor current frequency = slip × supply frequency

When the rotor is stand-still, N=0

$$s = \frac{N_s - N}{N_s} = 1\ and\ f_r = f$$

When the rotor is driven at synchronous speed N_s, So, $s = 0$ and $f_r = 0$

So, frequency of rotor current varies from $s = 0$ to $s = 1$

(c) Rotor current

Rotor current at *Standstill condition*

Let,

$E_2 =$ *e.m.f. induced per phase of the stator at standstill condition.*

$R_2 =$ *resistance per phase of the rotor*

$X_2 =$ *reactance per phase of the rotor at standstill*

$= 2\pi f L_2$

$Z_2 =$ *rotor impedance per phase at standstill*

$Z_2 = R_2 + jX_2$

$I_2 =$ *rotor current per phase at standstill*

$$I_2 = \frac{E_2}{Z_2}$$

Power factor at standstill,

$$\cos\phi_2 = \frac{R_2}{Z_2} = \frac{R_2}{\sqrt{R_2^2 + X_2^2}}$$

Rotor current at slips (in running condition)

Induced e.m.f. per phase in the rotor winding at slip s is,

$E_{2s} = sE_2$

Rotor winding resistance per phase $= R_2$

Rotor winding reactance per phase at slip s,

$= 2\pi f_r L_2$

$= 2\pi (sf) L_2$

$= s(2\pi f L_2)$

$= sX_2$

Rotor impedance per phase at slip s,

$Z_{2s} = R_2 + jsX_2$

Rotor current per phase,

$$I_{2s} = \frac{sE_2}{Z_{2s}}$$

$$= \frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

$$= \frac{E_2}{\sqrt{\left[\frac{R_2}{s}\right]^2 + X_2^2}}$$

Power factor at slip s,

$$\cos\phi_{2s} = \frac{R_2}{Z_{2s}} = \frac{R_2}{\sqrt{\left[\frac{R_2}{s}\right]^2 + X_2^2}}$$

Equivalent Circuit of Induction motor

- **Why equivalent circuit?**

- The behavior of three phase induction is very complicated, so it it required to represent the machine as an equivalent circuit in various operating condition.
- Induction motor works on the principle of transformer so it is called the rotating transformer.
- The equivalent circuit of any machine presents the various parameter of the machine such as its copper losses and core 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.

(a) Exact Equivalent Circuit

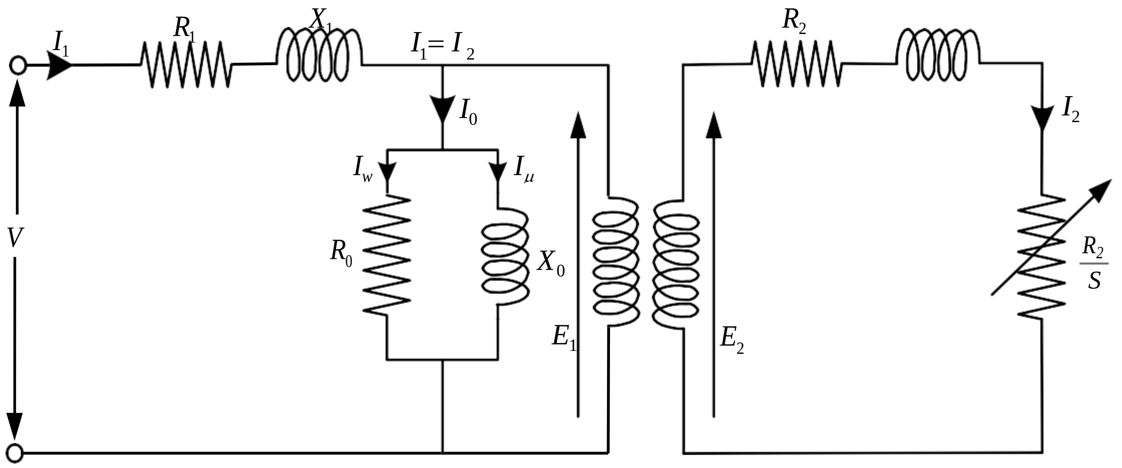

Figure 1.11 Exact equivalent circuit

Here,

R_1 = *stator winding resistance*

X_1 = *stator winding reactance*

R_0 = *the core loss component*

X_0 = *the magnetizing reactance of the winding*

R_2 / s = *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 –

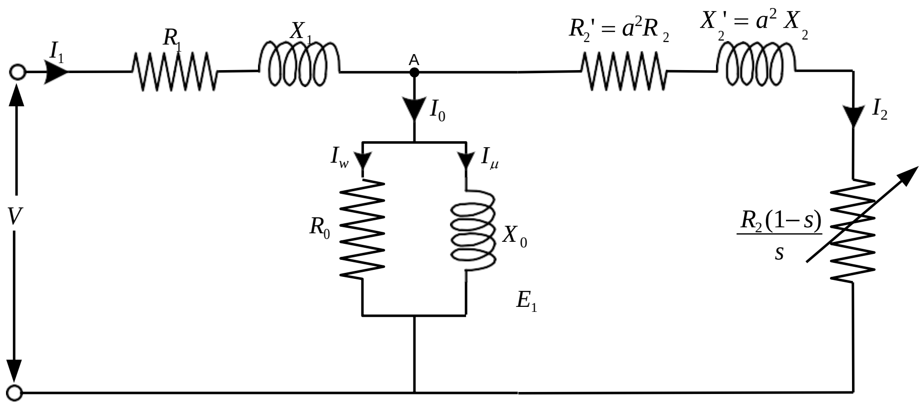

Figure 1.12 Equivalent circuit referred to stator side

Here,

R_2' = rotor winding resistancereferred to stator

X_2' = rotor winding reactance referred to stator

$\frac{R_2(1-s)}{s}$ = the resistance which presents the power which is converted to mechanical power output or useful power.

a = Effective turns ratio of inductor or motor.

(b) Approximate Equivalent Circuit

- The approximate equivalent circuit is drawn just to simplify our calculation by deleting node-Afrom given in *Figure. 1.12.*
- The shunt branch is shifted towards the primary side.

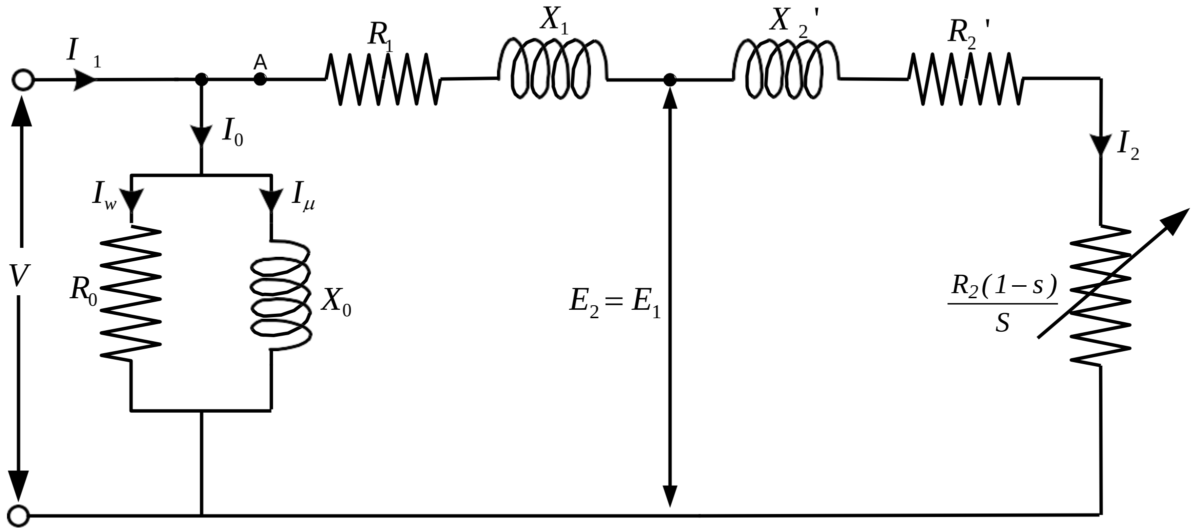

Figure 1.13Approximate equivalent circuit

- This has been done as the voltage drop between the stator resistance and reactance is less and there is not much difference between the supply voltage and the induced voltage. However, this is not appropriate due to following reasons:
- The magnetic circuit of induction motor has an air gap so exciting current is larger compared to transformer so exact equivalent circuit should be used.
- The rotor and stator inductance is larger in induction motor.
- In induction motor, we use distributed windings.
  This model can be used if approximate analysis has to be done for large motors. For smaller motors, we cannot use this.

○ **Power Relation of Equivalent Circuit**

- Input power to stator- *3* $VI_1cos\theta$*.* Where, *V*is the stator voltage applied. I_1 is the current drawn by the stator winding,$cos\theta$is the power factor.
- Rotor input = Power input- Stator copper and iron losses.
- Rotor Copper loss = Slip × power input to the rotor.
- Developed Power = (1 - s) × Rotor input power.

Induction motor as a Transformer and Vector Diagram

- We know that induction motor is a rotating transformer.
- Its stator works as a primary and rotor works as a secondary.
- The energy conversion takes place through induction.

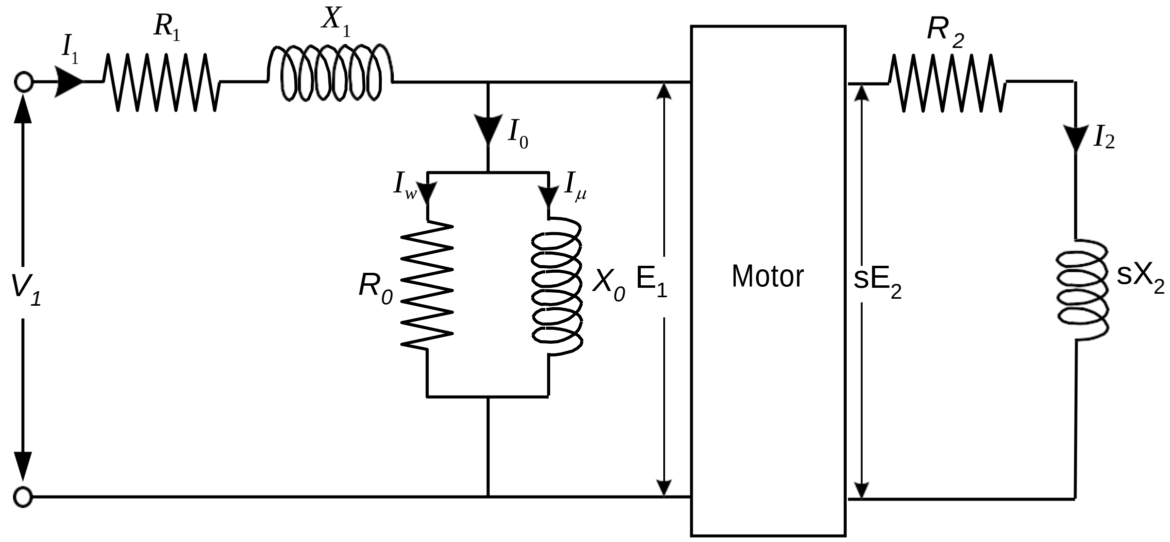

Figure 1.19 Equivalent circuit when induction motor as a transformer

Vector Diagram

- The vector diagram is also same for the transformer. It is shown in *Figure 1.20.*

$$V_1 = E_1 + I_1(R_1 + jX_1) \text{ and } E_2 = I_2(R_2 + jX_2)$$

However there some points of difference between the transformer and induction motor are:

- The magnetic leakage and leakage reactance of the stator and rotor of the induction motor are high as compare to transformer.
- Induction motor has an airgap so the magnetizing current in the motor is higher than transformer.
- Because of distributed winding in motor, the ratio of stator and rotor current is not equal to the ratio of the turns per phase in the rotor and the stator.

* Due to the rotating parts in induction motor losses are more compare to transformer.

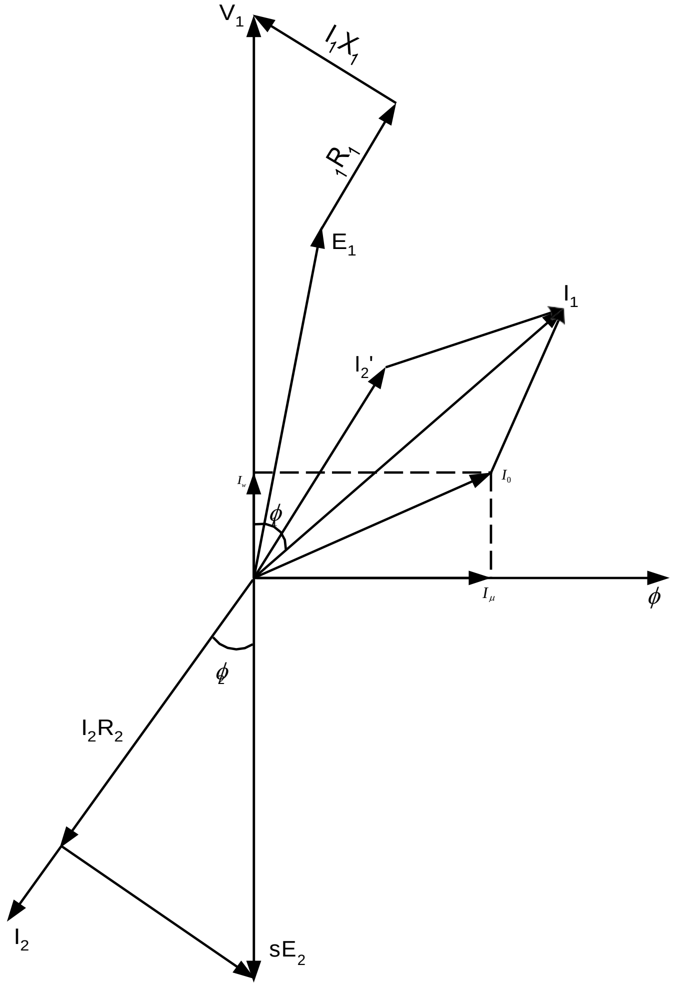

Figure 1.20 Vector diagram of induction motor

Effects of Harmonics in induction motor

* The induction motor performance is affected by the harmonics in the time variation of the impressed voltage. But its effect on the performance of the motor is not predominant hence it is not considered here.
* The torque-slip characteristics can be obtained when the space distribution of flux wave along the air gap periphery is sinusoidal.
* But the air gap flux is not purely sinusoidal as it contains odd harmonics (5^{th}, 7^{th}, 11^{th} etc). Hence at low speeds, the torque-slip characteristic not become smooth.
* The distribution of stator winding and variation of air gap reluctance due to stator and rotor slots are main causes of air gap flux harmonics.
* The harmonics caused due to variation of air gap reluctance are called tooth or slot harmonics.
* Due to these harmonics produced in air gap flux, unwanted torque are developed along with vibration and noise.
* Now eventhough stator currents are sinusoidal, the stator mmf is not sinusoidal as stator winding has the number of slots not more than 3 to 4 per phase.

- If carry out analysis of stator mmf with the help of Fourier series it can be seen that in addition to fundamental wave it contains odd harmonics mmf waves.
- The third harmonic flux waves produced by each of the three phases neutralize each other as it differs in time phase by 120^{o}.

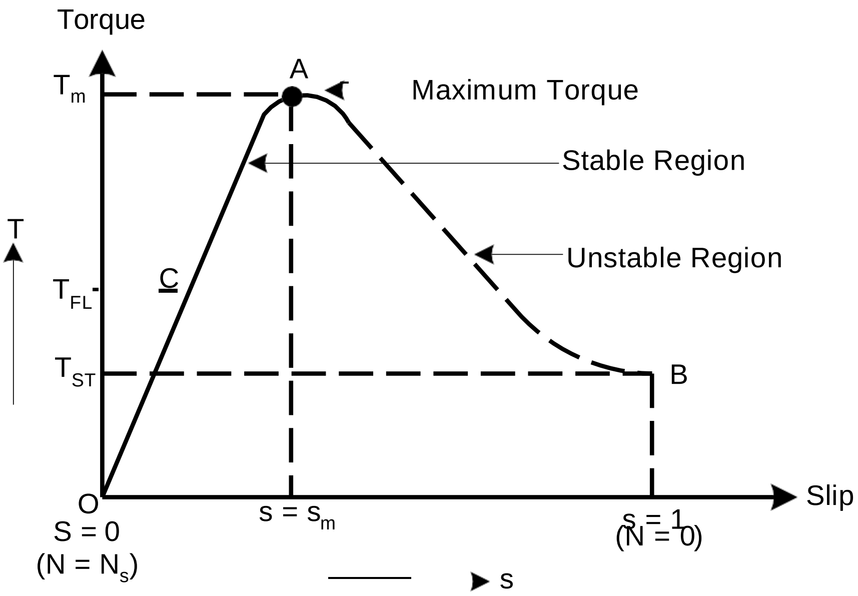

Figure 1.30 Torque –speed characteristics

- Thus air gap flux does not contain third harmonics and its multiplies.
- The fundamental mmf wave produces flux which rotates at synchronous speed which given as $N_s = \frac{2f}{P}$ rps where *f* is supply frequency and *P* is number of poles. Similarly fifth harmonic mmf wave produces flux which rotates at $\frac{2f}{5P} = \frac{N_s}{5}$ rps and in direction opposite to the fundamental mmf wave.
- The seven harmonic mmf produces flux which rotates at $\frac{N_s}{7}$ rps and in the direction of fundamental mmf wave.
- Thus it can be seen that harmonic mmf wave produces flux which rotates at *1/K* times the fundamental speed and in the direction of fundamental wave if *K = 6m + 1* and in the reversed direction if *K = 6m - 1* where m is any integer.
- The most important and predominant harmonics whose effects must be studied are 5th and 7th harmonics.
- The electromagnetic torque that is developed in the induction motor is because of zero relative speed between stator and rotor fields.
- This fact can be explained as follows:
- When rotor is revolving in the same direction of rotation as the stator field, the frequency of rotor currents is sf and the rotor field produced will have speed of sN_s rpm with respect to rotor in the forward direction.
- But there is mechanical rotation of rotor at n rpm which is superimposed on this. The speed of rotor field in space is thus given by sum of these speeds

$$sN_s + N = sN_s + N_s(1 - s) = N_s$$

- The stator and rotor fields are thus stationary with respect to each other which produces a steady torque maintaining the rotation.
- This torque existing at any mechanical speed n other than synchronous speed is called synchronous torque.
- The fifth harmonic field rotates at $\frac{N_s}{5}$ rps and in a direction opposite to direction of rotor. Therefore slip of rotor with respect to fifth harmonic field speed is

$$S_5 = \frac{N_{s(5^{th}\ harmonic)} - N}{N_{s(5^{th}\ harmonic)}} \quad ,where\ N\ is\ rotor\ speed$$

$$= \frac{-\frac{N_s}{5} - N}{-\frac{N_s}{5}}$$

$$= \frac{-\frac{N_s}{5} - N_s(1-s)}{-\frac{N_s}{5}}$$

$$= 1 + 5(1-s)$$

$$= 6 - 5s$$

- Here $-\frac{N_s}{5}$ represents fifth harmonic field rotating opposite to the rotor.
- The frequency of rotor currents induced by fifth harmonic rotating field is

$$f_{r(\,fifth\ harmonic)} = s_5 \times Stator\ frequency$$

$$= (6 - 5s) \times f$$

- Now speed of fifth harmonic rotor field with respect to rotor is given by

$$\frac{2(f_{r(\,fifth\ harmonic)})}{5P} = \frac{2}{5P} f(6-5s)$$

$$= \frac{N_s}{5}(6-5s)$$

- Now, speed of fifth harmonic rotor field with respect to stator

$$= Speed\ of\ fifth\ harmonic\ rotor\ field\ w.r.t.\ rotor + \quad Rotor\ Speed$$

$$= \frac{-N_s}{5}(6-5s) + N$$

$$= -\frac{6}{5}N_s + sN_s + N_s(1-s) - \frac{N_s}{5} \quad rps$$

- Negative sign is used before $N_s / 5\,(6 - 5s)$ which indicates 5th harmonic field rotates opposite to rotor movement.

- Thus it can be seen that speed of fifth harmonic stator field and rotor field is equal and relative speed between the two is zero.
- Thus it produces 5th harmonic induction motor torque similar to torque produced by fundamental component.
- Similar analysis can be made on 7th harmonic to show 7th harmonic torque produced similar to fundamental one.
- So, each space harmonic can be considered to produces its own asynchronous torque.
- The induction motor can be considered as equivalent to number of induction motors in series having poles equal to number of harmonics multiplied by number of poles.
- The torque produced by fundamental component and the harmonic are shown in the *Figure 1.37.*

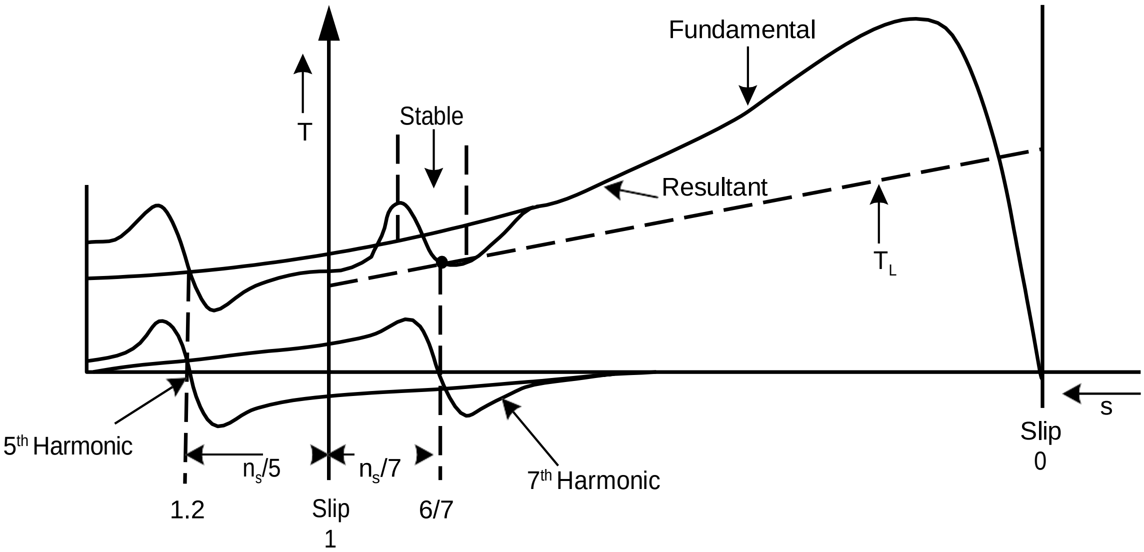

Figure 1.31 Harmonics in induction motor

Crawling and Cogging

(a) Crawling

- *Sometimes, squirrel cage induction motors exhibits a tendency to run at very slow speeds (as low as one-seventh of their synchronous speed). This phenomenon is called as **crawling** of an induction motor.*
- This action is due to the fact that, flux wave produced by a stator winding is not purely sine wave.
- It is a complex wave consisting a fundamental wave and odd harmonics like 3rd, 5th, 7th etc.
- The fundamental wave revolves synchronously at synchronous speed N_s whereas 3rd, 5th, 7th harmonics may rotate in forward or backward direction at $\frac{N_s}{3}, \frac{N_s}{5}, \frac{N_s}{7}$ speed respectively.
- Hence, harmonic torques are also developed in addition with fundamental torque.

- The 3rd harmonics are absent in a balanced 3-phase system. So 3rd harmonics do not produce rotating field and torque.
- The total motor torque now consist three components as:
  - (i) the fundamental torque withsynchronous speed N_s,
  - (ii) 5th harmonic torque with synchronous speed $\frac{N_s}{5}$,
  - *(iii)* 7th harmonic torque with synchronous speed $\frac{N_s}{7}$ (provided that higher harmonics are neglected).

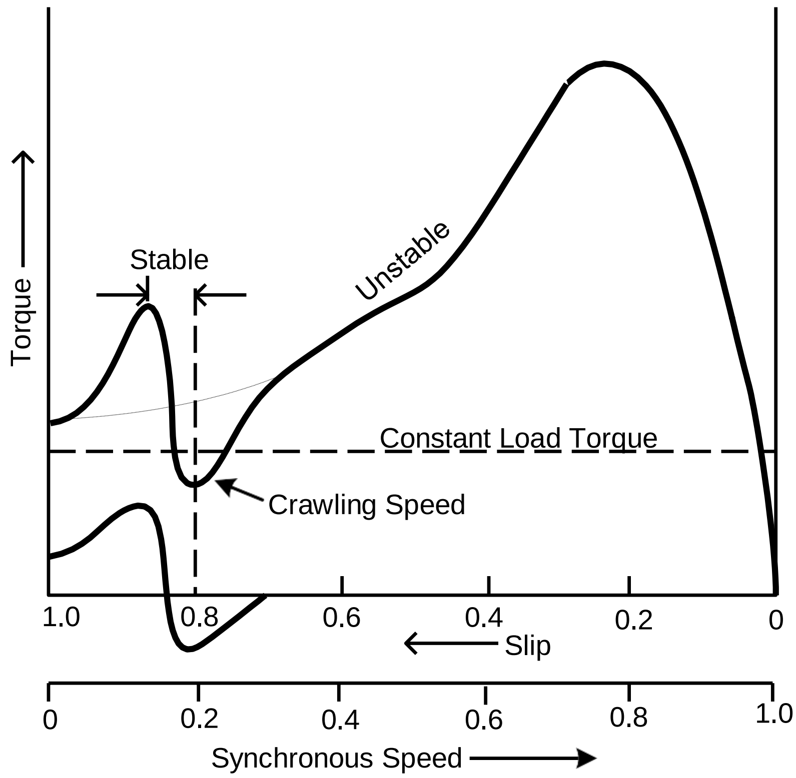

Figure 1.32Crawling in induction motor

- Now, 5th harmonic currents will have phase difference of 5 × 120 = 600° =2 × 360 – 120 = –120°. Hence the revolving speed set up will be in reverse direction with speed $\frac{N_s}{5}$.
- The small amount of 5th harmonic torque produces breaking action and can be neglected.

- The 7th harmonic currents will have phase difference of 7 × 120 = 840° = 2 × 360 +120 = + 120°.
- Hence they will set up rotating field in forward direction with synchronous speed equal to $\frac{N_s}{7}$.
- If we neglect all the higher harmonics, the resultant torque will be equal to sum of fundamental torque and 7th harmonic torque.
- The 7th harmonic torque reaches its maximum positive value just before1/7 thof N_s.
- If the mechanical load on the shaft involves constant load torque, the torque developed by the motor may fall below this load torque. In this case, motor will not accelerate upto its normal speed, but it will run at a speed which is nearly 1/7th of its normal speed. This phenomenon is called as ***crawling*** in induction motors

(b) Cogging (Magnetic locking or teeth locking)

- This characteristic of induction motor comes into picture when motor refuses to start at all.
- Sometimes it happens because of low supply voltage. But the main reason for starting problem in the motor is because of cogging in which the slots of the stator get locked up with the rotor slots.
- As we know that there is series of slots in the stator and rotor of the induction motor.
- When the slots of the rotor are equal in number with slots in the stator, they align themselves in such way that both face to each other and at this stage the reluctance of the magnetic path is minimum and motor refuse to start.
- This characteristic of the induction motor is called ***cogging***.
- One more reason for cogging, if the harmonic frequencies coincide with the slot frequency due to the harmonics present in the supply voltage then it causes torque modulation. As a result, of it cogging occurs. This characteristic is also known as ***magnetic teeth locking*** of the induction motor.

- ***Methods to eliminate cogging***
- The number of slots in rotor should not be equal to the number of slots in the stator.
- Skewing of the rotor slots, that means the stack of the rotor is arranged in such a way that it angled with the axis of the rotation.

Linear induction motor (LIM)

- Linear Induction motor is basically a special purpose motor that is in use to achieve linear motion rather than rotational motion as in the case of conventional motors.
- This is quite an engineering marvel, to convert a general motor for a special purpose with more or less similar working principle, thus enhancing its versatility of operation first consider its construction.

Construction

- Construction wise a LIM is similar to three phase induction motor in more ways than one as it has been shown in the *Figure 1.36* below.

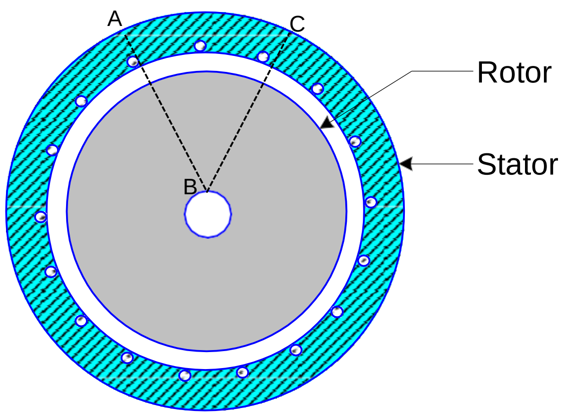

Figure 1.35Rotational induction motor

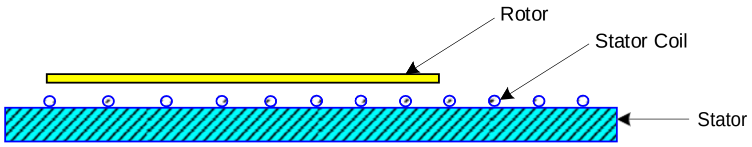

Figure 1.32 Linear induction motor

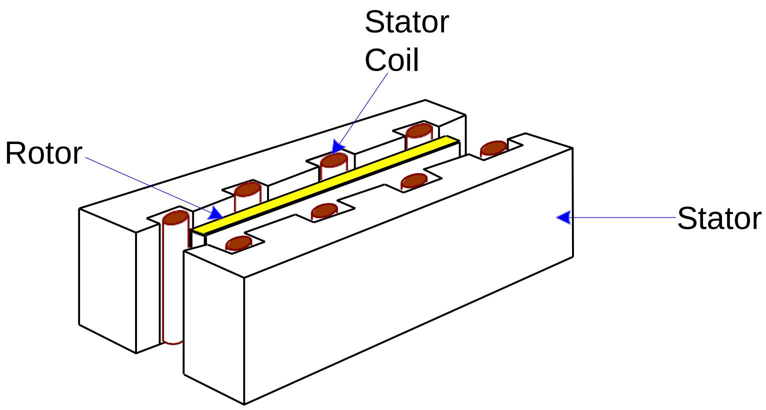

Figure 1.36 Linear induction motor 3-D view

- In LIM stator and rotor are called primary and secondary respectively.

- If the stator of the poly phase induction motor shown in the *Figure 1.35*is cut along the section and laid on a flat surface, then it forms the primary of the LIM housing the field system, and consequently the rotor forms the secondary consisting of flat aluminum conductors with ferromagnetic core for effective flux linkage.
- It has a primary winding on either side of the secondary, for more effective utilization of the induced flux from both sides.

Working of LIM

- When the primary of an LIM is excited by a balanced three phase power supply, a traveling flux is induced in the primary instead of rotating 3 φ flux, which will travel along the entire length of the primary.
- Electric current is induced into the aluminum conductors or the secondary due to the relative motion between the traveling flux and the conductors.
- This induced current interacts with the traveling flux wave to produce linear force or thrust F.
- If the secondary is fixed and the primary is free to move, the force will move the primary in the direction of the force, resulting in the required rectilinear motion.
- When supply is given, the synchronous speed of the field is given by the equation:

$$N_s = \frac{120\,f}{p}$$

- Where, f is supply frequency in Hz, and p = number of poles, ns is the synchronous speed of the rotation of magnetic field in rps.
- The developed field will results in a linear traveling field, the velocity of which is given by the equation,

$$V_s = 2\tau f \;\; m / Sec$$

- Where, Vs is velocity of the linear traveling field, and τ is the pole pitch.
- For a slip of s, the speed of the LIM is given by,

$$V = (1 - s)V_s$$

- **Applications of LIM**

- Automatic sliding doors in electric trains.
- Mechanical handling equipment, such as propulsion of a train of tubs along a certain route.
- Metallic conveyor belts.
- Pumping of liquid metal, material handling in cranes, etc.

- **Advantages of LIM**

- It has no rotating part so it gives low mechanical loss.
- It is simple and rugged in construction.
- It is more efficient compare to conventional motor.
- It has lower initial cost.
- It gives higher speed.

- **Disadvantages of LIM**

- Capital cost is very high because rail has to be installed for its operation.
- The three phase collector system is required for LIM is complicated.
- The maintenance of LIM is not easy.
- Power factor is very low.
- Draws large magnetizing current due to large airgap.

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MODULE-2
PERFORMANCE OF INDUCTION MOTORS

Following parameters are considered as performance parameters:

Torque

- Basic Principle of motor is to convert electrical power into mechanical power. So, that induced torque (electromechanical torque or developed torque) in induction motor depends on the rotor current, rotor power factor and rotating flux.
- The torque is given by,

$$T_{ind} \propto \phi I_2 \cos\phi_2$$

Where,

$\phi =$ *Rotating flux*

$I_2 =$ *Rotor current per phase*

$\cos\phi_2 =$ *Rotor power factor*

Now, rotor emf per phase at standstill,

$$E_2 \propto \phi_2$$

$$T_{ind} \propto E_2 I_2 \cos\phi_2$$

or

$$T_{ind} = kE_2 I_2 \cos\phi_2, \quad \text{(Where k is constant)}$$

By putting the value of I_2 *and* $\cos f_2$, *we get,*

$$T_{ind} = kE_2 \times \left[\frac{sE_2}{Z_s}\right]\left[\frac{R_2}{Z_s}\right]$$

$$= kE_2 \times \left[\frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}}\right]\left[\frac{R_2}{\sqrt{R_2^2 + (sX_2)^2}}\right]$$

$$T_{ind} = \frac{ksE_2^2 R_2}{R_2^2 + (sX_2)^2} \quad N \cdot m \quad \text{...(1.1)}$$

Case-I Starting torque

The torque developed by motor during starting period is called starting torque.

At the time of starting induction motor has slip=1.

Therefore, starting torque of induction motor can be obtained by putting slip=1 in torque equation.

To get maximum starting torque, by differentiating T_{st} w.r.t. R_2 and by putting $\frac{dT_{st}}{dR_2} = 0$.

$$T_{st} = \frac{kR_2}{R_2^2 + X_2^2} \quad \text{(Assuming Supply voltage V is constant)}$$

$$\frac{dT_{st}}{dR_2} = k\left[\frac{1}{R_2^2 + X_2^2} - \frac{R_2(2R_2)}{\left(R_2^2 + X_2^2\right)^2}\right] = 0$$

$$\frac{1}{R_2^2 + X_2^2} = \frac{2R_2^2}{\left(R_2^2 + X_2^2\right)^2}$$

$$R_2^2 + X_2^2 = 2R_2^2$$

$$R_2^2 = X_2^2$$

$$R_2 = X_2$$

So, the starting torque of an induction motor will be maximum when,

Rotor circuit resistance/phase = Standstill rotor reactance/phase.

Generally the rotor resistance is not more than 1 to 2 % of its leakage reactance for higher efficiency.

To get the high starting torque, extra resistance is added in the rotor circuit at the starting time and cut slowly as motor get speed.

Case-II Running torque

The torque developed by the motor during running condition is called running torque.

At the time of running, motor slip = *s*

So, the running torque of an induction motor at slip s,

$$T_{run} = \frac{ksR_2E_2^2}{R_2^2 + (sX_2)^2} \quad (N \cdot m) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1.2)$$

Now, torque will be the maximum if,

$$\frac{sR_2}{R_2^2 + s^2X_2^2} \text{ or } \frac{R_2}{\frac{R_2^2}{s} + sX_2^2} \text{ or } \frac{R_2}{\left\{\frac{R_2}{\sqrt{s}} - X_2\sqrt{s}\right\}^2 + 2R_2X_2} \text{ is Zero.}$$

The torque will be maximum when right hand side of the *equation 1.2* is maximum which is possible when $\frac{R_2}{s} - X_2 s = 0$

$$\text{So, } R_2 = sX_2 \text{ or } s = \frac{R_2}{X_2}$$

Therefore, induced torque becomes maximum when rotor resistance per phase is equal to the rotor reactance per phase under running condition.

By putting the $R_2 = sX_2$ *in the torque equation* 1.2, *we get*

$$T_{max} = \frac{ksR_2 E_2^2}{R_2^2 + R_2^2} = \frac{ksE_2^2}{2R_2} = \frac{kE_2^2}{2X_2} \quad \text{...(1.3)}$$

The above *equation 1.3* shows that the torque is independent of the rotor resistance.

If s_{max} is the value of slip at which the torque is obtained, then $s_{max} = \frac{R_2}{X_2}$

Hence, the speed of the motor at maximum torque is given by,

$$N_m = (1 - s_{max}) N_s$$

- **Relation between starting torque and maximum torque**

  By putting the value of starting torque *equation 1.1* and maximum torque *equation 1.3*, we get

$$\frac{T_{st}}{T_{max}} = \frac{kR_2 E_2^2}{R_2^2 + X_2^2} \times \frac{2sX_2}{ksE_2^2} = \frac{2R_2 X_2}{R_2^2 + X_2^2}$$

Deviding the numerator and denominator by X_2^2,

$$\frac{T_{st}}{T_{max}} = \frac{\frac{2R_2 X_2}{X_2^2}}{\frac{R_2^2 + X_2^2}{X_2^2}} = \frac{\frac{2R_2}{X_2}}{\left(\frac{R_2}{X_2}\right)^2 + 1}$$

The slip at which maximum torque occurs is given as s_{max},

$$s_{max} = \frac{R_2}{X_2}$$

$$So, \ \frac{T_{st}}{T_{max}} = \frac{2s_{max}}{s_{max}^2 + 1}$$

- **Relation between Full load torque and maximum torque**

  Similarly,

  Full load torque,

$$T_f = \frac{ksR_2E_2^2}{R_2^2 + s^2X_2^2}$$

and

$$\frac{T_f}{T_{max}} = \frac{ksR_2E_2^2}{R_2^2 + (sX_2)^2} \times \frac{2sX_2}{ksE_2^2}$$

$$= \frac{sR_2 2X_2}{R_2^2 + (sX_2)^2}$$

Deviding the numerator and denominator by X_2^2,

$$\frac{T_f}{T_{max}} = \frac{\frac{2sR_2X_2}{X_2^2}}{\frac{R_2^2 + (sX_2)^2}{X_2^2}}$$

$$\frac{T_f}{T_{max}} = \frac{2s\,s_{max}}{s_{max}^2 + s^2}$$

Effect of change of supply voltage

We know that at the time of starting,

$$T_{st} = \frac{kR_2E_2^2}{R_2^2 + X_2^2}$$

Since, $E_2 \infty V$

$$\therefore \; T_{st} = \frac{k_2R_2V_2^2}{R_2^2 + X_2^2}$$

$\left(\textit{Where } k_2 \textit{ is the another constant}\right)$

$$\therefore T_{st} \propto V_2^2$$

Equivalent Circuit of Induction motor

- **Why equivalent circuit?**

- The behavior of three phase induction is very complicated, so it it required to represent the machine as an equivalent circuit in various operating condition.
- Induction motor works on the principle of transformer so it is called the rotating transformer.
- The equivalent circuit of any machine presents the various parameter of the machine such as its copper losses and core 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.

(c) Exact Equivalent Circuit

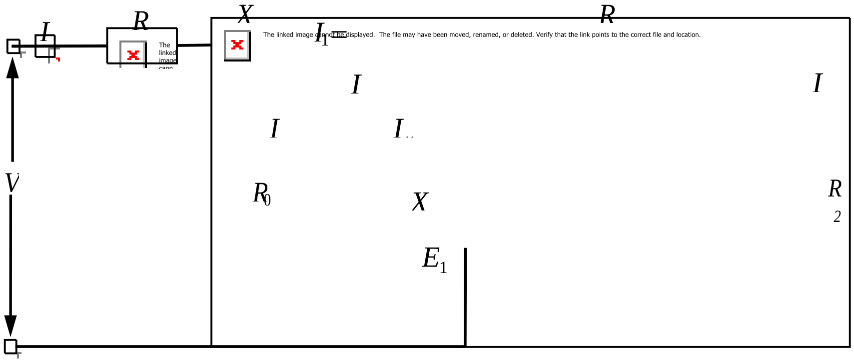


Figure 1.11 Exact equivalent circuit

Here,

R_1 = *stator winding resistance*

X_1 = *stator winding reactance*

R_0 = *the core loss component*

X_0 = *the magnetizing reactance of the winding*

R_2 / s = *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 –

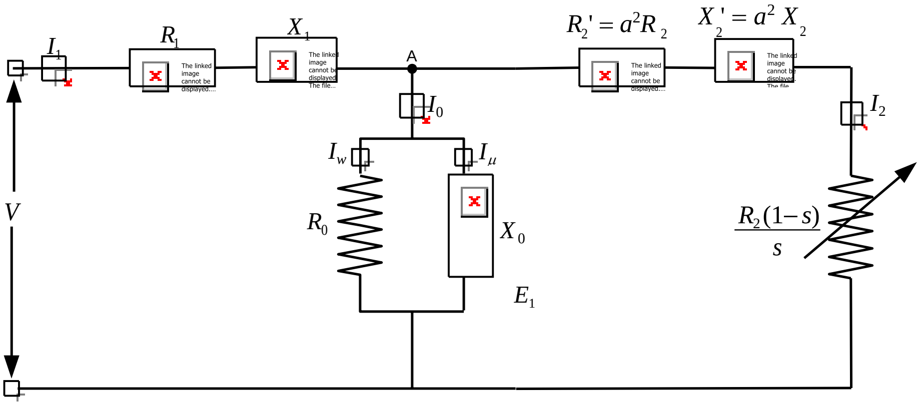


Figure 1.12 Equivalent circuit referred to stator side

Here,

R_2' = rotor winding resistancereferred to stator

X_2' = rotor winding reactance referred to stator

$\frac{R_2(1-s)}{s}$ = the resistance which presents the power which is converted to mechanical power output or useful power.

a = Effective turns ratio of inductor or motor.

(d) Approximate Equivalent Circuit

- The approximate equivalent circuit is drawn just to simplify our calculation by deleting node-Afrom given in *Figure. 1.12.*
- The shunt branch is shifted towards the primary side.

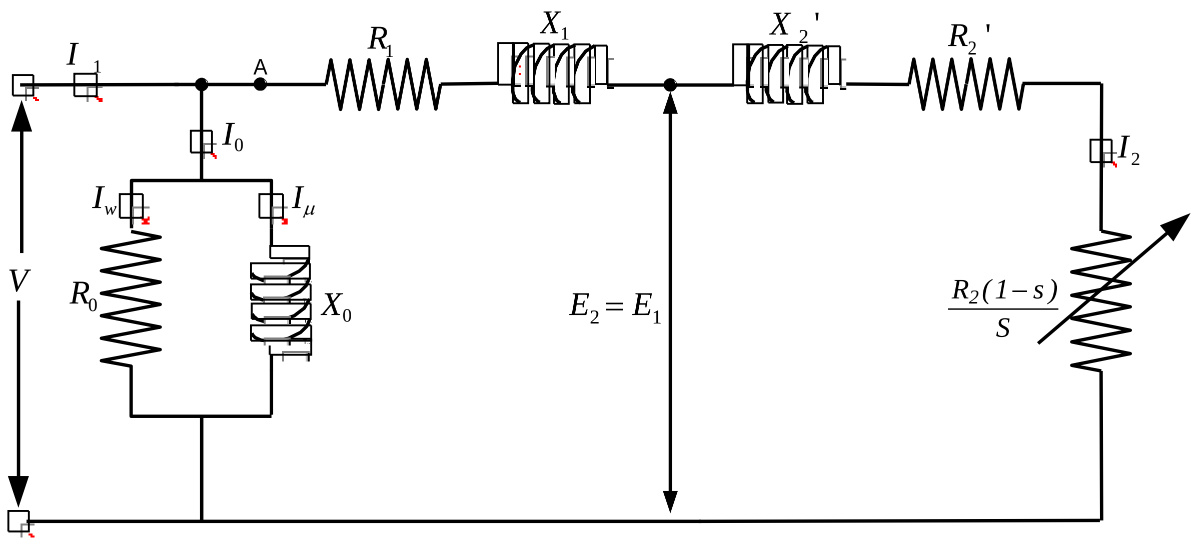


Figure 1.13Approximate equivalent circuit

- This has been done as the voltage drop between the stator resistance and reactance is less and there is not much difference between the supply voltage and the induced voltage. However, this is not appropriate due to following reasons:
- The magnetic circuit of induction motor has an air gap so exciting current is larger compared to transformer so exact equivalent circuit should be used.
- The rotor and stator inductance is larger in induction motor.
- In induction motor, we use distributed windings.
  This model can be used if approximate analysis has to be done for large motors. For smaller motors, we cannot use this.

○ **Power Relation of Equivalent Circuit**

- Input power to stator- *3* $VI_1\cos\theta$. Where, *V*is the stator voltage applied. I_1 is the current drawn by the stator winding,$\cos\theta$is the power factor.
- Rotor input = Power input- Stator copper and iron losses.
- Rotor Copper loss = Slip × power input to the rotor.
- Developed Power = (1 - s) × Rotor input power.

No-Load and blocked rotor test

(a) No-Load Test

- The test is similar to the open circuit test on a transformer.
- When motor running at no load, total input power is equal to constant iron loss, friction and windage losses of the motor that means by this method we can calculate the constant losses of induction motor.

- In this test motor runs at no-load means it is uncoupled from mechanical load and motor stator is supplied with rated voltage.
- The input power measured by the two wattmeter method.

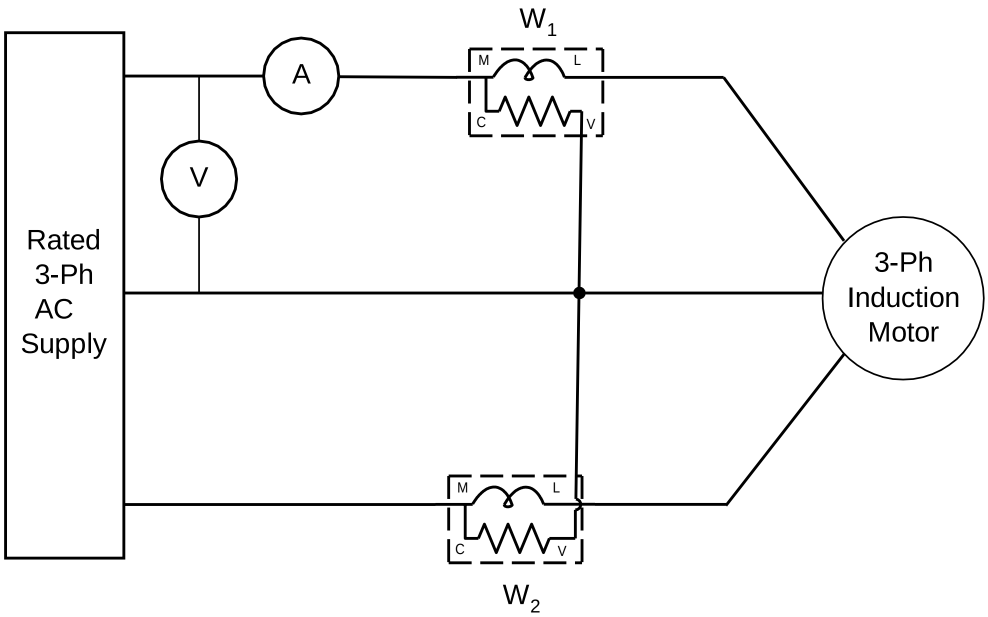


Figure 1.14 No-load test on 3- phase induction motor

- The ammeter measures the no-load current and voltmeter measures the supply voltage.
- No-load current is about 50% of the full load current, due to airgap. So, stator copper loss at no-load needs to be accounted.

$$P_{const} = P_i + P_{cu} + P_{fw} = P_1 + P_2 = \text{Sum of two wattmeter readings}$$

- Generally, the power factor of the induction motor under no-load condition is less than 0.5 at that time one wattmeter shows negative reading.
- After reverse the terminal of current coil of wattmeter and then take the reading of wattmeter.
  In this test the following parameters can be calculated.

$V_0 = \textit{Line voltage}$

$I_0 = \text{Line } \textit{current}$

$\mathrm{P}_i = \textit{Core loss}$

$\mathrm{P}_{cu} = \textit{Copper loss}$

$\mathrm{P}_{fw} = \textit{Friction and windage loss}$

$\mathrm{P}_1, \mathrm{P}_2 = \mathrm{Re}\ \textit{adings of wattmeter at no} - \textit{load}$

$\mathrm{P}_1 + \mathrm{P}_2 = \sqrt{3} V_0 I_0 \cos\phi_0$

$$\cos\phi_0 = \frac{P_1 + P_2}{V_0 I_0}$$

$$I_\mu = I_0 \sin\phi_0$$

$$I_w = I_0 \cos\phi_0$$

$$R_0 = \frac{V_0}{I_w}$$

$$X_0 = \frac{V_0}{I_\mu}$$

- ***Separation of losses***

- Friction and Windage loss can be separated from the Constant losses P_{const}.
- A number of readings of P_{const} at no-load is taken at different stator applied voltages from rated to breakdown value at rated frequency.
- The iron losses are the square of the flux density and therefore the applied voltage.
- The curve can be extended at left O cut the vertical axis at A.
- At vertical axis *V=0* and hence intercept OA represents the voltage independent loss, that is the loss due to friction and windage loss.
- Consider the following figure for separation of friction and windage losses.

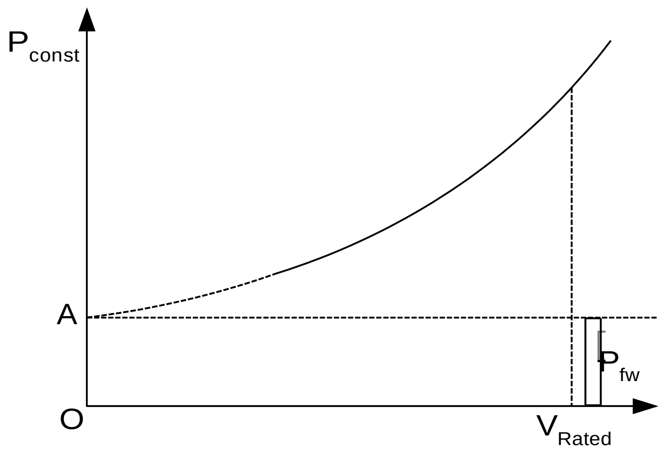


Figure 1.15Separation of friction and windage loss

(b) Blocked Rotor Test (Short Circuit Test)

- As the name of the test specifies the rotor of induction motor is blocked by external means so that it cannot rotate.
- The blocked rotor test of induction motor is similar to the short circuit test of a transformer.
- In blocked rotor test, a voltage to the stator winding of an induction motor is applied using *variac* so that rated current flows through the stator winding when rotor is blocked.

- The voltage required to circulate the rated current through the stator winding is around 10-15% of the rated voltage.
- After applying 10 to 15 % of the rated stator voltage, the core losses during the block rotor test is negligible, mind that core loss is directly proportional to the square of Voltage.
- Thus the wattmeter reading would effectively give the sum of stator and rotor copper loss.
- This wattmeter reading is then used determine the leakage impedance of induction motor as shown in *Figure 1.16* below:

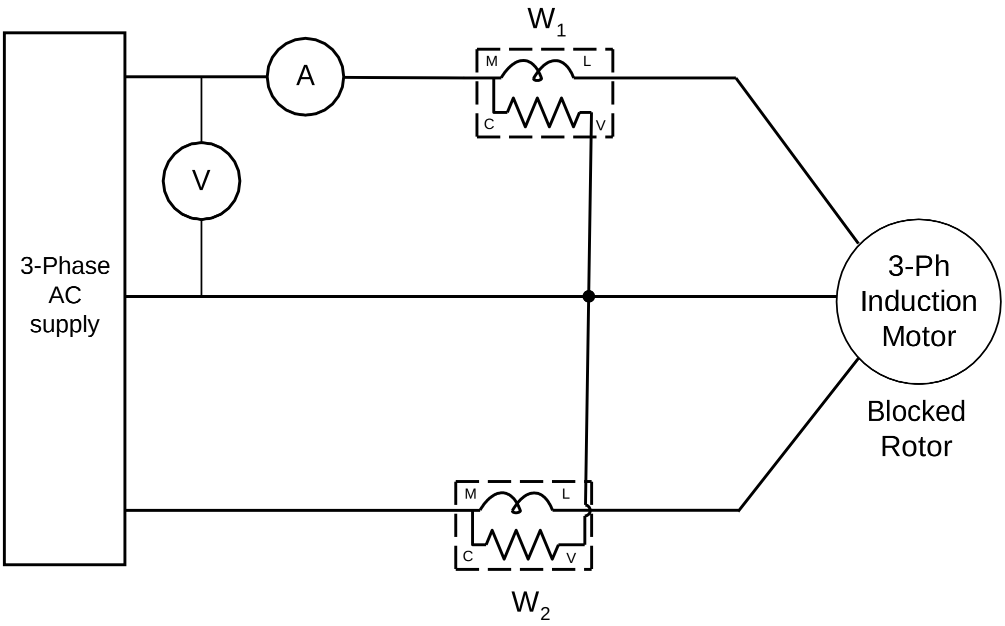


Figure 1.16Blocked rotor test of 3-ph induction motor

- The rotor is blockedso,mechanical loss will be negligible. So,
  Total Power input,

$$P_{in} = Stator\ copper\ Loss + Rotor\ copper\ Loss$$

$$= W_1 + W_2$$

Now,

$$V_s = Line\ voltage$$

$$I_s = Line\ current$$

$$P_1 \,\&\, P_2 = \text{Wattmeter readings at blocked rotor}$$

$$P_1 + P_2 = \sqrt{3} V_s I_s \cos\phi_s$$

$$\cos\phi_s = \frac{P_1 + P_2}{\sqrt{3} V_s I_s}$$

$$P_1 + P_2 = 3 (I_s)_{ph}^{2} R_{01} \quad (where,\ R_{01} = \text{Motor equivalent resistance per phase referred to stator})$$

$$R_{01} = \frac{P_1 + P_2}{3 (I_s)_{ph}^{2}}$$

$$Z_{01} = \frac{(V_s)_{ph}}{(I_s)_{ph}} \quad (where,\ Z_{01} = \text{Motor equivalent resistance per phase referred to stator})$$

$$X_{01} = \sqrt{Z_{01}^2 - R_{01}^2}$$

$$X_1 = X_2' = \frac{X_{01}}{2}$$

$$R_2' = R_{01} - R_1$$

Torque - Slip Characteristics of Induction Motor

- The torque slip curve gives the information about the variation of torque with the slip.
- The slip is defined as the ratio of difference of synchronous speed and actual rotor speed to the synchronous speed of the machine.
- The variation of slip can be obtained with the variation of speed that is when speed varies the slip will also vary and the torque corresponding to that speed will also vary.

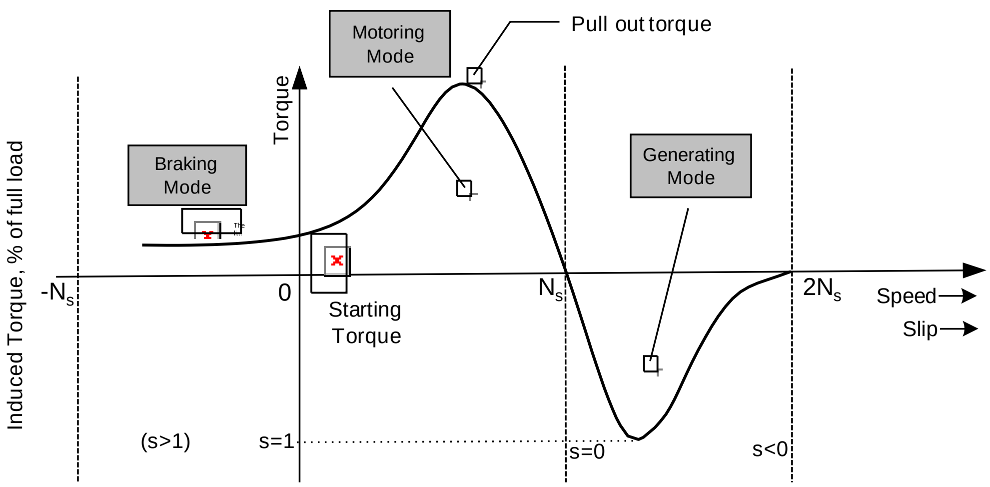


Figure 1.17 Torque-slip and Torque-speed characteristics of induction motor

- The torque-slip characteristic curve can be divided into three regions:
  - ➢ Motoring mode
  - ➢ Generating mode
  - ➢ Braking mode

- **Motoring Mode**

- In this mode of operation, by giving supply the motor always rotate below the synchronous speed.
- The induction motor torque varies from zero to full load torque as the slip varies.
- The slip varies from zero to one.
- It is zero at no load and one at standstill. From the curve it is seen that the torque is directly proportional to the slip.
- That is, more is the slip, more will be the torque produced and vice-versa.
- The linear relationship simplifies the calculation of motor parameter to great extent.

- **Generating Mode:**

- In this mode of operation induction motor runs above the synchronous speed and it should be driven by a prime mover.
- The stator winding is connected to a three phase supply in which it supplies electrical energy.
- Actually, in this case, the torque and slip both are negative so the motor receives mechanical energy and delivers electrical energy.
- An Induction motor is not much used as generator because it requires reactive power for its operation.
- That is, reactive power should be supplied from outside and if it runs below the synchronous speed by any means, it consumes electrical energy rather than giving it at the output. So, as far as possible, induction generators are generally avoided.

- **Braking Mode:**

- In the braking mode, the two leads or the polarity of the supply voltage is changed so that the motor starts to rotate in the reverse direction and as a result the motor stops. This method of braking is known as *plugging.*
- This method is used when it is required to stop the motor within a very short period of time. The kinetic energy stored in the revolving load is dissipated as heat.
- Also, motor is still receiving power from the stator which is also dissipated as heat. So as a result of which motor develops heat energy.
- If load which the motor drives accelerates the motor in the same direction as the motor is rotating, the speed of the motor may increase more than synchronous speed.
- In this case, it acts as an *induction generator* which supplies electrical energy to the mains which tends to slow down the motor to its synchronous speed, in this case the motor stops. This type of breaking principle is called *dynamic or regenerative braking*.

Power Flow in 3-phase induction motor

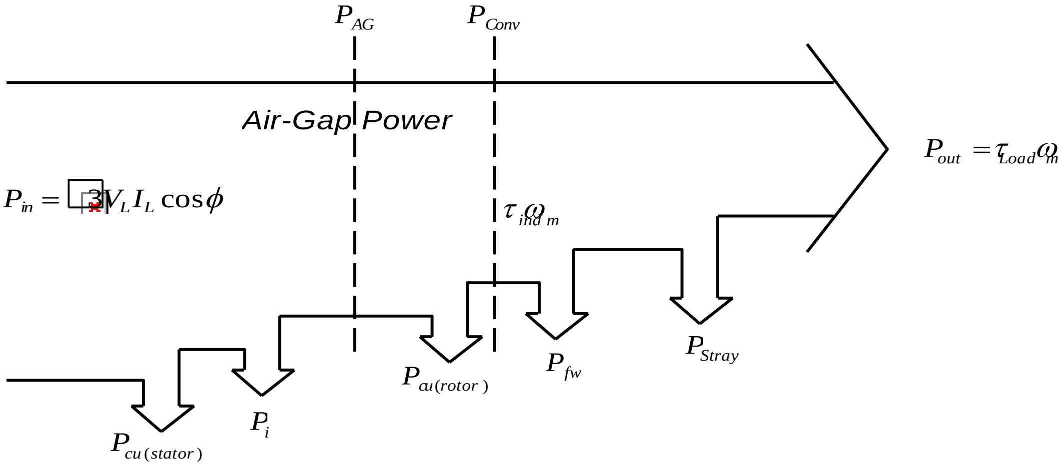


Figure 1.18Power flow diagram of induction motor

- An induction motor can be basically described as a rotating transformer.
- Its input is a three-phase system of voltages and currents.
- For an ordinary transformer, the output is electric power from the secondary windings.
- The secondary windings in an induction motor (the rotor) are shorted out, so no electrical output exists from normal induction motors. Instead, the output is mechanical.
- The relationship between the input electric power and the output mechanical power of this motor is shown in the power-flow diagram in *Figure 1.18*
- The input power to an induction motor P_{in} is in the form of three-phase electric voltage and current.
- The first losses encountered in the machine are I^2R losses in the stator windings (the stator copper loss $P_{cu(stator)}$.
- Then some amount of power is lost as hysteresis and eddy currents in the stator P_i. The power remaining at this point is transferred to the rotor of the machine across the air gap between the stator and rotor.
- This power is called the air-gap power $P_{AG}$of the machine. After the power is transferred to the rotor, some of it is lost as I^2R losses the rotor copper loss $P_{cu(rotor)}$, and the rest is converted from electrical to mechanical form P_{out}.
- Finally, friction and Windage losses P_{fw} and stray losses P_{Stray} are subtracted. The remaining power is the output of the motor Pout.
- The core losses do not always appear in the power-flow diagram at the point shown in *Figure 1.18.*
- Because of the nature of core losses, where they are accounted for in the machine is somewhat arbitrary.
- The core losses of an induction motor come partially from the stator circuit and partially from the rotor circuit.

- Since an induction motor normally operates at a speed near synchronous speed, the relative motion of the magnetic fields over the rotor surface is quite slow, and the rotor core losses are very tiny compared to the stator core losses.
- Since the largest fraction of the core losses comes from the stator circuit, all the core losses are lumped together at that point on the diagram.
- The higher the speed of an induction motor, the higher its friction, Windage, and stray losses.
- On the other hand, the higher the speed of the motor (up to N_s) the lower its core losses.
- Therefore, these three categories of losses are sometimes lumped together and called rotational losses.
- The total rotational losses of a motor are often considered to be constant with changing speed, since the component losses change in opposite directions with a change in speed.

Circle Diagram

- The circle diagram of an induction motor is very useful to study its performance under all operating conditions.
- The "Circle Diagram" means that it is the figure or curve which is drawn as a circular shape. As we know, the diagrammatic representation is easier to understand and remember compared to theoretical and mathematical descriptions.

○ ***Importance of Circle Diagram***

- The diagram provides information which is not provided by an ordinary phasor diagram.
- A phasor diagram gives relation between current and voltage only at a single circuit condition.
- If the condition changes, we need to draw the phasor diagram again. But a circle diagram may be referred to as a phasor diagram drawn in one plane for more than one circuit conditions.

- On the context of induction motor, which is our main interest, we can get information about its power output, power factor, torque, slip, speed, copper loss, efficiency etc. in a graphical or in a diagrammatic representation.

- ***Test performed to compute data required to draw circle diagram***

- *No-load and blocked rotor test* on an induction motor is performed. In no load test, the induction motor is run at no load and by two watt meter method, its total power consumed is measured.
- From this test no-load current and angle between voltage and current at no-load is calculated.

$$\phi_0 = \frac{P_0}{\sqrt{3} V_0 I_0}$$

- *The angle will be large as in the no load condition induction motor has high inductive reactance.*
- In block rotor test, rotor is blocked which is analogous to short circuited secondary of a transformer.
- From this test, short circuit current and the lag angle between voltage and current are calculated.

$$\phi_{sc} = \frac{P_{sc}}{\sqrt{3} V_{sc} I_{sc}}$$

- Current drawn if rated voltage is applied at blocked rotor condition,

$$I_{SN} = I_{SC} \frac{V_0}{V_{SC}}$$

- Power input at rated voltage and motor in the blocked rotor condition,

$$P_{SN} = P_{SC} \left(\frac{V_0}{V_{SC}} \right)^2$$

- ***Resistance Test***

- By voltmeter-ammeter method determine per phase equivalent stator resistance, R_1.
- If the machine is wound rotor type, find the equivalent rotor resistance R_2' also after measuring rotor resistance and required transformations are applied.

- ***How to draw circle diagram?***

- Draw horizontal axis OX and vertical axis OY. Here the vertical axis represents the voltage reference.
- With suitable scale, draw phasor OA with length corresponding to I_0 at an angle ϕ_0 from the vertical axis. Draw a horizontal line AB.
- Draw OS equal to I_{SN} at an angle ϕ_{SC} and join AS.
- Draw the perpendicular bisector to AS to meet the horizontal line AB at C.

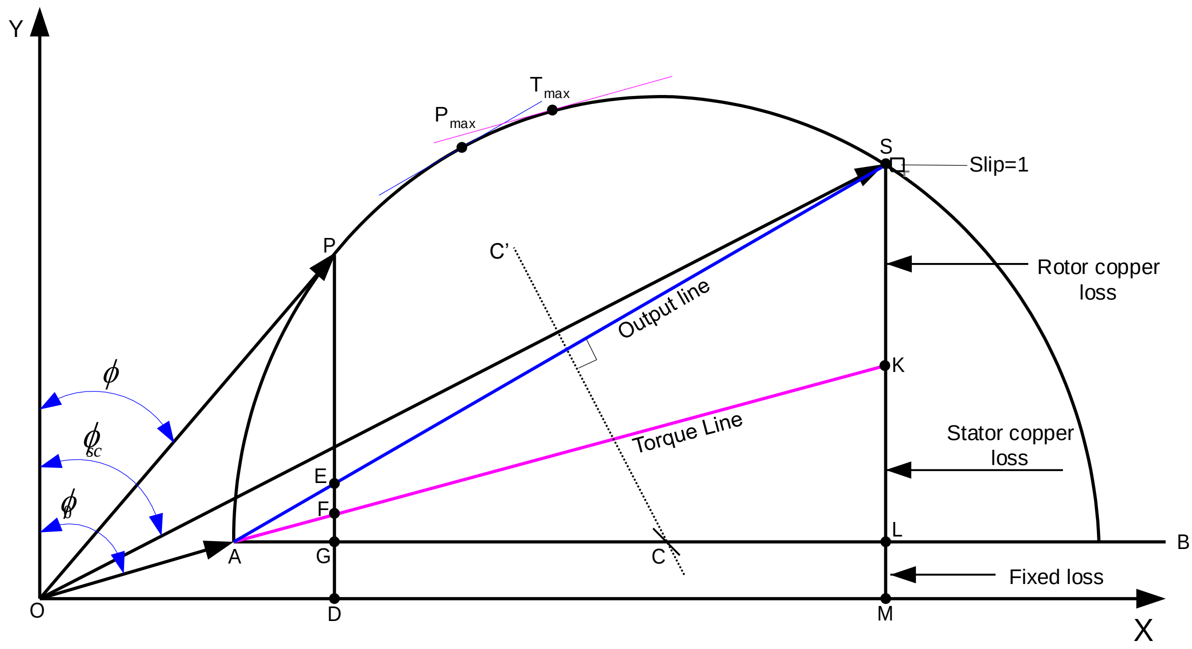


Figure 1.21 Circle Diagram of 3-phase Induction Motor

- With C as centre, draw a semi-circle passing through A and S. This forms the circle diagram which is the locus of the input current.
- From point S, draw a vertical line SL to meet the line AB.
- Fix the point K as below.
  For wound rotor machines where equivalent rotor resistance R_2' can be found out: Divide SL at point K so that SK: KL = equivalent rotor resistance: stator resistance.
- For squirrel cage rotor machines:
  Find Stator copper loss using I_{SN} and stator winding resistance R_1.

  Rotor copper loss = total copper loss – stator copper loss.
- Divide SL at point K so that SK : KL = rotor copper loss : stator copper loss
  Note: If data for separating stator copper loss and rotor copper loss is not available then assume that stator copper loss is equal to rotor copper loss. So divide SL at point K so that SK= KL.
- For a given operating point P, draw a vertical line PEFGD as shown.

  Then, PD = input power, PE = output power, EF = rotor copper loss, FG = stator copper loss, GD = constant loss (iron loss + mechanical loss)

- Efficiency of the machine at the operating point P, $\eta = \dfrac{PE}{PD}$
- Power factor of the machine at operating point P,is $\cos\phi$
- Slip of the machine at the operating point P, $s = \dfrac{EF}{PF}$
- Starting torque at rated voltage (in syn. watts) = SK
- To find the operating points corresponding to ***maximum power*** and ***maximum torque***, draw tangents to the circle diagram parallel to the output line and torque line

respectively. The points at which these tangents touch the circle are respectively the maximum power point (T_{max}) and maximum torque point(P_{max}) .

- ***Conclusion of Circle Diagram***
- This method is based on some approximations that we have used in order to draw the circle diagram and also, there is some rounding off of the values as well.
- So there is some error in this method but it can give good approximate results.
- Also, this method is very much time consuming so it is drawn at times where the drawing of circle diagram is absolutely necessary.
- Otherwise, we can go for mathematical formulas or equivalent circuit model in order to find out various parameters.

Induction generator:

Starting methods of three phase induction motor

- ***Why starters are required to start an induction motor?***
- If an induction motor is directly switched on from the supply, it takes 5 to 7 times its full load current and develops a torque which is only 1.5 to 2.5 times the full load torque. This large starting current produces a large voltage drop in the line, which may affect the operation of other devices connected to the same line. Hence, it is not advisable to start induction motors of rating above 5kW directly from the mains supply.

  Various starting methods of an induction motors are described below:
- **By Direct-on-line (DOL) starter**
- This type of starters are used to start small rating induction motors.
- In order to avoid excessive voltage drop in the supply line due to large starting current, a DOL starter is generally used for motors that are rated below 5kW.
- The rated supply is directly applied to the motor by using star delta starter.
- But, as mentioned above, here, the starting current would be very large, usually 5 to 7 times the rated current.
- Induction motors can be started (up to 5 kW) directly on-line using a DOL starter which generally consists of a contactor and a motor protection equipments. A DOL starter consists of a coil operated contactor which can be controlled by start and stop push buttons.
- When the start push button press, the contactor coil (C) gets energized and it closes power contacts (P), power is supplied to the motor and motor gets start.
- During its running, the contactor closed via *ab,* hence it is called hold on contact.
- The stop push button de-energizes the contactor so the motor stops.

- When voltage falls below a certain value the contactor coil (C) gets de-energized and hence the main contactor opens and the motor stop.
- When the motor is overloaded, the overload coil gets energized so the NC contact of O/L opens, the power supply to the (C) gets disconnected and the motor stop.
- The starting torque is likely to be 1.5 to 2.5 times the full load torque.

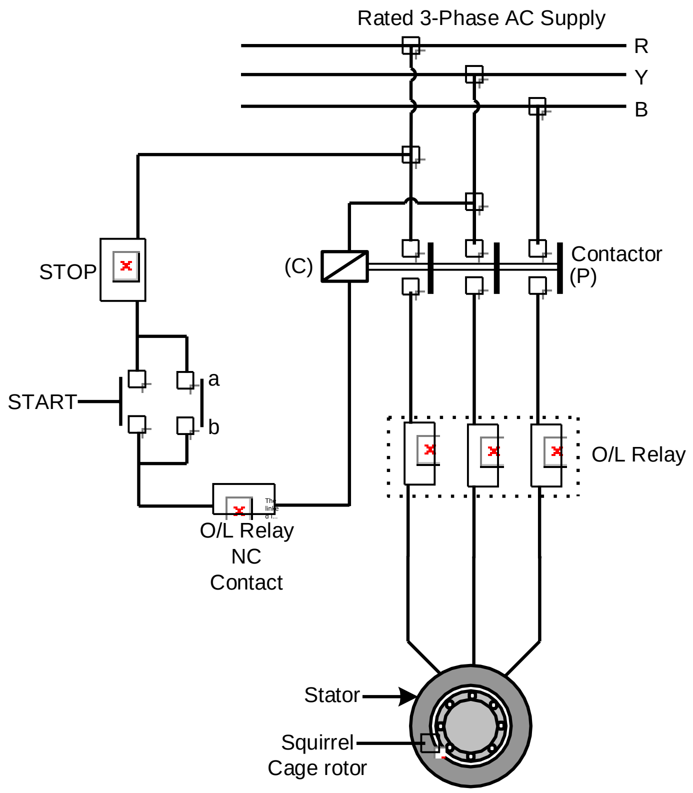


Figure 1.22 Direct-Online Starter (DOL)

- Sometimes fuses are also provided for short circuit protection in the circuit.
- The DOL starter is simple and cheap.

○ **Starting of squirrel cage motors**

- Starting in-rush current in squirrel cage motors is controlled by applying reduced voltage to the stator.
- These methods are sometimes called as reduced voltage methods for starting of***squirrel cage induction motors***. For this purpose, following methods are used:
  (a) Primary resistors starter
  (b) Autotransformer starter
  (c) Star-delta starter

(a) Primary resistors starter

- The purpose of primary resistors is to drop some voltage and apply a reduced voltage to the stator. Consider, the starting voltage is reduced by 50%.
- Then according to *V=I/Z*, the starting current will also be reduced by the same percentage.
- From the torque equation of a three phase induction motor, the starting torque is approximately proportional to the square of the applied voltage.
- That means, if the applied voltage is 50% of the rated value, the starting torque will be only 25% of its rated torque.
- Similarly, this method is generally used for a **smooth starting of small induction motors.**
- This is not recommended to for motors with high starting torque requirements.

- Resistors are such that 70% of the rated voltage can be applied to the motor.
- At the time of starting, full resistance is connected in the series with the stator winding and it is gradually decreased as the motor speeds up.
- When the motor reaches an appropriate speed, the resistances are disconnected from the circuit and the stator phases are directly connected to the supply lines.

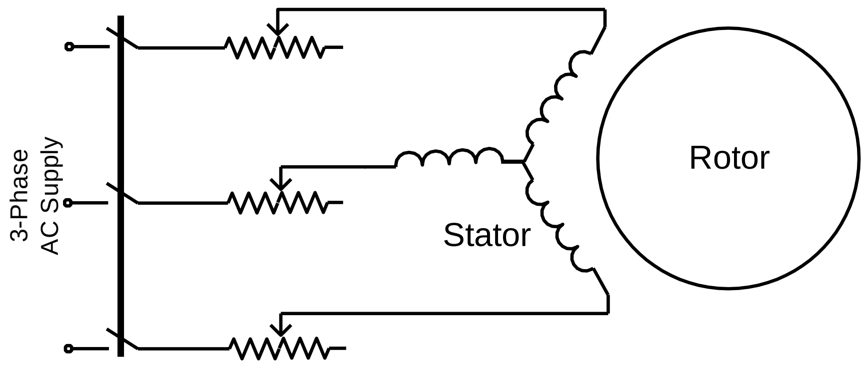


Figure 1.23 Primary resistance starter

(b) Auto-transformer starter

- An auto-transformer starter can be used for both star connected and delta connected squirrel cage motors.

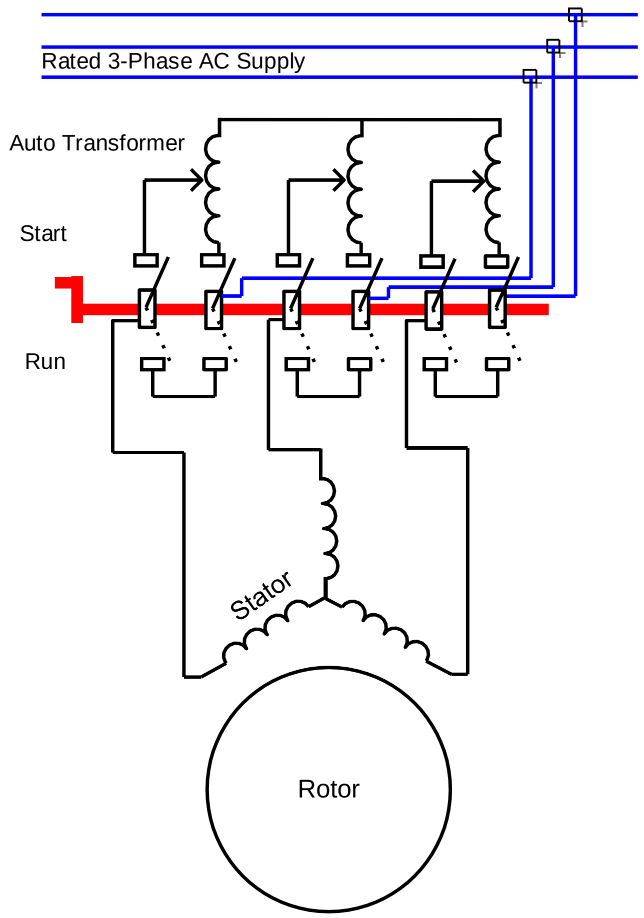


Figure 1.24 Auto-Transformer starter

- With auto-transformer starting, the current drawn from supply line is always less than the motor current by an amount equal to the transformation ratio.
- At starting, switch is at "start" position, and a reduced voltage (which is selected using a tap) is applied across the stator.
- When the motor reaches to an appropriate speed, say up to 80% of its rated speed, the auto-transformer automatically gets disconnected from the circuit as the switch goes to "run" position.
- The switch changing the connection from start to run position may be air-break (for small motors) or oil-immersed (for large motors) type.
- There are also provisions for no-voltage and overload, with time delay circuits on an auto transformer starter.

(c) Star-delta starter

- This starters are widely used for induction motor.
- Its design is such that the motor runs on delta connection during the running condition only.

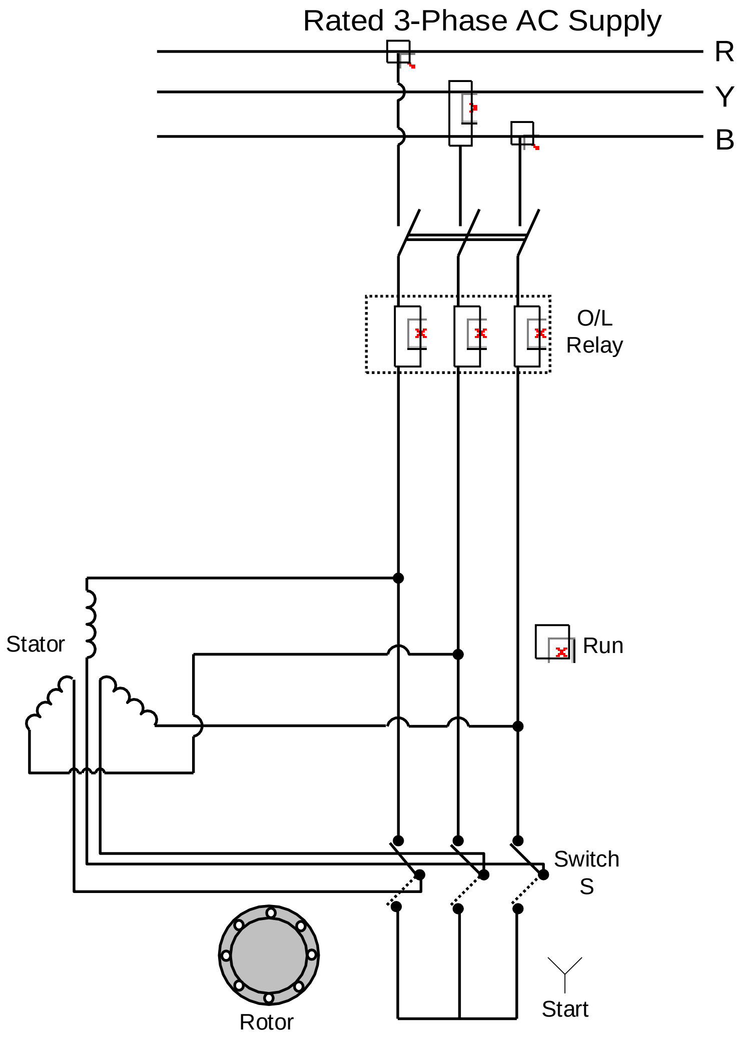


Figure 1.25Star-Delta starter

- When the changeover switch S is in the "start" position, the stator winding is connected in star position and after achieving a speed which is 80% of the rated speed, it is thrown to the "run" position.
- So, when the motor is connected in star during starting, the line current is reduced to one –third as compared to the starting current of delta connection.
- During the starting time, each stator phase gets a voltage $\frac{V_L}{\sqrt{3}}$ hence, the starting torque is reduced to one-third that obtained by direct delta connected.

○ **Starting of slip-ring induction motors**

- Slip-ring motors are started with full line voltage, as external resistance can be easily added in the rotor circuit with the help of slip-rings.
- A star connected rheostat is connected in series with the rotor via slip-rings. Introducing resistance in rotor current will decrease the starting current in rotor and, hence, in stator.
- Also, it improves power factor and the torque is increased. The connected rheostat may be hand-operated or automatic.
- As, introduction of additional resistance in rotor improves the starting torque, slip-ring motors can be started on load.
- The external resistance introduced is only for starting purposes, and is gradually cut out as the motor reaches to the speed.

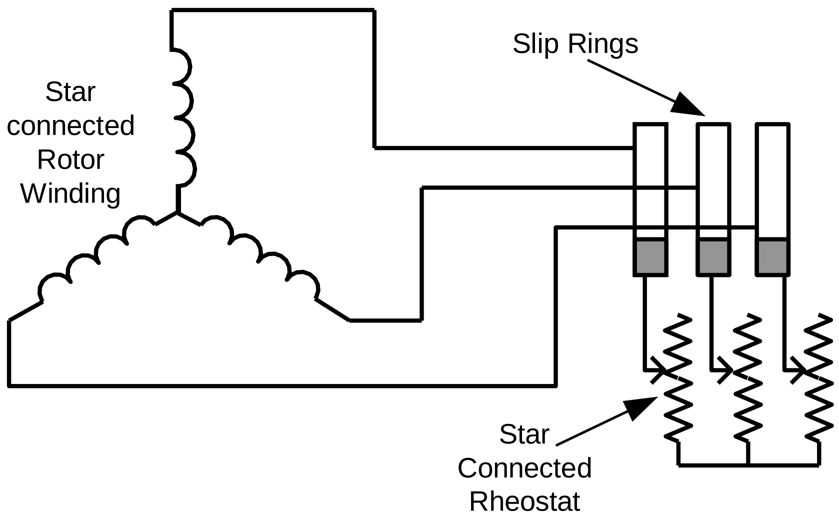


Figure 1.26Rotor resistance starter for slip ring induction motor

Speed control of induction motor

○ ***Why Speed control of induction motor?***

- Three phase induction motor is a constant speed motor. So it is difficult to control its speed. But by using different methods we can control its speed because speed of induction motor is inversely proportional to torque and at the starting, motor runs at maximum slip.

- Torque is directly proportional to slip. If supply voltage reduced then induction motor draws more current to magnetize rotor and operate under normal condition. But because of excessive current flowing through motor windings and motor get overheat up. Hence motor get damaged. Due this reason, we have to control the speed of three phase induction motor.
- Different methods to control the speed of induction motor are:
  - **Control from stator side**

  (a) By Supply voltage control
  (b) By variable frequency control
  (C) by pole changing method

  - **Control from rotor side**

  (d) By rotor resistance control
  (e) By slip energy recovery method
  (f) By injection an emf in the the rotor circuit

(a) By Supply Voltage Control

- We know that the torque developed by an induction motor varies as square of the voltage applied to its stator terminals.
- Thus by varying the applied voltage, the electromagnetic torque developed by the motor can be varied.
- This method is generally used for small squirrel-cage motors where cost is an important criterion and efficiency is not.
- However, this method has rather limited range of speed control. It means Speed control below the normal speed can be possible by this method.
- This method is very cheap, simple and rarely used because of a large variation in voltage changes in flux density, hence the magnetic circuit get disturb.

(b) By variable frequency Control

- This method of speed control widely used now a days.
- It can be achieved by using VFD (Variable Frequency Drive).
- By changing the supply frequency, the motor synchronous speed can be altered and thus the torque-speed of a three- phase induction motor can be controlled.
- By using variable frequency control, it is possible to adjust the speed of the motor either above or below the base speed.
- Increase in frequency increases the torque-speed relation and a decrease in frequency decreases the torque-speed relation of the motor.
- We can control the speed of induction motor by varying the stator supply voltage and frequency with the keep ratio of V/fconstant.
- When low voltage and low frequency is applied to the motor, the maximum torque available decreases at reduced speeds.
- If the ratio of V/f is kept constant, this technique allows the induction motor to deliver its rated torque at speeds up to its rated speed.

(c) By pole changing Method

- The primary factor in determining the speed of an induction motor is the number of poles, given by the formula;
- $N_s = \frac{120f}{P}\ rpm$ or $n_s = \frac{2f}{P}\ rps$
- $N_s =$ *Synchronous speed, in rpm*
- $f =$ *AC power frequency*
- $P =$ *Number of poles per phase winding*
- Pole changing in induction machine can be done using a pole changing motor.
- Pole changing can be used to achieve different speeds in induction machine by switching the configuration of the electrical stator windings in the ratio of 2:1, indirectly adding or removing poles and thus varying the rotor speed.
- The number of stator poles can be changed by
  (a) Multiple stator winding,
  (b) Method of consequent poles,
  (c) Pole amplitude modulation.

(d) By rotor resistance control

- This control method is used only for slip ring induction (wound rotor) motor.
- We can insert external resistance in the rotor circuit of slip ring induction motor
- This method gives large starting torque, low starting current and large pullout torque at small slip.
- The main drawback of this method is large power lost in the external resistance rotor circuit, especially at lower speeds.
- Speed below normal speed can be achieved by this method.
- We get wide range of speed by using this method.

(e) By slip energy recover method

- The slip power transferred across the air gap is transformed by electromagnetic induction to electric power in the rotor circuit.
- In the rotor resistance control method the slip frequency power gets wasted as copper loss which reduce the efficiency of induction motor.
- So, by recovering this wasted energy we get more efficiency of induction motor.
- There are so many methods used to recover this energy but among these one method is Scherbius drive method that shown in below *Figure 1.27*
- This method provide the speed control of induction motor below the synchronous speed.
- The slip power of the rotor converted into DC by the bridge rectifier.

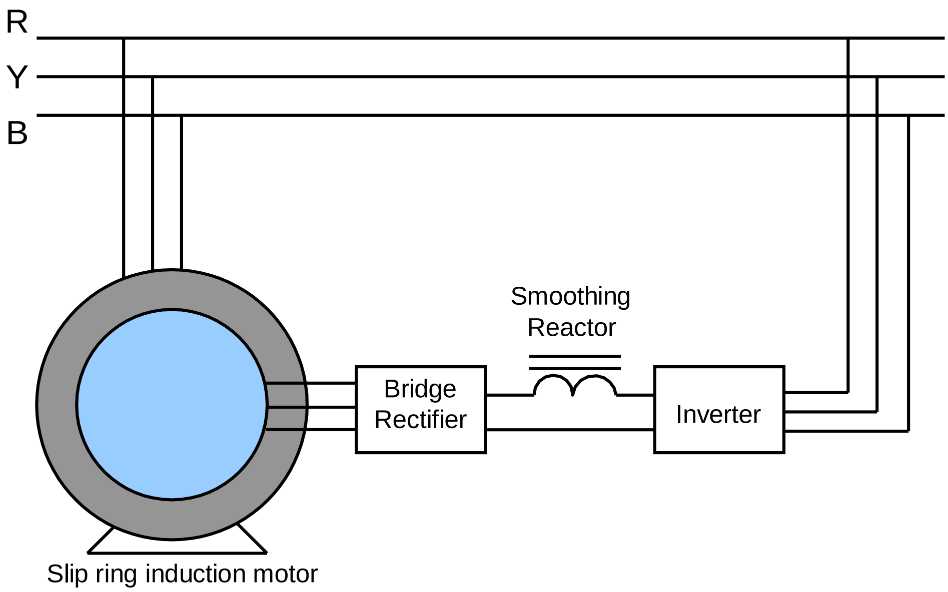


Figure 1.27Slip energy recovery method

- This rectified current can be smoothed by using smooth reactor.
- The output of the rectifier is converted into AC by inverter which is fed back to supply.

(f) By injecting emf in the rotor circuit

- In this method, a voltage is injected in the rotor circuit. The frequency of rotor circuit is a slip frequency and hence the voltage to be injected must be at a slip frequency.
- It is possible that the injected voltage may oppose the rotor induced emf or may assist the rotor induced emf.
- If it is in the phase opposition, effective rotor resistance increases. If it is in the phase of rotor induced emf, effective rotor resistance decreases.
- Thus by controlling the magnitude of the injected emf, rotor resistance and effectively speed can be controlled.
- Practically two methods are available which use this principle. These methods are,

○ **Kramer'scascade system**

- In Kramer's cascade, the slip-ring induction motor is started using rotor resistance starter.
- By changing the direction of phase rotation, the resistance of the rotor circuit is varied and thus speed of the slip ring motor is controlled.
- When machine is running, the rotor circuit EMF is rectified and connected to a separately excited DC motor. The DC motor is connected to the main shaft of induction motor by means of gears. By varying the field current of DC motor, the speed of shaft can be varied in sub synchronous region.

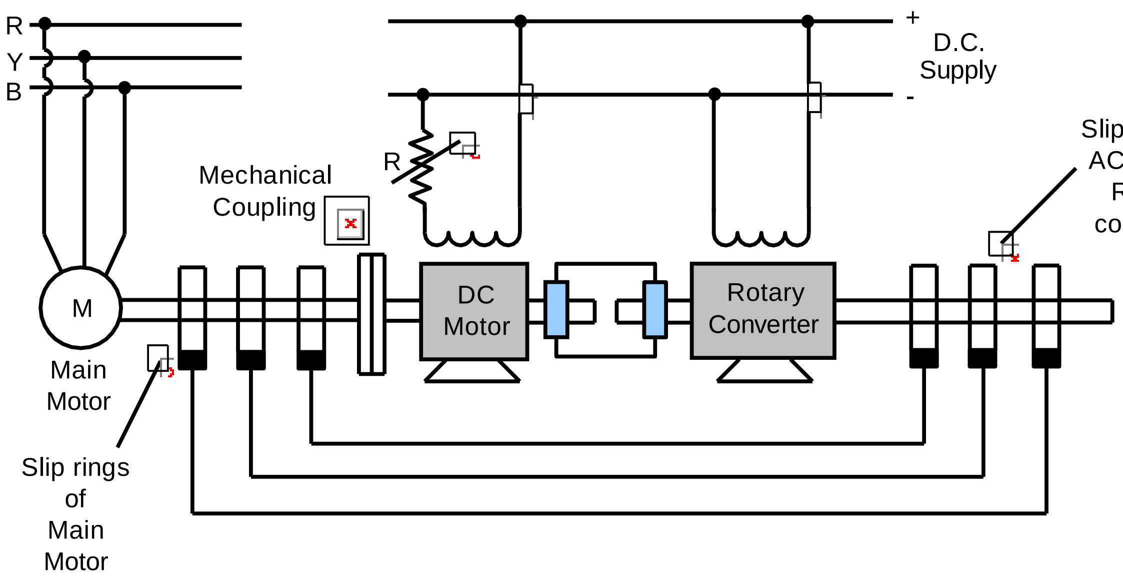
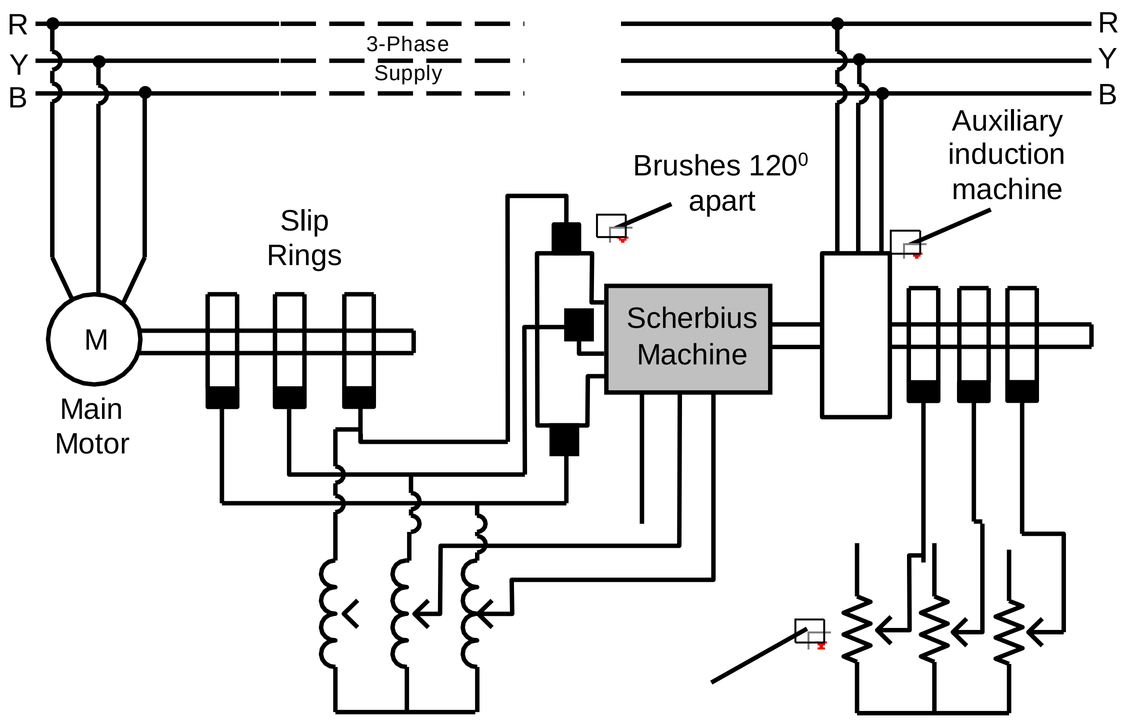


Figure 1.28Kramer's cascade system

- Very large motors above 4000 kW such as steel rolling mills use such type of speed control.
- The main advantage of this method is that a smooth speed control is possible. Similarly wide range of speed control is possible.
- Another advantage of the system is that the design of a rotary converter is practically independent of the speed control required.
- Similarly if rotary converter is overexcited, it draws leading current and thus power factor improvement is also possible along with the necessary speed control.

○ **Scherbius cascade system**

- It consists of main induction motor M, the speed of which is to be controlled.
- In Scherbius cascade, the slip power is converted into DC and then into 3 phase AC, which is fed back to three-phase lines.
- The slip-ring induction motor is started using rotor resistance starter. When machine is running, the rotor resistances are removed and rotor terminals are connected to the three-phase rectifier.
- The slip power is converted into DC, which is again connected to a three-phase bridge converter operating as an inverter. In which the firing angle is more than 90^0.
- The logic for gate pulses for different thyristors is obtained from three-phase lines. The converter converts the DC power into three-phase AC power having frequency same as line frequency.
- The slip power is fed back to the lines using regulating transformer having a definite turn ratio. The two additional equipments are, DC motor and rotary converter.


R
Y
B
3-Phase
Supply
R
Y
B
Auxiliary
induction
machine
Brushes 120⁰
apart
Slip
Rings
M
Main
Motor
Scherbius
Machine

Regulating
Transformer

Starting
Resiatance

Figure 1.29 Scherbius cascadesystem

Comparison of Squirrel cage induction motor with slip ring induction motor

Squirrel Cage Induction Motor	Slip ring (wound rotor) Induction Motor
• In Squirrel cage induction motors the rotor is simplest and rugged in construction	• In slip ring induction motors the rotor is wound type. • In the motor the slip rings, brushes are provided. • Compared to squirrel cage rotor the rotor construction is not simple.
• Cylindrical laminated core rotor with heavy bars or copper or aluminum or alloys are used for conductors.	• Cylindrical laminated core rotor is wound for as the number of poles of the stator.
• Rotor conductors or rotor bars are short circuited with end rings.	• At starting the 3 phase windings are connected to a star connected rheostat and during running condition, the windings is short circuited at the slip rings.
• Rotor bars are permanently short circuited and hence it is not possible to connect external resistance in the circuit in series with the rotor conductors.	• It is possible to insert additional resistance in the rotor circuit. • Therefore it is possible to increase the torque (the additional series resistance is used for starting purposes)
• Cheaper cost	• Cost is slightly higher.
• No moving contacts in the rotor.	• Carbon brushes, slip rings etc are provided in the rotor circuit.
• Higher efficiency.	• Comparatively less efficiency.
• Low starting torque. • It is 1.5 time full load torque.	• High starting torque. It can be obtained by adding external resistance in the rotor circuit.
• Speed control by rotor resistance is not possible.	• Speed control by rotor resistance is possible.
• Starting current is 5 to 7 times the full load.	• Less starting current.

Energy efficient motors

- Energy efficient motors are specially designed to increase the efficiency of induction motor.

- This motor designed with minimum losses and it is rugged, small in size and has silent operation compare to conventional motors.
- Energy efficient motors are available in wide range of ratings.
- The following parameters are recommended for energy efficiency motors.

➢ **Reduction in under loading**
- The size of the induction motor should be selected after load calculation.
- If replace the the oversize motor then it is very important to consider efficiency gain.
- If want to reduce the overloading then motor should be designed with star connection.
- In star connection motor runs at lower speed and lower voltage so it gives the same performance as connected in delta connected motor. In star connection motor gives the higher efficiency.

➢ **Sizing of the motor as per load**
- In industry motors are generally selected as per full load but actually motor runs at full load for short time period. So, the by using over rating motors it may be costly.
- The motor is selected on the basis of load duration curve.
- Therefore, selection of motor should be slightly lower anticipating load than highest.
- If the load is changing with time, apart from proper sizing the speed control methods can be applied.

➢ **Improving the quality factor**
- The performance of the motor of the motor depends on the quality of power input to the motor.
- The input power can be calculated by the actual Voltage and frequency supplied to the motor.
- If there is a large fluctuation in input voltage and frequency then motor gives the poor performance. Sometimes, motor get damaged also.
- So, unbalancing in voltage also affect on the motor performance greatly.

➢ **Rewinding of the motor**
- If motor burn out then we need to rewind the motor.
- Motor loss its original efficiency and power factor after rewinding it.
- So, to get higher efficiency near to original efficiency we need to care of size of the conductors, number of turns, insulation class and winding accuracy as well.

➢ **Improving maintenance**
- Most of the motors are made from the silicon steel (de-carbonized cold rolled silicon steel).
- So, after used long time period the electrical property of core does not change considerably but due to poor maintenance motor loss its efficiency.
- For example, by using improper lubrication and friction motor reduce its efficiency.

Induction generator

An **induction generator** or asynchronous generator is a type of alternating current (AC) electrical generator that uses the principles of induction motors to produce electric power. Induction generators operate by mechanically turning their rotors faster than synchronous speed. A regular AC induction motor usually can be used as a generator, without any internal modifications. Induction generators are useful in applications such as mini hydro power plants, wind turbines, or in reducing high-pressure gas streams to lower pressure, because they can recover energy with relatively simple controls.

An induction generator usually draws its excitation power from an electrical grid. Because of this, induction generators cannot usually black start a de-energized distribution system. Sometimes, however, they are self-excited by using phase-correcting capacitors.

Principle of operation

An induction generator produces electrical power when its rotor is turned faster than the synchronous speed. For a typical four-pole motor (two pairs of poles on stator) operating on a 60 Hz electrical grid, the synchronous speed is 1800 rotations per minute (rpm). The same four-pole motor operating on a 50 Hz grid will have a synchronous speed of 1500 RPM. The motor normally turns slightly slower than the synchronous speed; the difference between synchronous and operating speed is called "slip" and is usually expressed as per cent of the synchronous speed. For example, a motor operating at 1450 RPM that has a synchronous speed of 1500 RPM is running at a slip of +3.3%.

In normal motor operation, the stator flux rotation is faster than the rotor rotation. This causes the stator flux to induce rotor currents, which create a rotor flux with magnetic polarity opposite to stator. In this way, the rotor is dragged along behind stator flux, with the currents in the rotor induced at the slip frequency.

In generator operation, a prime mover (turbine or engine) drives the rotor above the synchronous speed (negative slip). The stator flux still induces currents in the rotor, but since the opposing rotor flux is now cutting the stator coils, an active current is produced in stator coils and the motor now operates as a generator, sending power back to the electrical grid.

Excitation

Equivalent circuit of induction generator

An induction machine requires an externally-supplied armature current. Because the rotor field always lags behind the stator field, the induction machine always consumes reactive power, regardless of whether it is operating as a generator or a motor.

A source of excitation current for magnetizing flux (reactive power) for the stator is still required, to induce rotor current. This can be supplied from the electrical grid or, once it starts producing power, from the generator itself. The generating mode for induction motors is complicated by the need to excite the rotor, which begins with only residual magnetization. In some cases, that residual magnetization is enough to self-excite the motor under load. Therefore, it is necessary to either snap the motor and connect it momentarily to a live grid or to add capacitors charged initially by residual magnetism and providing the required reactive power during operation. Similar is the operation of the induction motor in parallel with a synchronous motor serving as a power factor compensator. A feature in the generator mode in parallel to the grid is that the rotor speed is higher than in the driving mode. Then active energy is being given to the grid.[1]Another disadvantage of induction motor generator is that it consumes a significant magnetizing current **I**0 = (20-35)%.

An induction machine can be started by charging the capacitors, with a DC source, while the generator is turning typically at or above generating speeds. Once the DC source is removed the capacitors will provide the magnetization current required to begin producing voltage.

An induction machine that has recently been operating may also spontaneously produce voltage and current due to residual magnetism left in the core .

Active power

Active power delivered to the line is proportional to slip above the synchronous speed. Full rated power of the generator is reached at very small slip values (motor dependent, typically 3%). At synchronous speed of 1800 rpm, generator will produce no power. When the driving speed is increased to 1860 rpm (typical example), full output power is produced. If the prime mover is unable to produce enough power to fully drive the generator, speed will remain somewhere between 1800 and 1860 rpm range.

Required capacitance

A capacitor bank must supply reactive power to the motor when used in stand-alone mode. The reactive power supplied should be equal or greater than the reactive power that the machine normally draws when operating as a motor.

Torque vs. slip

The basic fundamental of induction generators is the conversion from mechanical energy to electrical energy. This requires an external torque applied to the rotor to turn it faster than the synchronous speed. However, indefinitely increasing torque doesn't lead to an indefinite increase in power generation. The rotating magnetic field torque excited from the armature works to counter the motion of the rotor and prevent over speed because of induced motion in the opposite direction. As the speed of the motor increases the counter torque reaches a max value of torque (breakdown torque) that it can operate until before the operating conditions become unstable. Ideally, induction generators work best in the stable region between the no-load condition and maximum torque region.

Rated current

The maximum power that can be produced by an induction motor operated as a generator is limited by the rated current of the machine's windings.

Grid and stand-alone connections

Typical connections when used as a standalone generator

In induction generators, the reactive power required to establish the air gap magnetic flux is provided by a capacitor bank connected to the machine in case of stand-alone system and in case of grid connection it draws reactive power from the grid to maintain its air gap flux. For a grid-connected system, frequency and voltage at the machine will be dictated by the electric grid, since it is very small compared to the whole system. For stand-alone systems, frequency and voltage are complex function of machine parameters, capacitance used for excitation, and load value and type.

Uses

Induction generators are often used in wind turbines and some micro hydro installations due to their ability to produce useful power at varying rotor speeds. Induction generators are mechanically and electrically simpler than other generator types. They are also more rugged, requiring no brushes or commutators.

Limitations

An induction generator connected to a capacitor system can generate sufficient reactive power to operate on its own. When the load current exceeds the capability of the generator to supply both magnetization reactive power and load power the generator will immediately cease to produce power. The load must be removed and the induction generator restarted with either a DC source, or if present, residual magnetism in the core.[2]

Induction generators are particularly suitable for wind generating stations as in this case speed is always a variable factor. Unlike synchronous motors, induction generators are load-dependent and cannot be used alone for grid frequency control.

Example application

As an example, consider the use of a 10 hp, 1760 r/min, 440 V, three-phase induction motor as an asynchronous generator. The full-load current of the motor is 10 A and the full-load power factor is 0.8.

Required capacitance per phase if capacitors are connected in delta:

Apparent power $S = \sqrt{3}\,E\,I = 1.73 \times 440 \times 10 = 7612$ VA

Active power $P = S \cos\theta = 7612 \times 0.8 = 6090$ W

Reactive power Q = = 4567 VAR

For a machine to run as an asynchronous generator, capacitor bank must supply minimum 4567 / 3 phases = 1523 VAR per phase. Voltage per capacitor is 440 V because capacitors are connected in delta.

Capacitive current $I_c = Q/E = 1523/440 = 3.46$ A

Capacitive reactance per phase $X_c = E/I_c = 127\ \Omega$

Minimum capacitance per phase:

$C = 1 / (2 \cdot \pi \cdot f \cdot X_c) = 1 / (2 \cdot 3.141 \cdot 60 \cdot 127) = 21$ microfarads.

If the load also absorbs reactive power, capacitor bank must be increased in size to compensate.

Prime mover speed should be used to generate frequency of 60 Hz:

Typically, slip should be similar to full-load value when machine is running as motor, but negative (generator operation):

if Ns = 1800, one can choose N=Ns+40 rpm

Required prime mover speed N = 1800 + 40 = 1840 rpm.

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MODULE-3

Single Phase Induction Motor

Introduction

We use the single-phase power system more widely than three phase system for domestic purposes, commercial purposes and some extent in industrial uses. Because, the single-phase system is more economical than a three-phase system and the power requirement in most of the houses, shops, offices are small, which can be easily met by a single phase system.

The single phase motors are simple in construction, cheap in cost, reliable and easy to repair and maintain. Due to all these advantages, the single phase motor finds its application in vacuum cleaners, fans, washing machines, centrifugal pumps, blowers, washing machines, etc.

The single phase AC motors are further classified as:

1. **Single phase induction motors or asynchronous motors.**
2. Single phase synchronous motors.
3. Commutator motors.

Construction of Single Phase Induction Motor

Like any other electrical motor asynchronous motor also have two main parts namely rotor and stator.

Stator:

As its name indicates stator is a stationary part of induction motor. A single phase AC supply is given to the stator of single phase induction motor.

Rotor:

The rotor is a rotating part of an induction motor. The rotor connects the mechanical load through the shaft. The rotor in the single-phase induction motor is of squirrel cage rotor type.

The **construction of single phase induction motor** is almost similar to the squirrel cage three-phase induction motor. But in case of a single phase induction motor, the stator has two windings instead of one three-phase winding in three phase induction motor.

Stator of Single Phase Induction Motor

The stator of the single-phase induction motor has laminated stamping to reduce eddy current losses on its periphery. The slots are provided on its stamping to carry stator or main winding. Stampings are made up of silicon steel to reduce the hysteresis losses. When we apply a single phase AC supply to the stator winding, the magnetic field gets produced, and the motor rotates at speed slightly less than the synchronous speed N_s.

Synchronous speed N_s is given by
Where,
f = supply voltage frequency,
P = No. of poles of the motor.
The construction of the stator of the single-phase induction motor is similar to that of three phase induction motor except there are two dissimilarities in the winding part of the single phase induction motor.

1. Firstly, the single-phase induction motors are mostly provided with concentric coils. We can easily adjust the number of turns per coil can with the help of concentric coils. The mmf distribution is almost sinusoidal.
2. Except for shaded pole motor, the asynchronous motor has two stator windings namely the main winding and the auxiliary winding. These two windings are placed in space quadrature to each other.

Rotor of Single Phase Induction Motor

The construction of the rotor of the single-phase induction motor is similar to the squirrel cage three-phase induction motor. The rotor is cylindrical and has slots all over its periphery. The slots are not made parallel to each other but are a little bit skewed as the skewing prevents magnetic locking of stator and rotor teeth and makes the working of induction motor more smooth and quieter (i.e. less noisy).
The squirrel cage rotor consists of aluminum, brass or copper bars. These aluminum or copper bars are called rotor conductors and placed in the slots on the periphery of the rotor. The copper or aluminum rings permanently short the rotor conductors called the end rings.

To provide mechanical strength, these rotor conductors are braced to the end ring and hence form a complete closed circuit resembling a cage and hence got its name as squirrel cage induction motor. As end rings permanently short the bars, the rotor electrical resistance is very small and it is not possible to add external resistance as the bars get permanently shorted. The absence of slip ring and brushes make the **construction of single phase induction motor** very simple and robust.

Working Principle of Single Phase Induction Motor

the working of any electrical motor whether its AC or DC motor, we require two fluxes as the interaction of these two fluxes produced the required torque.
When we apply a single phase AC supply to the stator winding of single phase induction motor, the alternating current starts flowing through the stator or main winding. This alternating current produces an

alternating flux called main flux. This main flux also links with the rotor conductors and hence cut the rotor conductors.

According to the Faraday's law of electromagnetic induction, emf gets induced in the rotor. As the rotor circuit is closed one so, the current starts flowing in the rotor. This current is called the rotor current. This rotor current produces its flux called rotor flux. Since this flux is produced due to the induction principle so, the motor working on this principle got its name as an induction motor. Now there are two fluxes one is main flux, and another is called rotor flux. These two fluxes produce the desired torque which is required by the motor to rotate.

Why Single Phase Induction Motor is not Self Starting?

According to double field revolving theory, we can resolve any alternating quantity into two components. Each component has a magnitude equal to the half of the maximum magnitude of the alternating quantity, and both these components rotate in the opposite direction to each other. For example – a flux, φ can be resolved into two components

Each of these components rotates in the opposite direction i. e if one $\varphi_m/2$ is rotating in a clockwise direction then the other $\varphi_m / 2$ rotates in an anticlockwise direction.When we apply a single phase AC supply to the stator winding of single phase induction motor, it produces its flux of magnitude, φ_m. According to the double field revolving theory, this alternating flux, φ_m is divided into two components of magnitude $\varphi_m/2$. Each of these components will rotate in the opposite direction, with the synchronous speed, N_s.Let us call these two components of flux as forwarding component of flux, φ_f and the backward component of flux, φ_b. The resultant of these two components of flux at any instant of time gives the value of instantaneous stator flux at that particular instant.

Now at starting condition, both the forward and backward components of flux are exactly opposite to each other. Also, both of these components of flux are equal in magnitude. So, they cancel each other and hence the net torque experienced by the rotor at the starting condition is zero. So, the **single phase induction motors** are not self-starting motors.

Methods for Making Single Phase Induction as Self Starting Motor

From the above topic, we can easily conclude that the single-phase induction motors are not self-starting because the produced stator flux is alternating in nature and at the starting, the two components of this flux cancel each other and hence there is no net torque. The solution to this problem is that if we make the stator flux rotating type, rather than alternating type, which rotates in one particular direction only. Then the induction motor will become self-starting.

Now for producing this rotating magnetic field, we require two alternating flux, having some phase difference angle between them. When these two fluxes interact with each other, they will produce a resultant flux. This resultant flux is rotating in nature and rotates in space in one particular direction only.

Once the motor starts running, we can remove the additional flux. The motor will continue to run under the influence of the main flux only. Depending upon the methods for making asynchronous motor as Self Starting Motor, there are mainly four **types of single phase induction motor** namely,

1. Split phase induction motor,
2. Capacitor start inductor motor,
3. Capacitor start capacitor run induction motor,
4. Shaded pole induction motor.
5. Permanent split capacitor motor or single value capacitor motor.

Comparison between Single Phase and Three Phase Induction Motors

1. Single phase induction motors are simple in construction, reliable and economical for small power rating as compared to three phase induction motors.
2. The electrical power factor of single phase induction motors is low as compared to three phase induction motors.
3. For the same size, the single-phase induction motors develop about 50% of the output as that of three phase induction motors.
4. The starting torque is also low for asynchronous motors/single phase induction motor.
5. The efficiency of single phase induction motors is less compared to that of three phase induction motors.

Single phase induction motors are simple, robust, reliable and cheaper for small ratings. They are available up to 1 KW rating.Single-phase motors do not have a unique rotating magnetic field like multi-phase motors. The field alternates (reverses polarity) between pole pairs and can be viewed as two fields rotating in opposite directions. They require a secondary magnetic field that causes the rotor to move in a specific direction. After starting, the alternating stator field is in relative rotation with the rotor. Several methods are commonly used:

Shaded-pole motor

A common single-phase motor is the shaded-pole motor and is used in devices requiring low starting torque, such as electric fans, small pumps, or small household appliances. In this motor, small single-turn copper "shading coils" create the moving magnetic field. Part of each pole is encircled by a copper coil or strap; the induced current in the strap opposes the change of flux through the coil. This causes a time lag in the flux passing through the shading coil, so that the maximum field intensity moves higher across the pole face on each cycle. This produces a low level rotating magnetic field which is large enough to turn both the rotor and its attached load. As the rotor picks up speed the torque builds up to its full level as the principal magnetic field is rotating relative to the rotating rotor.

A **reversible shaded-pole motor** was made by Barber-Colman several decades ago. It had a single field coil, and two principal poles, each split halfway to create two pairs of poles. Each of these four "half-poles" carried a coil, and the coils of diagonally opposite half-poles were connected to a pair of terminals. One terminal of each pair was common, so only three terminals were needed in all.

The motor would not start with the terminals open; connecting the common to one other made the motor run one way, and connecting common to the other made it run the other way. These motors were used in industrial and scientific devices.

An unusual, **adjustable-speed**, low-torque shaded-pole motor could be found in traffic-light and advertising-lighting controllers. The pole faces were parallel and relatively close to each other, with the disc centered between them, something like the disc in a watthour meter. Each pole face was split, and had a shading coil on one part; the shading coils were on the parts that faced each other.

Applying AC to the coil created a field that progressed in the gap between the poles. The plane of the stator core was approximately tangential to an imaginary circle on the disc, so the travelling magnetic field dragged the disc and made it rotate.

The stator was mounted on a pivot so it could be positioned for the desired speed and then clamped in position. Placing the poles nearer to the center of the disc made it run faster, and toward the edge, slower.

Split-phase motor

Another common single-phase AC motor is the *split-phase induction motor*,[18] commonly used in major appliances such as air conditioners and clothes dryers. Compared to the shaded pole motor, these motors provide much greater starting torque.

A split-phase motor has a secondary startup winding that is 90 electrical degrees to the main winding, always centered directly between the poles of the main winding, and connected to the main winding by a set of electrical contacts. The coils of this winding are wound with fewer turns of smaller wire than the main winding, so it has a lower inductance and higher resistance. The position of the winding creates a small phase shift between the flux of the main winding and the flux of the starting winding, causing the rotor to rotate. When the speed of the motor is sufficient to overcome the inertia of the load, the contacts are opened automatically by a centrifugal switch or electric relay. The direction of rotation is determined by the connection between the main winding and the start circuit. In applications where the motor requires a fixed rotation, one end of the start circuit is permanently connected to the main winding, with the contacts making the connection at the other end.

Capacitor start motor

A capacitor start motor is a split-phase induction motor with a starting capacitor inserted in series with the startup winding, creating an LC circuit which produces a greater phase shift (and so, a much greater starting torque) than both split-phase and shaded pole motors.

Resistance start motor

A resistance start motor is a split-phase induction motor with a starter inserted in series with the startup winding, creating reactance. This added starter provides assistance in the starting and initial direction of rotation. The start winding is made mainly of thin wire with fewer turns to make it high resistive and less inductive. The main winding is made with thicker wire with larger number of turns which makes it less resistive and more inductive.

Permanent-split capacitor motor

Another variation is the *permanent-split capacitor (or PSC) motor*.Also known as a capacitor-run motor, this type of motor uses a non-polarized capacitor with a high voltage rating to generate an electrical phase shift between the run and start windings. PSC motors are the dominant type of split-phase motor in Europe and much of the world, but in North America, they are most frequently used in variable torque applications (like blowers, fans, and pumps) and other cases where variable speeds are desired.

A capacitor with a relatively low capacitance, and relatively high voltage rating, is connected in series with the start winding and remains in the circuit during the entire run cycle.[19] Like other split-phase motors, the main winding is used with a smaller start winding, and rotation is changed by reversing the connection between the main winding and the start circuit, or by having polarity of main winding switched while start winding is always connected to a capacitor. There are significant differences, however; the use of a speed sensitive centrifugal switch requires that other split-phase motors must operate at, or very close to, full speed. PSC motors may operate within a wide range of speeds, much lower than the motor's electrical speed. Also, for applications like automatic door openers that require the motor to reverse rotation often, the use of a mechanism requires that a motor must slow to a near stop before contact with the start winding is re-established. The 'permanent' connection to the capacitor in a PSC motor means that changing rotation is instantaneous.

Three-phase motors can be converted to PSC motors by making common two windings and connecting the third via a capacitor to act as a start winding. However, the power rating needs to be at least 50% larger than for a comparable single-phase motor due to an unused winding.

Three-phase system with rotating magnetic fields.

Polyphase synchronous motor

If connections to the rotor coils of a three-phase motor are taken out on slip-rings and fed a separate field current to create a continuous magnetic field (or if the rotor consists of a permanent magnet), the result is called a synchronous motor because the rotor will rotate synchronously with the rotating magnetic field produced by the polyphase electrical supply. Another synchronous motor system is the brushless wound-rotor doubly fed synchronous motor system with an independently excited rotor multiphase AC winding set that may experience slip-induction beyond synchronous speeds but like all synchronous motors, does not rely on slip-induction for torque production.

The synchronous motor can also be used as an alternator.

Contemporary synchronous motors are frequently driven by solid state variable-frequency drives. This greatly eases the problem of starting the massive rotor of a large synchronous motor. They may also be started as induction motors using a squirrel-cage winding that shares the common rotor: once the motor reaches synchronous speed, no current is induced in the squirrel-cage winding so it has little effect on the synchronous operation of the motor, aside from stabilizing the motor speed on load changes.

Synchronous motors are occasionally used as traction motors; the TGV may be the best-known example of such use.

Huge numbers of three phase synchronous motors are now fitted to electric cars. They have a neodymium or other rare-earth permanent magnet.One use for this type of motor is its use in a power factor correction scheme. They are referred to as synchronous condensers. This exploits a feature of the machine where it consumes power at a leading power factor when its rotor is over excited. It thus appears to the supply to be a capacitor, and could thus be used to correct the lagging power factor that is usually presented to the electric supply by inductive loads. The excitation is adjusted until a near unity power factor is obtained (often automatically). Machines used for this purpose are easily identified as they have no shaft extensions. Synchronous motors are valued in any case because their power factor is much better than that of induction motors, making them preferred for very high power applications.

Some of the largest AC motors are pumped-storage hydroelectricity generators that are operated as synchronous motors to pump water to a reservoir at a higher elevation for later use to generate electricity using the same machinery. Six 500-megawatt generators are installed in the Bath County Pumped Storage Station in Virginia, USA. When pumping, each unit can produce 642,800 horsepower (479.3 megawatts).

Single-phase synchronous motor

Small single-phase AC motors can also be designed with magnetized rotors (or several variations on that idea; see "Hysteresis synchronous motors" below).

If a conventional squirrel-cage rotor has flats ground on it to create salient poles and increase reluctance, it will start conventionally, but will run synchronously, although it can provide only a modest torque at synchronous speed. This is known as a reluctance motor.

Because inertia makes it difficult to instantly accelerate the rotor from stopped to synchronous speed, these motors normally require some sort of special feature to get started. Some include a squirrel-cage structure to bring the rotor close to synchronous speed. Various other designs use a small induction motor (which may share the same field coils and rotor as the synchronous motor) or a very light rotor with a one-way mechanism (to ensure that the rotor starts in the "forward" direction). In the latter instance, applying AC power creates chaotic (or seemingly chaotic) jumping movement back and forth; such a motor will always start, but lacking the anti-reversal mechanism, the direction it runs is unpredictable. The Hammond organ tone generator used a non-self-starting synchronous motor (until comparatively recently), and had an auxiliary conventional shaded-pole starting motor. A spring-loaded auxiliary manual starting switch connected power to this second motor for a few seconds.

Hysteresis synchronous motor

These motors are relatively costly, and are used where exact speed (assuming an exact-frequency AC source) and rotation with low flutter (high-frequency variation in speed) are essential. Applications included tape recorder capstan drives (the motor shaft could be the capstan), and, before the advent of crystal control, motion picture cameras and recorders. Their distinguishing feature is their rotor, which is a smooth cylinder of a magnetic alloy that stays magnetized, but can be demagnetized fairly easily as well as re-magnetized with poles in a new location. Hysteresis refers to how the magnetic flux in the metal lags behind the external magnetizing force; for instance, to demagnetize such a material, one could apply a magnetizing field of opposite polarity to that which originally magnetized the material. These motors have a stator like those of capacitor-run squirrel-cage induction motors. On startup, when slip decreases sufficiently, the rotor becomes magnetized by the stator's field, and the poles stay in place. The motor then runs at synchronous speed as if the rotor were a permanent magnet. When stopped and restarted, the poles are likely to form at different locations. For a given design, torque at synchronous speed is only relatively modest, and the motor can run at below synchronous speed. In simple words, it is lagging magnetic field behind magnetic flux.

Other AC motor types

Universal motor and series wound motor

A universal motor is a design that can operate on either AC or DC power. In universal motors the stator and rotor of a brushed DC motor are both wound and supplied from an external source, with the torque being a function of the rotor current times the stator current so reversing the current in both rotor and stator does not reverse the rotation. Universal motors can run on AC as well as DC provided the frequency is not so high that the inductive reactance of the stator winding and eddy current losses become problems. Nearly all universal motors are series-wound because their stators have relatively few turns, minimizing inductance. Universal motors are compact, have high starting torque and can be varied in speed over a wide range with relatively simple controls such as rheostats and PWM choppers. Compared with induction motors, universal motors do have some drawbacks inherent to their brushes and commutators: relatively high levels of electrical and acoustic noise, low reliability and more frequent required maintenance.

Universal motors are widely used in small home appliances and hand power tools. Until the 1970s they dominated electric traction (electric, including diesel-electric railway and road vehicles); many traction power networks still use special low frequencies such as 16.7 and 25 Hz to overcome the aforementioned problems with losses and reactance. Still widely used, universal traction motors have been increasingly displaced by polyphase AC induction and permanent magnet motors with variable-frequency drives made possible by modern power semiconductor devices.

Repulsion motor

Repulsion motors are wound-rotor single-phase AC motors that are a type of induction motor. In a repulsion motor, the armature brushes are shorted together rather than connected in series with the field, as is done with universal motors. By transformer action, the stator induces currents in the rotor, which create torque by repulsion instead of attraction as in other motors. Several types of repulsion motors have been manufactured, but the *repulsion-start induction-run* (RS-IR) motor has been used most frequently. The RS-IR motor has a centrifugal switch that shorts all segments of the commutator so that the motor operates as an induction motor once it is close to full speed. Some of these motors also lift the brushes out of contact with source voltage regulation. Repulsion motors were developed before suitable motor starting capacitors were available, and few repulsion motors are sold as of 2005.

MODULE-4
SYNCHRONOUS GENERATOR

INTRODUCTION

An **alternator** is an electrical generator that converts mechanical energy to electrical energy in the form of alternating current.[2] For reasons of cost and simplicity, most alternators use a rotating magnetic field with a stationary armature.[3] Occasionally, a linear alternator or a rotating armature with a stationary magnetic field is used. In principle, any AC electrical generator can be called an alternator, but usually the term refers to small rotating machines driven by automotive and other internal combustion engines.

An alternator that uses a permanent magnet for its magnetic field is called a magneto. Alternators in power stations driven by steam turbines are called turbo-alternators. Large 50 or 60 Hz three-phase alternators in power plants generate most of the world's electric power, which is distributed by electric power grids.[4]

Alternating current generating systems were known in simple forms from the discovery of the magnetic induction of electric current in the 1830s. Rotating generators naturally produced alternating current but, since there was little use for it, it was normally converted into direct current via the addition of a commutator in the generator. The early machines were developed by pioneers such as Michael Faraday and Hippolyte Pixii. Faraday developed the "rotating rectangle", whose operation was *heteropolar* – each active conductor passed successively through regions where the magnetic field was in opposite directions.[9] Lord Kelvin and Sebastian Ferranti also developed early alternators, producing frequencies between 100 and 300 Hz..

Principle of operation

A conductor moving relative to a magnetic field develops an electromotive force (EMF) in it (Faraday's Law). This EMF reverses its polarity when it moves under magnetic poles of opposite polarity. Typically, a rotating magnet, called the rotor turns within a stationary set of conductors wound in coils on an iron core, called the stator. The field cuts across the conductors, generating an induced EMF (electromotive force), as the mechanical input causes the rotor to turn.

The rotating magnetic field induces an AC voltage in the stator windings. Since the currents in the stator windings vary in step with the position of the rotor, an alternator is a synchronous generator.[3]

The rotor's magnetic field may be produced by permanent magnets, or by a field coil electromagnet. Automotive alternators use a rotor winding which allows control of the alternator's generated voltage by varying the current in the rotor field winding. Permanent magnet machines avoid the loss due to magnetizing current in the rotor, but are restricted in size, due to the cost of the magnet material. Since the permanent magnet field is constant, the terminal voltage varies directly with the speed of the generator. Brushless AC generators are usually larger than those used in automotive applications.

An automatic voltage control device controls the field current to keep output voltage constant. If the output voltage from the stationary armature coils drops due to an increase in demand, more current is fed into the rotating field coils through the voltage regulator (VR). This increases the magnetic field around the field coils which induces a greater voltage in the armature coils. Thus, the output voltage is brought back up to its original value.

Alternators used in central power stations also control the field current to regulate reactive power and to help stabilize the power system against the effects of momentary faults. Often there are three sets of stator windings, physically offset so that the rotating magnetic field produces a three phase current, displaced by one-third of a period with respect to each other. [17]

Synchronous speeds

One cycle of alternating current is produced each time a pair of field poles passes over a point on the stationary winding. The relation between speed and frequency is where is the frequency in Hz (cycles per second). is the number of poles (2, 4, 6, …) and is the rotational speed in revolutions per minute (RPM). Very old descriptions of alternating current systems sometimes give the frequency in terms of alternations per minute, counting each half-cycle as one *alternation*; so 12,000 alternations per minute corresponds to 100 Hz.

The output frequency of an alternator depends on the number of poles and the rotational speed. The speed corresponding to a particular frequency is called the *synchronous speed* for that frequency. This table[18] gives some examples:

Poles	Rotation speed (RPM), giving…		
	50 Hz	**60 Hz**	**400 Hz**
2	3,000	3,600	24,000
4	1,500	1,800	12,000
6	1,000	1,200	8,000
8	750	900	6,000
10	600	720	4,800
12	500	600	4,000
14	428.6	514.3	3,429
16	375	450	3,000
18	333.3	400	2,667
20	300	360	2,400
40	150	180	1,200

Classifications

Alternators may be classified by method of excitation, number of phases, the type of rotation, cooling method, and their application.

By excitation

There are two main ways to produce the magnetic field used in the alternators, by using permanent magnets which create their own persistent magnetic field or by using field coils. The alternators that use permanent magnets are specifically called magnetos.

In other alternators, wound field coils form an electromagnet to produce the rotating magnetic field.

A device that uses permanent magnets to produce alternating current is called a permanent magnet alternator (PMA). A permanent magnet generator (PMG) may produce either alternating current, or direct current if it has a commutator.

Direct-connected direct-current (DC) generator

This method of excitation consists of a smaller direct-current (DC) generator fixed on the same shaft with the alternator. The DC generator generates a small amount of electricity just enough to *excite* the field coils of the connected alternator to generate electricity. A variation of this system is a type of alternator which uses direct current from the battery for initial excitation upon start-up, after which the alternator becomes self-excited.[19]

Transformation and rectification

This method depends on residual magnetism retained in the iron core to generate weak magnetic field which would allow a weak voltage to be generated. This voltage is used to excite the field coils for the alternator to generate stronger voltage as part of its *build up* process. After the initial AC voltage buildup, the field is supplied with rectified voltage from the alternator.[19]

Brushless alternators

A brushless alternator is composed of two alternators built end-to-end on one shaft. Until 1966, alternators used brushes with rotating field.[20] With advancement in semiconductor technology, brushless alternators are possible. Smaller brushless alternators may look like one unit but the two parts are readily identifiable on the large versions. The larger of the two sections is the main alternator and the smaller one is the exciter. The exciter has stationary field coils and a rotating armature (power coils). The main alternator uses the opposite configuration with a rotating field and stationary armature. A bridge rectifier, called the rotating rectifier assembly, is mounted on the rotor. Neither brushes nor slip rings are used, which reduces the number of wearing parts. The main alternator has a rotating field as described above and a stationary armature (power generation windings).

Varying the amount of current through the stationary exciter field coils varies the 3-phase output from the exciter. This output is rectified by a rotating rectifier assembly, mounted on the rotor, and the resultant DC supplies the rotating field of the main alternator and hence alternator output. The result of all this is that a small DC exciter current indirectly controls the output of the main alternator.

By number of phases

Another way to classify alternators is by the number of phases of their output voltage. The output can be single phase, or polyphase. Three-phase alternators are the most common, but polyphase alternators can be two phase, six phase, or more.[19]

By rotating part

The revolving part of alternators can be the armature or the magnetic field. The revolving armature type has the armature wound on the rotor, where the winding moves through a stationary magnetic field. The revolving armature type is not often used.[19] The revolving field type has magnetic field on the rotor to rotate through a stationary armature winding. The advantage is that then the rotor circuit carries much less power than the armature circuit, making the slip ring connections smaller and less costly; only two contacts are needed for the direct-current rotor, whereas often a rotor winding has three phases and multiple sections which would each require a slip-ring connection. The stationary armature can be wound for any convenient medium voltage level, up to tens of thousands of volts; manufacture of slip ring connections for more than a few thousand volts is costly and inconvenient.

Cooling methods

Many alternators are cooled by ambient air, forced through the enclosure by an attached fan on the same shaft that drives the alternator. In vehicles such as transit buses, a heavy demand on the electrical system may require a large alternator to be oil-cooled. [22] In marine applications water-cooling is also used. Expensive automobiles may use water-cooled alternators to meet high electrical system demands.

Specific applications

Electric generators

Most power generation stations use synchronous machines as their generators. Connection of these generators to the utility grid requires synchronization conditions to be met.[23]

Automotive alternators

Alternators are used in modern automobiles to charge the battery and to power the electrical system when its engine is running.

Until the 1960s, automobiles used DC dynamo generators with commutators. With the availability of affordable silicon diode rectifiers, alternators were used instead.

Diesel electric locomotive alternators

In later diesel electric locomotives and diesel electric multiple units, the prime mover turns an alternator which provides electricity for the traction motors (AC or DC).

The traction alternator usually incorporates integral silicon diode rectifiers to provide the traction motors with up to 1200 volts DC (DC traction, which is used directly) or the common inverter bus (AC traction, which is first inverted from dc to three-phase ac).

The first diesel electric locomotives, and many of those still in service, use DC generators as, before silicon power electronics, it was easier to control the speed of DC traction motors. Most of these had two generators: one to generate the excitation current for a larger main generator.

Optionally, the generator also supplies head end power (HEP) or power for electric train heating. The HEP option requires a constant engine speed, typically 900 RPM for a 480 V 60 Hz HEP application, even when the locomotive is not moving.

Marine alternators

Marine alternators used in yachts are similar to automotive alternators, with appropriate adaptations to the salt-water environment. Marine alternators are designed to be explosion proof so that brush sparking will not ignite explosive gas mixtures in an engine room environment. They may be 12 or 24 volt depending on the type of system installed. Larger marine diesels may have two or more alternators to cope with the heavy electrical demand of a modern yacht. On single alternator circuits, the power may be split between the engine starting battery and the domestic or house battery (or batteries) by use of a split-charge diode (battery isolator) or a voltage-sensitive relay.

Radio alternators

High frequency alternators of the variable-reluctance type were applied commercially to radio transmission in the low-frequency radio bands. These were used for transmission of Morse code and, experimentally, for transmission of voice and music. In the Alexanderson alternator, both the field winding and armature winding are stationary, and current is induced in the armature by virtue of the changing magnetic reluctance of the rotor (which has no windings or current carrying parts). Such machines were made to produce radio frequency current for radio transmissions, although the efficiency was low.

Synchronous Generator Working Principle

The electrical machine can be defined as a device that converts electrical energy into mechanical energy or mechanical energy into electrical energy. An electrical generator can be defined as an electrical machine that converts mechanical energy into electrical energy. An electrical generator typically consists of two parts;

stator and rotor. There are various types of electrical generators such as direct current generators, alternating current generators, vehicular generators, human powered electrical generators, and so on. In this article, let us discuss about synchronous generator working principle.

Synchronous Generator

The rotating and stationary parts of an electrical machine can be called as rotor and stator respectively. The rotor or stator of electrical machines acts as a power-producing component and is called as an armature. The electromagnets or permanent magnets mounted on the stator or rotor are used to provide magnetic field of an electrical machine. The generator in which permanent magnet is used instead of coil to provide excitation field is termed as permanent magnet synchronous generator or also simply called as synchronous generator.

Construction of Synchronous Generator

In general, synchronous generator consists of two parts rotor and stator. The rotor part consists of field poles and stator part consists of armature conductors. The rotation of field poles in the presence of armature conductors induces an alternating voltage which results in electrical power generation.

The speed of field poles is synchronous speed and is given by Where, 'f' indicates alternating current frequency and 'P' indicates number of poles.

Synchronous Generator Working Principle

The principle of operation of synchronous generator is electromagnetic induction. If there exits a relative motion between the flux and conductors, then an emf is induced in the conductors. To understand the synchronous generator working principle, let us consider two opposite magnetic poles in between them a rectangular coil or turn is placed as shown in the below **figure.**

If the rectangular turn rotates in clockwise direction against axis a-b as shown in the below figure, then after completing 90 degrees rotation the conductor sides AB and CD comes in front of the S-pole and N-pole respectively. Thus, now we can say that the conductor tangential motion is perpendicular to magnetic flux lines from north to south pole.

So, here rate of flux cutting by the conductor is maximum and induces current in the conductor, the direction of the induced current can be determined using Fleming's right hand rule. Thus, we can say that current will pass from A to B and from C to D. If the conductor is rotated in a clockwise direction for another 90 degrees, then it will come to a vertical position as shown in the below **figure.**

Now, the position of conductor and magnetic flux lines are parallel to each other and thus, no flux is cutting and no current will be induced in the conductor. Then, while the conductor rotates from clockwise for another 90 degrees, then rectangular turn comes to a horizontal position as shown in the below figure. Such that, the conductors AB and CD are under the N-pole and S-pole respectively. By applying Fleming's right hand rule, current induces in conductor AB from point B to A and current induces in a conductor CD from point D to C.

So, the direction of current can be indicated as A – D – C – B and direction of current for the previous horizontal position of rectangular turn is A – B – C – D. If the turn is again rotated towards vertical position, then the induced current again reduces to zero. Thus, for one complete revolution of rectangular turn the current in the conductor reaches to maximum & reduces to zero and then in the opposite direction it reaches to maximum & again reaches to zero. Hence, one complete revolution of rectangular turn produces one full sine wave of current induced in the conductor which can be termed as the generation of alternating current by rotating a turn inside a magnetic field.

Now, if we consider a practical synchronous generator, then field magnets rotate between the stationary armature conductors. The synchronous generator rotor and shaft or turbine blades are mechanically coupled to each other and rotates at synchronous speed. Thus, the magnetic flux cutting produces an induced emf which causes the current flow in armature conductors. Thus, for each winding the current flows in one direction for the first half cycle and current flows in the other direction for the second half cycle with a time lag of 120 degrees (as they displaced by 120 degrees). Hence, the output power of synchronous generator can be shown as below **figure.**

Do you want to know more about synchronous generators and are you interested in designing electronics projects? Feel free to share your views, ideas, suggestions, queries, and comments in the comment section below.

EMF Equation of a Synchronous Generator

The generator which runs at a synchronous speed is known as the synchronous generator. The synchronous generator converts the mechanical power into electrical energy for the grid.The Derivation of **EMF Equation** of a synchronous generator is given below.

Let,

P be the number of poles

ϕ is Flux per pole in Webers

N is the speed in revolution per minute (r.p.m)

f be the frequency in Hertz

Z_{ph} is the number of conductors connected in series per phase

T_{ph} is the number of turns connected in series per phase

K_c is the coil span factor

K_d is the distribution factor

Flux cut by each conductor during one revolution is given as **Pϕ** Weber. Time taken to complete one revolution is given by **60/N** sec

Average EMF induced per conductor will be given by the equation shown below

$$\frac{P\varphi}{60/N} = \frac{P\varphi N}{60} \quad \text{volts}$$

Average EMF induced per phase will be given by the equation shown below

$$\frac{P\varphi N}{60} \times Z_{ph} = \frac{P\varphi N}{60} \times 2T_{ph} \quad \text{and}$$

$$T_{ph} = \frac{Z_{ph}}{2}$$

$$\text{Average EMF} = 4 \times \varphi \times T_{ph} \times \frac{PN}{120} = 4\varphi f T_{ph}$$

The average EMF equation is derived with the following assumptions given below.

Coils have got the full pitch.

All the conductors are concentrated in one stator slot.

Root mean square (R.M.S) value of the EMF induced per phase is given by the equation shown below.

E_{ph} = Average value x form factor

Therefore,

$$E_{ph} = 4\varphi f T_{ph} \times 1.11 = 4.44\, \varphi\, f\, T_{ph} \quad \text{volts}$$

If the coil span factor K_c and the distribution factor K_d , are taken into consideration than the Actual EMF induced per phase is given as

$$E_{ph} = 4.44\, K_c K_d \varphi\, f\, T_{ph} \quad \text{volts} \;\ldots\ldots.. (1)$$

Equation (1) shown above is the EMF equation of the Synchronous Generator.

Coil Span Factor

The Coil Span Factor is defined as the ratio of the induced emf in a coil when the winding is short pitched to the induced emf in the same coil when the winding is full pitched.

Distribution Factor

Distribution factor is defined as the ratio of induced EMF in the coil group when the winding is distributed in a number of slots to the induced EMF in the coil group when the winding is concentrated in one slot.

Armature Reaction in Alternator or Synchronous Generator

Every rotating electrical machine works based on Faraday's law. Every electrical machine requires a magnetic field and a coil (Known as armature) with a relative motion between them. In case of an alternator, we supply electricity to pole to produce magnetic field and output power is taken from the armature. Due to relative motion between field and armature, the conductor of armatures cut the flux of magnetic field and hence there would be changing flux linkage with these armature conductors. According to Faraday's law of electromagnetic induction there would be an emf induced in the armature. Thus, as soon as the load is connected with armature terminals, there is a current flowing in the armature coil.

As soon as current starts flowing through the armature conductor there is one reverse effect of this current on the main field flux of the alternator (or synchronous generator). This reverse effect is referred as **armature**

reaction in alternator or synchronous generator. In other words, the effect of armature (stator) flux on the flux produced by the rotor field poles is called armature reaction. We already know that a current carrying conductor produces its own magnetic field, and this magnetic field affects the main magnetic field of the alternator. It has two undesirable effects, either it distorts the main field, or it reduces the main field flux or both. They deteriorate the performance of the machine. When the field gets distorted, it is known as a cross magnetizing effect. And when the field flux gets reduced, it is known as the demagnetizing effect.

The electromechanical energy conversion takes place through magnetic field as a medium. Due to relative motion between armature conductors and the main field, an emf is induced in the armature windings whose magnitude depends upon the relative speed and as well as the magnetic flux. Due to armature reaction, flux is reduced or distorted, the net emf induced is also affected and hence the performance of the machine degrades.

Armature Reaction in Alternator

In an alternator like all other synchronous machines, the effect of armature reaction depends on the power factor i.e the phase relationship between the terminal voltage and armature current. Reactive power (lagging) is the magnetic field energy, so if the generator supplies a lagging load, this implies that it is supplying magnetic energy to the load. Since this power comes from excitation of synchronous machine, the net reactive power gets reduced in the generator.

Hence, the armature reaction is demagnetizing. Similarly, the armature reaction has magnetizing effect when the generator supplies a leading load (as leading load takes the leading VAR) and in return gives lagging VAR (magnetic energy) to the generator. In case of purely resistive load, the armature reaction is cross magnetizing only.

The armature reaction of alternator or synchronous generator, depends upon the phase angle between, stator armature current and induced voltage across the armature winding of alternator. The phase difference between these two quantities, i.e. Armature current and voltage may vary from – $90^{\circ}$to+90°Ifthisangleisθ,then,

To understand actual effect of this angle on armature reaction of alternator, we will consider three standard cases,

When $\theta = 0$

When $\theta = 90^{\circ}$

When $\theta = -90^{\circ}$

Armature Reaction of Alternator at Unity Power Factor

At unity power factor, the angle between armature current I and induced emf E, is zero. That means, armature current and induced emf are in same phase. But we know theoretically that emf induced in the armature is due to changing main field flux, linked with the armature conductor. As the field is excited by DC, the main field flux is constant in respect to field magnets, but it would be alternating in respect of armature as there is a relative motion between field and armature in the alternator. If

main field flux of the alternator in respect of armature can be represented as Then induced emf E across the armature is proportional to, $d\varphi_f/dt$.

Hence, from these above equations (1) and (2) it is clear that the angle between, φ_f and induced emf E will be 90^o.

Now, armature flux φ_a is proportional to armature current I. Hence, armature flux φ_a is in phase with armature current I.

Again at unity electrical power factor I and E are in same phase. So, at unity power factor, φ_a is phase with E. So at this condition, armature flux is in phase with induced emf E and field flux is in quadrature with E. Hence, armature flux φ_a is in quadrature with main field flux φ_f.

As this two fluxes are perpendicular to each other, the **armature reaction of the alternator at unity power factor** is purely distorting or cross-magnetizing type.

As the armature flux pushes the main field flux perpendicularly, distribution of main field flux under a pole face does not remain uniformly distributed. The flux density under the trailing pole tips increases somewhat while under the leading pole tips it decreases.

Armature Reaction of Alternator at Lagging Zero Power Factor

At lagging zero electrical power factor, the armature current lags by 90^o to induced emf in the armature. As the emf induced in the armature coil due to main field flux thus the emf leads the main field flux by 90^o. From equation (1) we get, the field flux,

Hence, at $\omega t = 0$, E is maximum and φ_f is zero.

At $\omega t = 90^o$, E is zero and φ_f has maximum value.

At $\omega t = 180^o$, E is maximum and φ_f zero.

At $\omega t = 270^o$, E is zero and φ_f has negative maximum value.

Here, φ_f got maximum value 90^o before E. Hence φ_f leads E by 90^o.

Now, armature current I is proportional to armature flux φ_a, and I lags E by 90^o. Hence, φ_a lags E by 90^o.

So, it can be concluded that, field flux φ_f leads E by 90^o.

Therefore, armature flux and field flux act directly opposite to each other. Thus, armature reaction of the alternator at lagging zero power factor is a purely demagnetising type. That means, armature flux directly weakens main field flux.

Armature Reaction of Alternator at Leading Power Factor

At leading power factor condition, armature current "I" leads induced emf E by an angle 90°. Again, we have shown just, field flux φ_f leads, induced emf E by 90°. Again, armature flux φ_a is proportional to armature current I. Hence, φ_a is in phase with I. Hence, armature flux φ_a also leads E, by 90° as I leads E by 90°. As in this case both armature flux and field flux lead, induced emf E by 90°, it can be said, field flux and armature flux are in the same direction. Hence, the resultant flux is simply arithmetic sum of field flux and armature flux. Hence, at last, it can be said that armature reaction of alternator due to a purely leading electrical power factor is the magnetizing type.

Nature of Armature Reaction

The armature reaction flux is constant in magnitude and rotates at synchronous speed.

The armature reaction is cross magnetising when the generator supplies a load at unity power factor.

When the generator supplies a load at leading power factor the armature reaction is partly demagnetising and partly cross-magnetising.

When the generator supplies a load at leading power factor the armature reaction is partly magnetising and partly cross-magnetising.

Armature flux acts independently of main field flux.

Zero Power Factor(ZPF) or Potier Triangle Method For Regulation Of Alternator

Zero Power Factor (ZPF) for regulation of alternator:

This **Zero power factor (ZPF) method** is used to determine the **voltage regulation of synchronous generator or alternator**. This method is also called **Potier method**. In the operation of an alternator, the armature resistance drop IRa and armature leakage reactance drop IXL are actually emf quantities while the armature reaction is basically MMF quantity. In the synchronous Impedance, all the quantities are treated as EMF quantities as against this in MMF method all are treated as MMF quantities.

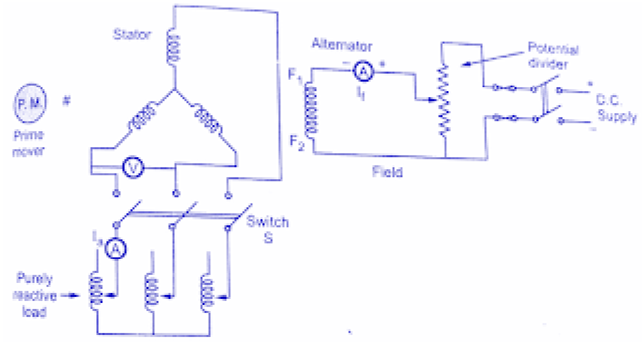
Key Point: This **zpf method** is based on the separation of armature leakage reactance and armature reaction effects. The armature leakage reactance XL is called Potier reactance in this method, hence **ZPF method** is also called **Potier reactance method**.

To determine armature leakage reactance and armature reaction MMF separately two tests are performed on the alternator. The two tests are

1. **Open circuit test**
2. **Zero power factor test**

1.Open circuit test:

The below is the block diagram to perform open circuit test on the alternator.



Open circuit test is done step by step from the following points,

1.TheswitchSisopened.

2. The alternator is made to rotate using prime mover at synchronous speed and same speed is maintainedconstantthroughoutthetest.

3. The excitation value is changed using a potential divider, from zero up to the rated value in a definite number of steps. The open circuit EMF is measured with the help of voltmeter. The readingsaretabulated.

4. A graph of If and (Voc)ph i.e. field current and open circuit voltage per phase is plotted to some scale. This is open circuit characteristics.

2.Zero power factor test:

To conduct *zero power factor test*, the switch S is kept closed. Due to this, a purely inductive load gets connected to an alternator through an ammeter. A purely inductive load has a power factor of cos 90° i.e. zero lagging hence the test is called **zero power factor test**.

The machine speed is maintained constant at its synchronous value. The load current delivered by an alternator to purely inductive load is maintained constant at its rated full load value by varying excitation and by adjusting variable inductance of the inductive bad. Note that, due to purely inductive load, an alternator will always operate at **zero power factor** lagging.

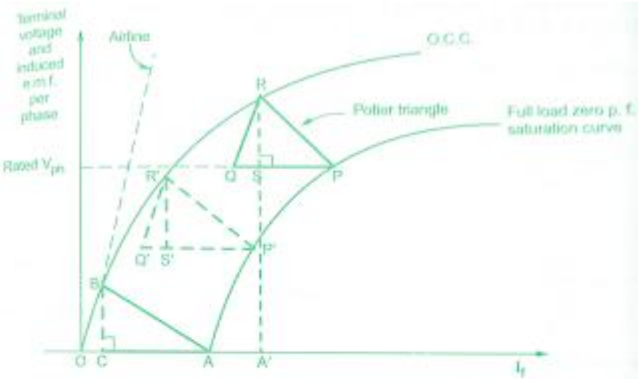
Key Point: *In this test, there is no need to obtain a number of points to obtain the curve. Only two points are enough to construct a curve called **zero power factor** saturation curve.*

The below is the graph of terminal voltage against excitation when delivering full load **zero power factor** current. One point for this curve is zero terminal voltage (short circuit condition) and the field current required to deliver full load short circuit armature current. While other point field current required to obtain rated terminal voltage while delivering rated full load armature current. With the help of these two points, the **zero power factor** saturation curve can be obtained as

1. Plot open circuit characteristics on a graph paper as shown in the below **figure.**

2. Plot the excitation corresponding to zero terminal voltage i.e. short circuit full **zero power**

factor armature current. This point is shown as A in the below figure which the x-axis. Another point is the rated voltage when the alternator is delivering full current at zero p.f. lagging. This point is P as shown in the below figure.



3. Draw the tangent to O.C.C. through origin which is line OB as shown dotted in below figure. This is called air line.

4. Draw the horizontal line PQ parallel and equal to OA.

5. From point, Q draw the line parallel to the air line which intersects O.C.C. at point R. Join RQ and join PR. The triangle PQR is called **Potier triangle**.

6. From point R, drop a perpendicular on PQ to meet at point S.

7. The **zero power factor** full load saturation curve is now be constructed by moving triangle PQR so that R remains always on OCC and line PQ always remains horizontal. The dotted triangle is shown in the above figure. It must be noted that the **Potier triangl**e once obtained is constant for a given armature current and hence can be transferred as it is.

8.Though point A, draw a line parallel to PR meeting OCC at point B. From B, draw a perpendicular on OA to meet it at point C. Triangles OAB and PQR are similar triangles.

9. The perpendicular RS gives the voltage drop due to the armature leakage reactance i.e. IXL

10. The length PS gives field current necessary to overcome the demagnetising effect of armature reaction at full load.

11. The length SQ represents field current required to induce an EMF for balancing leakage reactance drop RS. These values can be obtained from any **Potier triangle** such as OAB, PQR and so on.

So armature leakage reactance can be obtained as,

$$l\,(RS) = l\,(BC) = (I_{aph})_{F.L.} \times X_{L\,ph}$$

$$X_{L\,ph} = \frac{l\,(RS) \text{ or } l(BC)}{(I_{aph})\ F.L.}\quad \Omega$$

This is nothing but the Potier reactance.

Voltage Regulation of Synchronous Generator By MMF method:-

This method is also known as amp - turns method. In this method the all the emfs produced by rotor and stator are replaced by their equivalent MMFs (fluxes), and hence called **mmf method**.

In this method also it is assumed that the magnetic circuit is unsaturated. In this method both the reactance drops are replaced by their equivalent mmfs. Figure shows the complete phasor diagram for the mmf method. Similar to emf method OC and SC characteristics are used for the determination of regulation by mmf method. Using the details it is possible determine the regulation at different power factors.

From the phasor diagram it can be seen that the mmf required to produce the emf E1= (V + IRa) is FR1.In large machines resistance drop may neglected.

The mmf required to over come the reactance drops is (A+Ax) as shown in phasor diagram. The mmf (A+Ax) can be found from SC characteristic as under SC condition both reactance drops will be present.

Following procedure can be used for determination of regulation by mmf method.

(i) By conducting OC and SC test plot OCC and SCC as shown in figure 2.

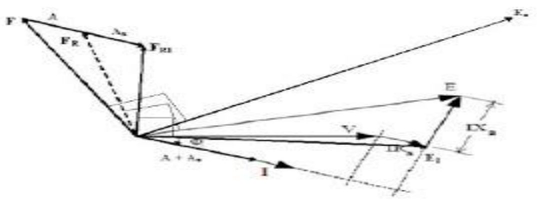
(ii) From the OCC find the field current If1 required to produce the voltage, E1= (V + IRa).

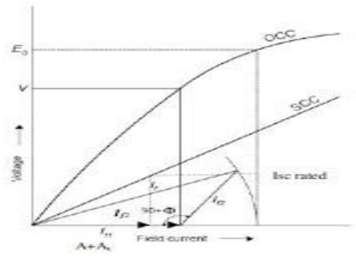
(iii) From SCC find the magnitude of field current If2=(A+Ax) to produce the required armature current. A+Ax can also found from ZPF characteristics.

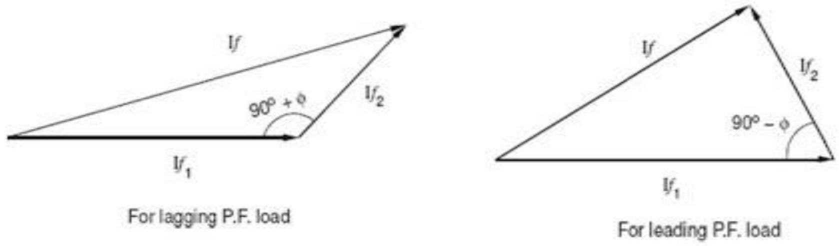
(iv) Draw If2 at angle (90+Ø) from If1, where Ø is the phase angle of current w. r. t voltage. If current is leading, take the angle of If2 as (90- Ø) as shown in figure 36.

(v) Determine the resultant field current, If and mark its magnitude on the field current axis.

(vi) From OCC. find the voltage corresponding to If, which will be E0 and hence find the regulation.







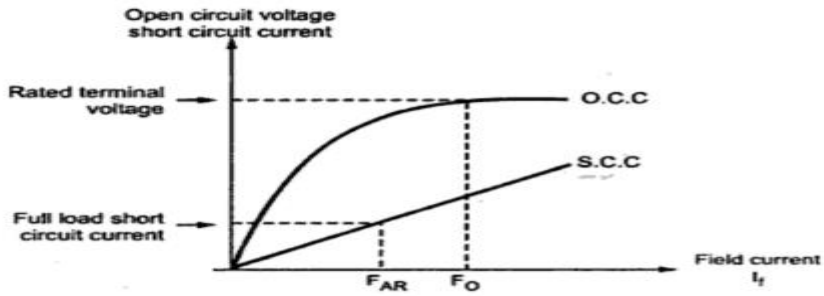
Note : In most of the cases as number of turns on the field winding is not known, the m.m.f. is calculate and expressed i terms of the field current itself.

Because of the assumption of unsaturated magnetic circuit the regulation computed by this method will be less than the actual and hence this method of regulation is called **optimistic method.**

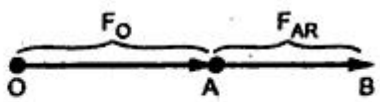
Another Derivation For MMF Method:-

Theory is same as above

The two components of total field m.m.f. which are FO and FAR are indicated in O.C.C. (open circuit characteristics) and S.C.C. (short circuit characteristics) as shown in the Figure.



Zero lagging p.f. : As long as power factor is zero lagging, the armature reaction is completely demagnetising. Hence the resultant FR is the algebraic sum of the two components FO and FAR. Field m.m.f. is not only required to produce rated terminal voltage but also required to overcome completely demagnetising armature reaction effect.



This is shown in the Fig

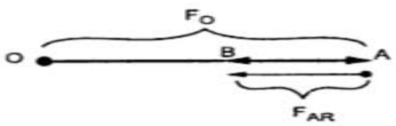
OA = FO

AB = FAR demagnetising

OB = FR = FO + FAR

Total field m.m.f. is greater than FO.

Zero leading p.f. : When the power factor is zero leading then the armature reaction is totally magnetizing and helps main flux to induce rated terminal voltage. Hence net field m.m.f. required is less than that required to induce rated voltage normally, as part of its function is done by magnetising armature reaction component. The net field m.m.f. is the algebraic difference between the two components FO and FAR.



This is shown in the Fig.

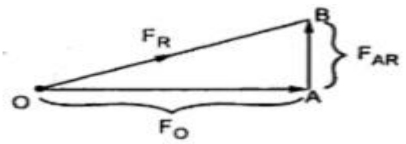
OA = FO

AB = FAR magnetising

OB = FO - FAR = FR

Total m.m.f. is less than FO.

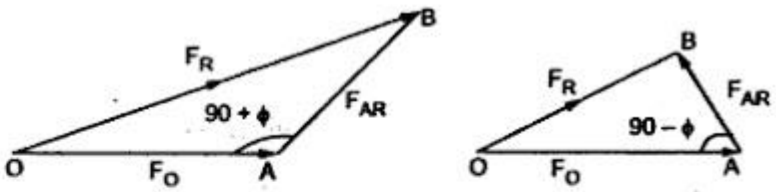
Unity p.f. : Under unity power factor condition, the armature reaction is cross magnetizing and its effect is to distort the main flux. Thus and F are at right angles to each other and hence resultant m.m.f. is the vector sum of FO and FAR.



OA = FO

AB = FAR cross magnetising

OB=FR=FO=FAR.



(a) cos ϕ lagging (b) cos ϕ leading

$(FR)^2 = (FO)^2 + (FAR)^2 - 2(FO)(FAR)Cos(FO \wedge FAR)$

FO^FAR =90-Φ if Φ leading

=90+Φ if Φ is lagging

Regulation :-

%R=Eph-Vph/Vph *100

Synchronization (alternating current)

In an alternating current electric power system, **synchronization** is the process of matching the speed and frequency of a generator or other source to a running network. An AC generator cannot deliver power to an electrical grid unless it is running at the same frequency as the network. If two segments of a grid are disconnected, they cannot exchange AC power again until they are brought back into exact synchronization.

A direct current (DC) generator can be connected to a power network by adjusting its open-circuit terminal voltage to match the network voltage, by either adjusting its speed or its field excitation. The exact engine speed is not critical. However, an AC generator must match both the amplitude and the timing of the network voltage, which requires both speed and excitation to be systematically controlled for synchronization. This extra complexity was one of the arguments against AC operation during the war of currents in the 1880s. In modern grids, synchronization of generators is carried out by automatic systems.

Conditions

There are five conditions that must be met before the synchronization process takes place. The source (generator or sub-network) must have equal line voltage, frequency, phase sequence, phase angle, and waveform to that of the system to which it is being synchronized.[1].

Waveform and phase sequence are fixed by the construction of the generator and its connections to the system. During installation of a generator, careful checks are made to ensure the generator terminals and all control wiring is correct so that the order of phases (phase sequence) matches the system. Connecting a generator with the wrong phase sequence will result in a short circuit as the system voltages are opposite to those of the generator terminal voltages.[2]

The voltage, frequency and phase angle must be controlled each time a generator is to be connected to a grid.

Generating units for connection to a power grid have an inherent droop speed control that allows them to share load proportional to their rating. Some generator units, especially in isolated systems, operate with isochronous frequency control, maintaining constant system frequency independent of load.

Process

The sequence of events is similar for manual or automatic synchronization. The generator is brought up to approximate synchronous speed by supplying more energy to its shaft - for example, opening the valves on a steam turbine, opening the gates on a hydraulic turbine, or increasing the fuel rack setting on a diesel engine. The field of the generator is energized and the voltage at the terminals of the generator is observed and compared with the system. The voltage magnitude must be the same as the system voltage. If one machine is slightly out of phase it will pull into step with the others but, if the phase difference is large, there will be heavy cross-currents which can cause voltage fluctuations and, in extreme cases, damage to the machines.

From top to bottom: synchroscope, voltmeter, frequency meter. When the two systems are synchronized, the pointer on the synchrosope is stationary and points straight up.

Synchronizing lamps

Formerly, three light bulbs were connected between the generator terminals and the system terminals (or more generally, to the terminals of instrument transformers connected to generator and system). As the generator speed changes, the lights will flicker at the beat frequency proportional to the difference between generator frequency and system frequency. When the voltage at the generator is opposite to the system voltage (either ahead or behind in phase), the lamps will be bright. When the voltage at the generator matches the system voltage, the lights will be dark. At that instant, the circuit breaker connecting the generator to the system may be closed and the generator will then stay in synchronism with the system.

An alternative technique used a similar scheme to the above except that the connections of two of the lamps were swapped either at the generator terminals or the system terminals. In this scheme, when the generator was in synchronism with the system, one lamp would be dark, but the two with the swapped connections would be of equal brightness. Synchronizing on "dark" lamps was preferred over "bright" lamps because it was easier to discern the minimum brightness. However, a lamp burnout could give a false-positive for successful synchronization.

Synchroscope

Another manual method of synchronization relies on observing an instrument called a "synchroscope", which displays the relative frequencies of system and generator. The pointer of the synchroscope will indicate "fast" or "slow" speed of the generator with respect to the system. To minimize the transient current when the generator circuit breaker is closed, usual practice is to initiate the close as the needle slowly approaches the in-phase point. An error of a few electrical degrees between system and generator will result in a momentary inrush and abrupt speed change of the generator.

Synchronizing relays

Synchronizing relays allow unattended synchronization of a machine with a system. Today these are digital microprocessor instruments, but in the past electromechanical relay systems were applied. A synchronizing relay is useful to remove human reaction time from the process, or when a human is not available such as at a remote controlled generating plant. Synchroscopes or lamps are sometimes installed as a supplement to automatic relays, for possible manual use or for monitoring the generating unit.

Sometimes as a precaution against out-of-step connection of a machine to a system, a "synchro check" relay is installed that prevents closing the generator circuit breaker unless the machine is within a few electrical degrees of being in-phase with the system. Synchro check relays are also applied in places where several sources of supply may be connected and where it is important that out-of-step sources are not accidentally paralleled.

Synchronous operation

While the generator is synchronized, the frequency of the system will change depending on load and the average characteristics of all the generating units connected to the grid.[1] Large changes in system frequency can cause the generator to fall out of synchronism with the system. Protective devices on the generator will operate to disconnect it automatically.

Synchronous speeds

Synchronous speeds for synchronous motors and alternators depend on the number of poles on the machine and the frequency of the supply.

The relationship between the supply frequency, f, the number of poles, p, and the synchronous speed (speed of rotating field), n_s is given by:

In the following table, frequencies are shown in hertz (Hz) and rotational speeds in revolutions per minute (rpm):

No. of poles	Speed (rpm) at 50 Hz	Speed (rpm) at 60 Hz
2	3,000	3,600
4	1,500	1,800
6	1,000	1,200
8	750	900
10	600	720
12	500	600
14	429	514
16	375	450
18	333	400
20	300	360
22	273	327
24	250	300
26	231	277
28	214	257
30	200	

Two Reaction Theory – Salient Pole Synchronous Machine

Two Reaction Theory was proposed by **Andre Blondel**. The theory proposes to resolve the given armature MMFs into two mutually perpendicular components, with one located along the axis of the rotor of the salient pole. It is known as the **direct axis** or **d axis** component. The other component is located perpendicular to the axis of the rotor salient pole. It is known as the **quadrature axis** or **q axis** component.

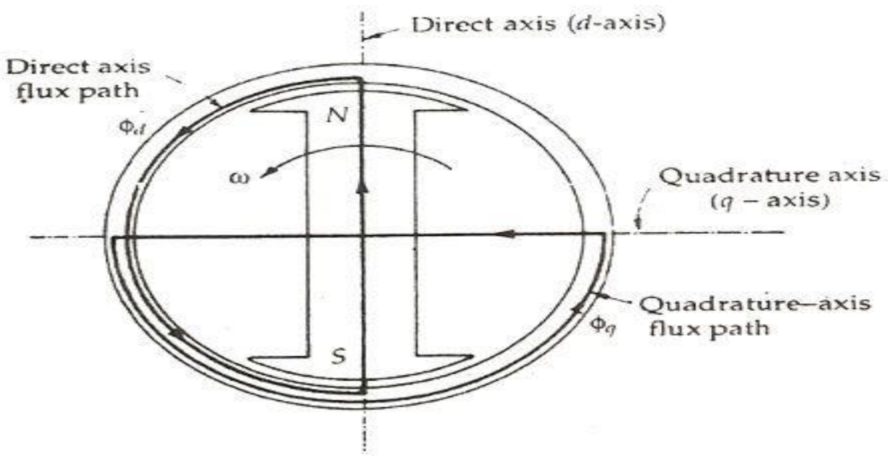
The d axis component of the armature MMF F_a is denoted by F_d and the q axis component by F_q. The component F_d is either magnetizing or demagnetizing. The component F_q results in a cross-magnetizing effect. If Ψ is the angle between the armature current I_a and the excitation voltage E_f and F_a is the amplitude of the armature MMF, then

$$F_d = F_a \sin\Psi \qquad \text{and}$$

$$F_q = F_a \cos\Psi$$

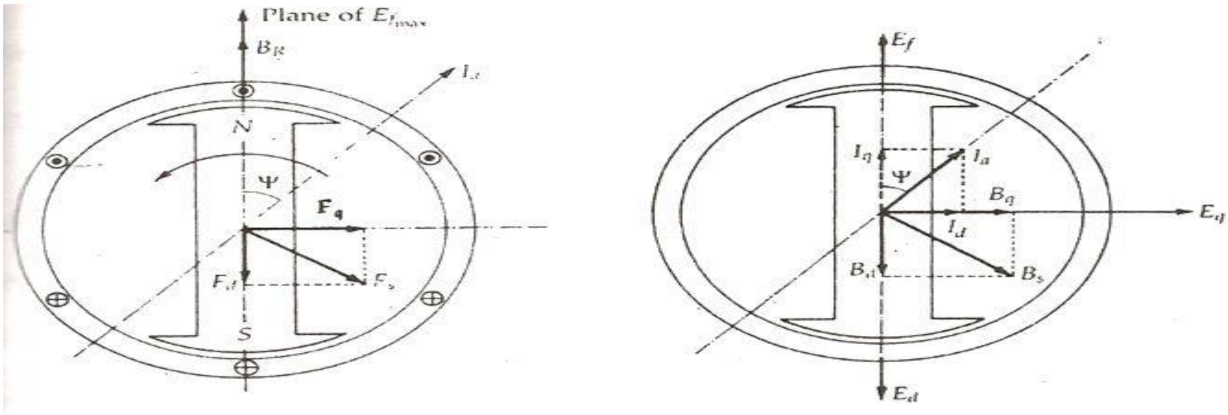
Salient Pole Synchronous Machine Two Rection Theory

In the cylindrical rotor synchronous machine, the air gap is uniform. The pole structure of the rotor of a salient pole machine makes the air gap highly non-uniform. Consider a 2 pole, salient pole rotor rotating in the anticlockwise direction within a 2 pole stator as shown in the figure below.



The axis along the axis of the rotor is called the direct or the d axis. The axis perpendicular to d axis is known as the quadrature or q axis. The direct axis flux path involves two small air gaps and is the path of the minimum reluctance. The path shown in the above figure by ϕ_q has two large air gaps and is the path of the maximum reluctance.

The rotor flux B_R is shown vertically upwards as shown in the figure below.



The rotor flux induces a voltage E_f in the stator. The stator armature current I_a will flow through the synchronous motor when a lagging power factor load is connected it. This stator armature current I_a lags behind the generated voltage E_f by an angle Ψ.

The armature current produces stator magnetomotive force F_s. This MMF lags behind I_a by angle 90 degrees. The MMF F_S produces stator magnetic field B_S long the direction of Fs. The stator MMF is resolved into two components, namely the direct axis component F_d and the quadrature axis component F_q.

If,

ϕ_d is the direct axis flux

Φ_q is the quadrature axis flux

R_d is the reluctance of the direct axis flux path

Therefore

$$\varphi_d = \frac{F_d}{R_d}$$

$$\varphi_q = \frac{F_q}{R_q}$$

As, $R_d < R_q$, the direct axis component of MMF F_d produces more flux than the quadrature axis component of the MMF. The fluxes of the direct and quadrature axis produce a voltage in the windings of the stator by armature reaction.

Let,

E_{ad} be the direct axis component of the armature reaction voltage.

E_{aq} be the quadrature axis component of the armature reaction voltage.

Since each armature reaction voltage is directly proportional to its stator current and lags behind by 90 degrees angles. Therefore, armature reaction voltages can be written as shown below.

$$E_{ad} = -j\, X_{ad}\, I_d \quad \dots\dots\dots (1)$$

$$E_{aq} = -j\, X_{aq}\, I_q \quad \dots\dots\dots (2)$$

Where,

X_{ad} is the armature reaction reactance in the direct axis per phase.

X_{aq} is the armature reaction reactance in the quadrature axis per phase.

The value of X_{ad} is always greater than X_{aq}. As the EMF induced by a given MMF acting on the direct axis is smaller than for the quadrature axis due to its higher reluctance.

The total voltage induced in the stator is the sum of EMF induced by the field excitation. The equations are written as follows:-

$$E' = E_f + E_{ad} + E_{aq} \quad \dots\dots\dots (3) \quad \text{or}$$

$$E' = E_f - j\,X_{ad}I_d - j\,X_{aq}I_q \quad \dots\dots. (4)$$

The voltage E' is equal to the sum of the terminal voltage V and the voltage drops in the resistance and leakage reactance of the armature. The equation is written as

$$E' = V + R_aI_a + j\,X_1I_a \quad \dots\dots. (5)$$

The armature current is divided into two components; one is the phase with the excitation voltage E_f and the other is in phase quadrature to it.

If

I_q is the axis component of I_a in phase with E_f.

I_d is the d axis I_a lagging E_f by 90 degrees.

Therefore,

$$I_a = I_d + I_q \quad \dots\dots. (6)$$

Combining the equation (4) and (5) we get

$$E_f = V + R_aI_a + jX_1I_a + jX_{ad}I_d + jX_{aq}I_q \dots\dots\dots (7)$$

Combining the equation (6) and (7) we get

$$E_f = V + R_a(I_d + I_q) + j\,X_1(I_d + I_q) + jX_{ad}I_d + jX_{aq}I_q \dots\dots\dots (8)$$

$$E_f = V + R_a(I_d + I_q) + j(X_1 + X_{ad})I_d + j(X_1 + X_{aq})\,I_q \quad \dots\dots (9)$$

Let,

$$X_d \triangleq X_1 + X_{ad} \dots\dots\dots. (10)$$

$$X_q \triangleq X_1 + X_{aq} \dots\dots\dots. (11)$$

The reactance $\mathbf{X_d}$ is called the **direct axis synchronous reactance**, and the reactance $\mathbf{X_q}$ is called the **quadrature axis synchronous reactance.**

Combining the equations (9) (10) and (11), we get the equations shown below.

$$E_f = V + R_aI_d + R_aI_q + jX_dI_d + jX_qI_q \dots\dots\dots. (12) \quad \text{or}$$

$$E_f = V + R_aI_a + jX_dI_d + jX_qI_q \dots\dots\dots. (13)$$

The equation (12) shown above is the final voltage equation for a salient pole synchronous generator.

Parallel Operation of Alternator

Alternator is really an AC generator. In alternator, an EMF is induced in the stator (stationary wire) with the influence of rotating magnetic field (rotor) due to Faraday's law of induction. Due to the synchronous speed of rotation of field poles, it is also known as synchronous generator. Here, we can discuss about **parallel operation of alternator**. When the AC power systems are interconnected for efficiency, the alternators should also have to be connected in parallel. There will be more than two alternators connected in parallel in generating stations.

Condition for Parallel Operation of Alternator

There are some conditions to be satisfied for **parallel operation of the alternator**. Before entering into that, we should understand some terms which are as follows.

The process of connecting two alternators or an alternator and an infinite bus bar system in parallel is known as synchronizing.

Running machine is the machine which carries the load.

Incoming machine is the alternator or machine which has to be connected in parallel with the system.

The conditions to be satisfied are

The phase sequence of the incoming machine voltage and the bus bar voltage should be identical.

The RMS line voltage (terminal voltage) of the bus bar or already running machine and the incoming machine should be the same.The phase angle of the two systems should be equal.

The frequency of the two terminal voltages (incoming machine and the bus bar) should be nearly the same. Large power transients will occur when frequencies are not nearly equal.

Departure from the above conditions will result in the formation of power surges and current. It also results in unwanted electro-mechanical oscillation of rotor which leads to the damage of equipment.

General Procedure for Paralleling Alternators

The figure below shows an alternator (generator 2) being paralleled with a running power system (generator 1). These two machines are about to synchronize for supplying power to a load. Generator 2 is about to parallel with the help of a switch, S1. This switch should never be closed without satisfying the above conditions.

To make the terminal voltages equal. This can be done by adjusting the terminal voltage of incoming machine by changing the field current and make it equal to the line voltage of running system using voltmeters.

There are two methods to check the phase sequence of the machines. They are as follows

First one is using a Synchroscope. It is not actually check the phase sequence but it is used to measure the difference in phase angles.

Second method is three lamp method (Figure 2). Here we can see three light bulbs are connected to the terminals of the switch, S1. Bulbs become bright if the phase difference is large. Bulbs become dim if the phase difference is small. The bulbs will show dim and bright all together if phase sequence is the same. The bulbs will get bright in progression if the phase sequence is opposite. This phase sequence can be made equal by swapping the connections on any two phases on one of the generators.

Next, we have to check and verify the incoming and running system frequency. It should be nearly the same. This can be done by inspecting the frequency of dimming and brightening of lamps.

When the frequencies are nearly equal, the two voltages (incoming alternator and running system) will alter the phase gradually. These changes can be observed and the switch, S1 can be made closed when the phase angles are equal.

Advantages of Parallel Operating Alternators

When there is maintenance or an inspection, one machine can be taken out from service and the other alternators can keep up for the continuity of supply.

Load supply can be increased.

During light loads, more than one alternator can be shut down while the other will operate in nearly full load.

High efficiency.

The operating cost is reduced.

Ensures the protection of supply and enables cost-effective generation.

The generation cost is reduced.

Breaking down of a generator does not cause any interruption in the supply.

Reliability of the whole power system increases.

MODULE-5

SYNCHRONOUS MOTOR

Synchronous motor

A **synchronous electric motor** is an AC motor in which, at steady state, the rotation of the shaft is synchronized with the frequency of the supply current; the rotation period is exactly equal to an integral number of AC cycles. Synchronous motors contain multiphase AC electromagnets on the stator of the motor that create a magnetic field which rotates in time with the oscillations of the line current. The rotor with permanent magnets or electromagnets turns in step with the stator field at the same rate and as a result, provides the second synchronized rotating magnet field of any AC motor. A synchronous motor is termed *doubly fed* if it is supplied with independently excited multiphase AC electromagnets on both the rotor and stator.

The synchronous motor and induction motor are the most widely used types of AC motor. The difference between the two types is that the synchronous motor rotates at a rate locked to the line frequency since it does not rely on current induction to produce the rotor's magnetic field. By contrast, the induction motor requires *slip*: the rotor must rotate slightly slower than the AC alternations in order to induce current in the rotor winding. Small synchronous motors are used in timing applications such as in synchronous clocks, timers in appliances, tape recorders and precision servomechanisms in which the motor must operate at a precise speed; speed accuracy is that of the power line frequency, which is carefully controlled in large interconnected grid systems.

Synchronous motors are available in **self-excited** sub-fractional horsepower sizes[2] to high power industrial sizes.[1] In the fractional horsepower range, most synchronous motors are used where precise constant speed is required. These machines are commonly used in analog electric clocks, timers and other devices where correct time is required. In higher power industrial sizes, the synchronous motor provides two important functions. First, it is a highly efficient means of converting AC energy to work. Second, it can operate at leading or unity power factor and thereby provide power-factor correction.

Type

Synchronous motors fall under the more general category of *synchronous machines* which also includes the synchronous generator. Generator action will be observed if the field poles are "driven ahead of the resultant air-gap flux by the forward motion of the prime mover". Motor action will be observed if the field poles are "dragged behind the resultant air-gap flux by the retarding torque of a shaft load".[1]

There are two major types of synchronous motors depending on how the rotor is magnetized: *non-excited* and *direct-current excited*

Non-excited motors

In non-excited motors, the rotor is made of steel. At synchronous speed it rotates in step with the rotating magnetic field of the stator, so it has an almost-constant magnetic field through it. The external stator field magnetizes the rotor, inducing the magnetic poles needed to turn it. The rotor is made of a high-retentivity steel such as cobalt steel. These are manufactured in permanent magnet, reluctance and hysteresis designs:[4]

Reluctance motors

These have a rotor consisting of a solid steel casting with projecting (salient) toothed poles. Typically there are fewer rotor than stator poles to minimize torque ripple and to prevent the poles from all aligning simultaneously—a position that cannot generate torque.[2][5] The size of the air gap in the magnetic circuit and thus the reluctance is minimum when the poles are aligned with the (rotating) magnetic field of the stator, and increases with the angle between them. This creates a torque pulling the rotor into alignment with the nearest pole of the stator field. Thus at synchronous speed the rotor is "locked" to the rotating stator field. This cannot start the motor, so the rotor poles usually have squirrel-cage windings embedded in them, to provide torque below synchronous speed. The machine starts as an induction motor until it approaches synchronous speed, when the rotor "pulls in" and locks to the rotating stator field.[6]

Reluctance motor designs have ratings that range from fractional horsepower (a few watts) to about 22 kW. Very small reluctance motors have low torque, and are generally used for instrumentation applications. Moderate torque, multi-horsepower motors use squirrel cage construction with toothed rotors. When used with an adjustable frequency power supply, all motors in the drive system can be controlled at exactly the same speed. The power supply frequency determines motor operating speed.

Hysteresis motors

These have a solid smooth cylindrical rotor, cast of a high coercivity magnetically "hard" cobalt steel.[5] This material has a wide hysteresis loop (high coercivity), meaning once it is magnetized in a given direction, it requires a large reverse magnetic field to reverse the magnetization. The rotating stator field causes each small volume of the rotor to experience a reversing magnetic field. Because of hysteresis the phase of the magnetization lags behind the phase of the applied field. The result of this is that the axis of the magnetic field induced in the rotor lags behind the axis of the stator field by a constant angle δ, producing a torque as the rotor tries to "catch up" with the stator field. As long as the rotor is below synchronous speed, each particle of the rotor experiences a reversing magnetic field at the "slip" frequency which drives it around its hysteresis loop, causing the rotor field to lag and create torque. There is a 2-pole low reluctance bar structure in the rotor. As the rotor approaches synchronous speed and slip goes to zero, this magnetizes and aligns with the stator field, causing the rotor to "lock" to the rotating stator field.

A major advantage of the hysteresis motor is that since the lag angle δ is independent of speed, it develops constant torque from startup to synchronous speed. Therefore, it is self-starting and doesn't need an induction winding to start it, although many designs do have a squirrel-cage conductive winding structure embedded in the rotor to provide extra torque at start-up.

Hysteresis motors are manufactured in sub-fractional horsepower ratings, primarily as servomotors and timing motors. More expensive than the reluctance type, hysteresis motors are used where precise constant speed is required.

Permanent-magnet motors

A **permanent-magnet synchronous motor (PMSM)** uses permanent magnets embedded in the steel rotor to create a constant magnetic field. The stator carries windings connected to an AC supply to produce a rotating magnetic field. At synchronous speed the rotor poles lock to the rotating magnetic field. Permanent magnet synchronous motors are similar to brushless DC motors.

Because of the constant magnetic field in the rotor these cannot use induction windings for starting. These motors require a variable-frequency power source to start.[7][8][9][10][11]

The main difference between a permanent magnet synchronous motor and an asynchronous motor is the rotor.

Permanent magnet motors have been used as gearless elevator motors since 2000.

DC-excited motors

Usually made in larger sizes (larger than about 1 horsepower or 1 kilowatt) these motors require direct current (DC) supplied to the rotor for excitation. This is most straightforwardly supplied through slip rings, but a brushless AC induction and rectifier arrangement may also be used.[13] The direct current may be supplied from a separate DC source or from a DC generator directly connected to the motor shaft.

Control techniques

A permanent magnet synchronous motor and reluctance motor requires a control system for operating (VFD or servo drive).

There are a large number of control methods for PMSM, which is selected depending on the construction of the electric motor and the scope.

Control methods can be divided into:

Sinusoidal

a) Scalar

b) Vector (FOC, DTC)

2. Trapezoidal

a) Open loop

b) Closed loop (with and without Hall sensor)

Synchronous speed

The synchronous speed of a synchronous motor is given:[15]

in RPM, by:
and in rad·s^{-1}, by:
where:
is the frequency of the AC supply current in Hz,

is the number of poles.

is the pair number of poles. = /2

If is the number of pole pairs (rarely, *planes of commutation*) instead, simply divide both formulas by 2.

Examples

A single-phase, 4-pole (2-pole-pair) synchronous motor is operating at an AC supply frequency of 50 Hz. The number of pole-pairs is 2, so the synchronous speed is:
A three-phase, 12-pole (6-pole-pair) synchronous motor is operating at an AC supply frequency of 60 Hz. The number of pole-pairs is 6, so the synchronous speed is:

Construction

The principal components of a synchronous motor are the stator and the rotor. The stator of synchronous motor and stator of induction motor are similar in construction. With the wound-rotor synchronous doubly fed electric machine as the exception, the stator frame contains *wrapper plate*. *Circumferential ribs* and *keybars* are attached to the wrapper plate. To carry the weight of the machine, *frame mounts* and *footings* are required. When the field winding is excited by DC excitation, brushes and slip rings are required to connect to the excitation supply. The field winding can also be excited by a brushless exciter. Cylindrical, round rotors, (also known as non salient pole rotor) are used for up to six poles. In some machines or when a large number of poles are needed, a salient pole rotor is used. The construction of synchronous motor is similar to that of a synchronous alternator.

Operation

The operation of a synchronous motor is due to the interaction of the magnetic fields of the stator and the rotor. Its stator winding, which consists of a 3 phase winding, is provided with a 3 phase supply, and the rotor is provided with a DC supply. The 3 phase stator winding carrying 3 phase currents produces 3 phase rotating magnetic flux (and therefore a rotating magnetic field). The rotor locks in with the rotating magnetic field and rotates along with it. Once the rotor field locks in with the rotating magnetic field, the motor is said to be in synchronization. A single-phase (or two-phase derived from single phase) stator winding is possible, but in this case the direction of rotation is not defined and the machine may start in either direction unless prevented from doing so by the starting arrangements.

Once the motor is in operation, the speed of the motor is dependent only on the supply frequency. When the motor load is increased beyond the breakdown load, the motor falls out of synchronization and the field winding no longer follows the rotating magnetic field. Since the motor cannot produce (synchronous) torque if it falls out of synchronization, practical synchronous motors have a partial or complete squirrel-cage damper (amortisseur) winding to stabilize operation and facilitate starting. Because this winding is smaller than that of an equivalent induction motor and can overheat on long operation, and because large slip-frequency voltages are induced in the rotor excitation winding, synchronous motor protection devices sense this condition and interrupt the power supply (out of step protection).

Starting methods

Above a certain size, synchronous motors are not self-starting motors. This property is due to the inertia of the rotor; it cannot instantly follow the rotation of the magnetic field of the stator. Since a synchronous motor produces no inherent average torque at standstill, it cannot accelerate to synchronous speed without some supplemental mechanism.

Large motors operating on commercial power frequency include a squirrel-cage induction winding which provides sufficient torque for acceleration and which also serves to damp oscillations in motor speed in operation.[2] Once the rotor nears the synchronous speed, the field winding is excited, and the motor pulls into synchronization. Very large motor systems may include a "pony" motor that accelerates the unloaded synchronous machine before load is applied. Motors that are electronically controlled can be accelerated from zero speed by changing the frequency of the stator current.

Very small synchronous motors are commonly used in line-powered electric mechanical clocks or timers that use the power line frequency to run the gear mechanism at the correct speed. Such small synchronous motors are able to start without assistance if the moment of inertia of the rotor and its mechanical load is sufficiently small [because the motor] will be accelerated from slip speed up to synchronous speed during an accelerating half cycle of the reluctance torque." Single-phase synchronous motors such as in electric wall clocks can freely rotate in either direction unlike a shaded-pole type. See Shaded-pole synchronous motor for how consistent starting direction is obtained.

The operational economics is an important parameter to address different motor starting methods. Accordingly, the excitation of the rotor is a possible way to solve the motor starting issue. In additions, modern proposed starting methods for large synchronous machines includes repetitive polarity inversion of the rotor poles during startup.

Applications, special properties, and advantages

Use as synchronous condenser

By varying the excitation of a synchronous motor, it can be made to operate at lagging, leading and unity power factor. Excitation at which the power factor is unity is termed *normal excitation voltage*.[31] The magnitude of current at this excitation is minimum.[31] Excitation voltage more than normal excitation is called over excitation voltage, excitation voltage less than normal excitation is called under excitation.[31] When the motor is over excited, the back emf will be greater than the motor terminal voltage. This causes a demagnetizing effect due to armature reaction.

The V curve of a synchronous machine shows armature current as a function of field current. With increasing field current armature current at first decreases, then reaches a minimum, then increases. The minimum point is also the point at which power factor is unity.

This ability to selectively control power factor can be exploited for power factor correction of the power system to which the motor is connected. Since most power systems of any significant size have a net lagging power factor, the presence of overexcited synchronous motors moves the system's net power factor closer to unity, improving efficiency. Such power-factor correction is usually a side effect of motors already present in the system to provide mechanical work, although motors can be run without mechanical load simply to provide power-factor correction. In large industrial plants such as factories the interaction between synchronous motors and other, lagging, loads may be an explicit consideration in the plant's electrical design

Steady state stability limit

where, is the torque

is the torque angle

is the maximum torque

here,

When load is applied, torque angle increases. When = 90° the torque will be maximum. If load is applied further then the motor will lose its synchronism, since motor torque will be less than load torque. The maximum load torque that can be applied to a motor without losing its synchronism is called steady state stability limit of a synchronous motor.

Other

Synchronous motors are especially useful in applications requiring precise speed and/or position control.

Speed is independent of the load over the operating range of the motor.

Speed and position may be accurately controlled using open loop controls; e.g., stepper motors.

Low-power applications include positioning machines, where high precision is required, and robot actuators.

They will hold their position when a DC current is applied to both the stator and the rotor windings.

A clock driven by a synchronous motor is in principle as accurate as the line frequency of its power source. (Although small frequency drifts will occur over any given several hours, grid operators actively adjust line frequency in later periods to compensate, thereby keeping motor-driven clocks accurate; see *Utility frequency#Stability*.)

Record player turntables

Increased efficiency in low-speed applications (e.g., ball mills).

SUBJECTIVE QUESTION PAPER

MODULE-I

1.Draw the Phasor diagram of an induction motor for any load.

2. Explain Crawling & Cogging.

3.Explain with diagram why rotor is rotating in the same direction of the rotating field and under what condition both will rotate in the opposite direction.

4.Explain the principle of operation of a 3- Phase induction motor and how the direction of rotation can be reversed?

5. With diagram explain the construction details of a slip ring induction motor.

6.Write notes on rotor EMF and rotor reactance

MODULE-II

1.Draw the complete speed torque characteristics of an induction motor for three actions and discuss the influence of rotor resistance on the starting of the motor.

2.The full load slip of 3 phase induction motor is 3%.The resistance and standstill reactance of the rotor 0.03 and 0.18 ohm per phase respectively .Estimate the percentage reduction in stator voltage to develop full load torque at half the full load speed .

3.Develop an expression of maximum torque of an induction motor.

4.Explain the procedure for construction of circle diagram and explain how to obtain max torque, max output and starting torque from the circle diagram.

5. Write a note on induction generator.

6.The starting torque of a three phase induction motor with $R_2/X_2=1$ and negligible stator impedance is 25N-m.Determine the starting torque when the rotor resistance is **(a)** doubled **(b)** halved.

MODULE-III

1.Compare single phase induction motor and three phase induction motor.

2.Explain the principle of operation single phase induction motor.

3.Explain double revolving field theory

4.Explain the working principle of capacitor start induction run motor.

5.Explain how a rotating magnetic field produced in a shaded pole induction motor.

6.A.230V 4pole 50HZ single phase capacitor start induction motor has the following parameters. Main winding impedance is 6+j4 ohm and starting winding impedance is 8+j6 ohm. Calculate the capacitance to be added in series with starting winding such that the angle between I_M and I_S is 90^0 .

MODULE-IV

1 .Explain the constructional details of the alternator used in thermal station.

2. Explain in detail why the air gap of synchronous machine is always greater than induction machine

3 . Explain with neat circuit diagram predetermination of voltage regulation of alternator by potier triangle method.

4. Explain the need and condition for paralleling the alternator.

5. In a 1500KVA ,3.3KV,50HZ 3-phase star connected alternator, a field current of 60A produces a short circuit current of 350A and open circuit voltage of 1.5KV (line to line) calculate the voltage regulation at full load 0.8PF lag and 0.9pf lead .The armature resistance per phase is 0.4ohm.

6. Two similar 4000KVA alternator operating in parallel. the governor of the first machines is such that frequency drops from 50HZ at no load to 47HZ at full load and the second is at 50HZ at no load and 48.5 HZ at full load.

(a) How they will share a load of 6000KVA

(b)How much max UPF load can they carry

MODULE-V

1.Explain the principle of operation of synchronous motor and why they are not self starting?

2.Explain the different methods of starting of synchronous motors.

3.What is the hunting and explain its effects and remedies in details

4.Explain the effect of increased load with constant excitation in a synchronous motor.

5.Draw and explain V and inverted V curves of a synchronous motor

6.Explain the effect of load in synchronous motor with phasor diagram