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CONTENTS

Alternator(Synchronous Generator)

An alternator is defined as a machine which converts mechanical energy to electrical energy in the form of alternating current (at a specific voltage and frequency). Alternators are also known as synchronous generators.

History of Alternator

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

Use of Alternator

The power for the electrical system of a modern vehicle gets produced from an alternator. In previous days, we used DC generators or dynamos for this purpose, but after the development of alternator, we replaced the DC dynamos by more robust and lightweight alternator. Although the electrical system of motor vehicles requires direct current, still an alternator along with diode rectifier instead of a DC generator is a better choice as the complicated commutation is absent in alternator. This particular type of generator used in the vehicle is known as an automotive alternator (learn how an alternator is constructed).

Another use of alternators is in diesel-electric locomotive. The engine of this locomotive is nothing but an alternator, driven by a diesel engine. The alternating current produced by this generator is converted to DC by integrated silicon diode rectifiers to feed all the DC traction motors. These DC traction motors drive the wheel of the locomotive.

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

One of the primary uses of alternators is in the production of bulk ac power for commercial purposes.

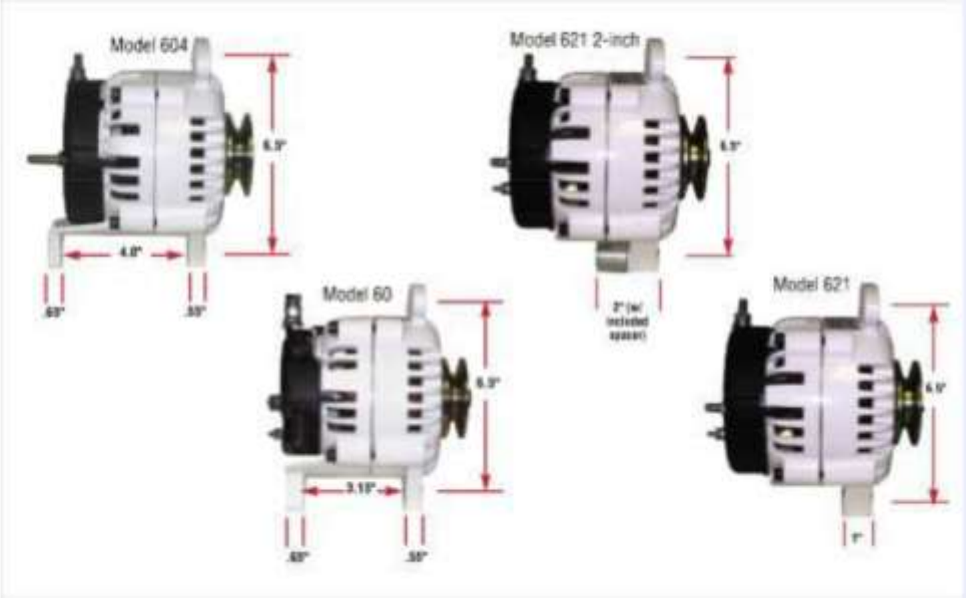
In thermal power plants, in hydel power plants, even in nuclear power plants, alternators only converts mechanical energy to electrical energy for supplying to the power system.

Types of Alternators

Alternators or synchronous generators can be classified in many ways depending upon their applications and designs.

The five different types of alternators include:

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



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

1. **Salient Pole Type**
2. **Smooth Cylindrical Type**

Salient Pole Type

We use it as low and medium speed alternator. It has a large number of projecting poles having their cores bolted or dovetailed onto a heavy magnetic wheel of cast iron or steel of good magnetic quality.

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

Smooth Cylindrical Type

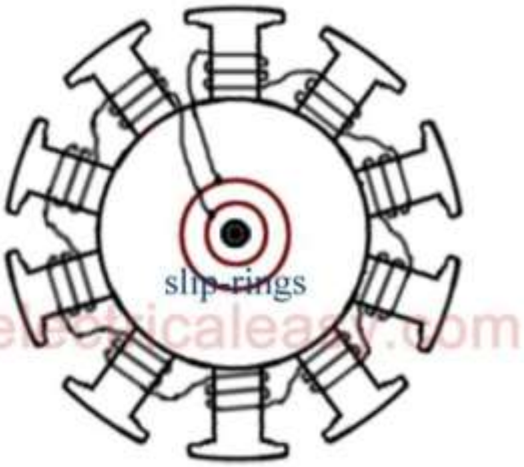
We use it for a steam turbine driven alternator. The rotor of this generator rotates at very high speed. The rotor consists of a smooth solid forged steel cylinder having certain numbers of slots milled out at intervals along the outer periphery for accommodating field coils.

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

Salient Pole Rotor Vs. Non-Salient Pole Rotor

Rotors of an electrical machine are classified as: (i) Salient pole rotors and (ii) Non-salient pole rotors. Both types are explained below.

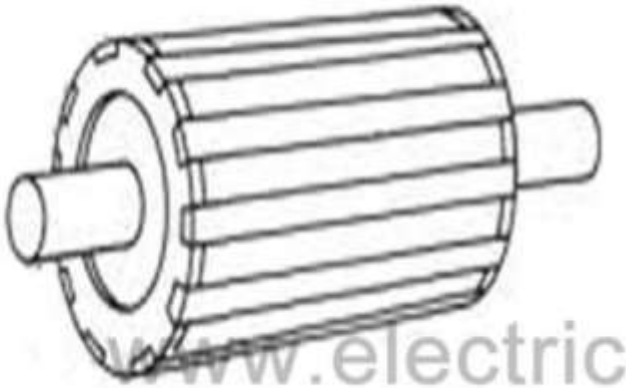
Salient Pole Rotor



In salient pole type of rotor consist of large number of projected poles (salient poles) mounted on a magnetic wheel. Construction of a salient pole rotor is as shown in the figure at left. The projected poles are made up from laminations of steel. The rotor winding is provided on these poles and it is supported by pole shoes.

- Salient pole rotors have large diameter and shorter axial length.
- They are generally used in lower speed electrical machines, say 100 RPM to 1500 RPM.
- As the rotor speed is lower, more number of poles are required to attain the required frequency. (Ns = 120f / P therefore, f = Ns*p/120 i.e. frequency is proportional to number of poles). Typically number of salient poles is between 4 to 60.
- Flux distribution is relatively poor than non-salient pole rotor, hence the generated emf waveform is not as good as cylindrical rotor.
- Salient pole rotors generally need damper windings to prevent rotor oscillations during operation.
- Salient pole synchronous generators are mostly used in hydro power plants.

Non-Salient Pole (Cylindrical) Rotor



Cylindrical rotor

Cross sectional view

Non-salient pole rotors are cylindrical in shape having parallel slots on it to place rotor windings. It is made up of solid steel. The construction of non-salient pole rotor (cylindrical rotor) is as shown in figure above.

Sometimes, they are also called as drum rotor.

- **They are smaller in diameter but having longer axial length.**
- **Cylindrical rotors are used in high speed electrical machines, usually 1500 RPM to 3000 RPM.**
- **Windage loss as well as noise is less as compared to salient pole rotors.**
- **Their construction is robust as compared to salient pole rotors.**
- **Number of poles is usually 2 or 4.**
- **Damper windings are not needed in non-salient pole rotors.**
- **Flux distribution is sinusoidal and hence gives better emf waveform.**
- **Non-salient pole rotors are used in nuclear, gas and thermal power plants.**

Introduction

An alternating voltage is generated in a single conductor or alternating coil rotating in a uniform magnetic field with stationary poles an alternating voltage will also be generated in stationary armature conductor when the field poles rotate past the conductors. thus , we see that as long as there is a relative motion between the armature conductors and field flux there will be a voltage generated in the armature conductors. in both cases the wave shape of voltage is a sine curve.

A.C. generator are usually called alternator the are also called synchronous generators. rotating machines that rotate at a fixed speed by the supply frequency and the number of poles are called synchronous machines.

A synchronous generator is a machine for converting mechanical power from a prime mover to a.c. electrical power at a specific voltage and frequency. a synchronous machine rotates at constant speed is called synchronous speed. synchronous generators are usually 3-phase type because of the several advantages of 3-phase generation, transmission and distribution. Large synchronous generators are used to generate bulk power at thermal, hydro and nuclear power stations.

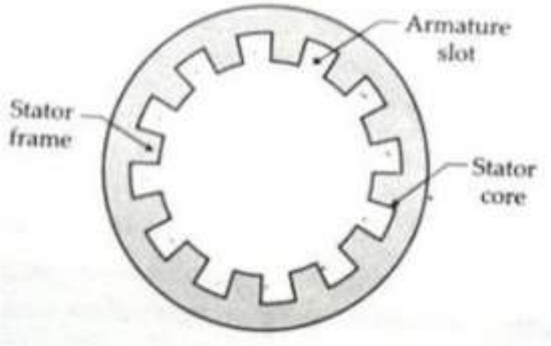
Synchronous generator with power rating of several hundred MVA are very commonly used in generating stations. the biggest size used in india has a rating of 500 MVA used in super power thermal power stations. synchronous generator are primary sources of the world's electric power system today.For bulk power generation , stator winding of synchronous generators are designed for voltage ranging from 6.6 kV to 33 kV.

Construction of three -phase synchronous machines

An alternator consists of two main parts namely, the stator and the rotor. the stator is the stationary part of the machine. It carries the armature winding in which the voltage is generated. the output of the machine is taken from the stator. the rotor is the rotating part of machine. the rotor produces the main field flux.

Stator: the various parts of the stator include the frame, stator core , stator windings and cooling arrangement. Frame may be cast iron for small-size machines and welded steel type for large size machines. In order to reduce hysteresis and eddy-current losses, the stator core is assembled with high grade silicon content steel lamination. A 3-phase winding is put in the slots cut on the inner periphery of the stator as show in fig the winding of each phase is distributed over a several slots. when current flow in a distributed winding it produces an essentially

sinusoidal apace distribution of emf.



Rotor: There are two types of rotor construction namely, the salient pole and cylindrical rotor type.

Synchronous Generator or Alternator:

It is known that the electric supply used now-a-days for commercial, as well as domestic purposes, is of alternating type.Similar to d.c machines, the a.c machines associated with alternating voltages, are also classified as generators and motors.

Machines generating ac EMF are called alternators or synchronous generators. While the machines accepting input from a.c supply to produce a mechanical output are called synchronous motors.Both these machines work at a specific constant speed called synchronous speed and hence is general called synchronous machines.

Difference between DC Generator and Alternator:

It is seen that in the case of a d.c generator, basically, the nature of the induced e.m.f in the armature conductors is of alternating type. By using commutator and brush assembly it is converted to d.c and made available to the external circuit.

If commutator is dropped from a d.c generator and induced e.m.f is tapped from an armature directly outside, the nature of such emf will be alternating. Such a machine without a commutator, providing an a.c emf to the external circuit is called an alternator.

Construction of Synchronous generator or alternator:

In Synchronous generator or alternators the stationary winding is called 'stator' while the rotating winding is called 'Rotor'.

Stator:

The stator in the synchronous generator is a stationary armature.This consists of a core and the slots to hold the armature winding similar to the armature of a d.c generator.The stator core uses a laminated construction.It is built up of special steel stampings insulated from each other with varnish or paper.The laminated construction is basically to keep down eddy current losses.

Generally choice of material is steel to keep down hysteresis losses.The entire core is fabricated in a frame made of steel plates.The core has slots on its periphery for housing the armature conductors.The frame

does not carry any flux and serves as the support to the core.Ventilation is maintained with the help of holes cast in the frame.

Rotor:

There are two types of rotors used in the synchronous generators or alternators:

1) Salient pole rotor

2)Smooth cylindrical rotor

1) Salient pole rotor:

This is also called projected pole type as all the poles are projected out from the surface of the rotor.The poles are built up of thick steel laminations.The poles are bolted to the rotor as shown in the figure.The pole face has been given a specific shape.The field winding is provided on the pole shoe.These rotors have large diameters and small axial lengths.

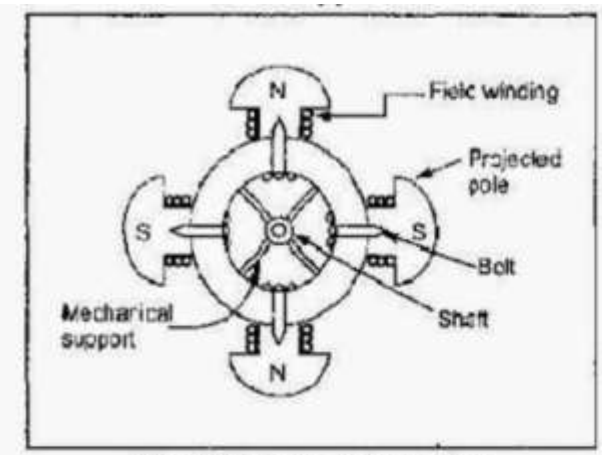


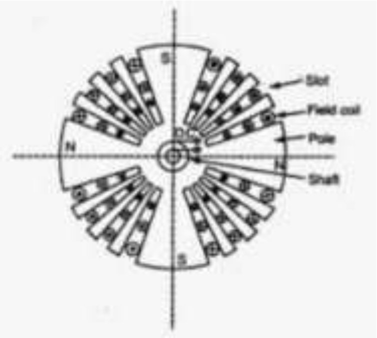
Fig. 6.3 Salient pole type rotor

The limiting factor for the size of the rotor is the centrifugal force acting on the rotating member of the machine. As the mechanical strength of salient pole type is less, this is preferred for low-speed alternators ranging from 125 r.p.m to 50 r.p.m.The prime movers used to drive such rotor are generally water turbines and I.C. engines.

2)Smooth cylindrical rotor:

This is also called non-salient type or non-projected pole type or round rotor.This rotor consists of a smooth solid steel cylinder, having a number of slots to accommodate the field coil.These slots are covered at the top with the help of steel or manganese wedges.The unslotted portions of the cylinder itself act as the poles.The poles are not projecting out and the surface of the rotor is smooth which maintains a uniform air gap

between stator and rotor.



These rotors have small diameters and large axial lengths.This is to keep peripheral speed within limits.The main advantage of this type is that these are mechanically very strong and thus preferred for high-speed alternators ranging between 1500 to 3000 r.p.m. Such high-speed alternators are called 'turbo-alternators'.The prime movers used to drive such type of rotors are generally steam turbines, electric motors.

Working Principle of Synchronous generator :

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

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

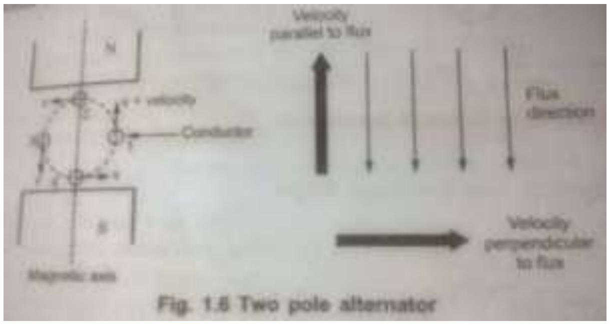
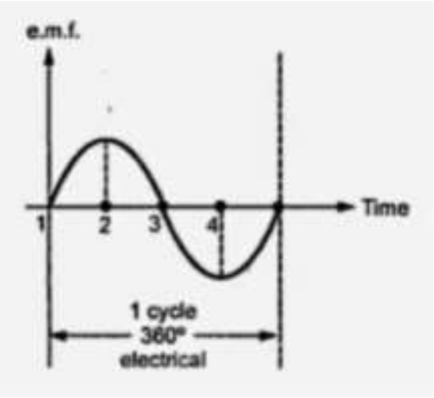


Fig. 1.6 Two pole alternator

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

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

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



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

Armature Winding of Alternator

Armature winding in an alternator may be either closed type open type. Closed winding forms star connection in armature winding of alternator.

There are some common properties of armature winding.

1. **First and most important property of an armature winding is, two sides of any coil should be under two adjacent poles. That means, coil span = pole pitch.**
2. **The winding can either be single layer or double layer.**
3. **Winding is so arranged in different armature slots, that it must produce sinusoidal emf.**

Types of Armature Winding of Alternator

There are different types of armature winding used in alternator. The windings can be classified as

1. **Single phase and poly phase armature winding.**
2. **Concentrated winding and distributed winding.**
3. **Half coiled and whole coiled winding.**
4. **Single layer and double layer winding.**
5. **Lap, wave and concentric or spiral winding and**
6. **Full pitched coil winding and fractional pitched coil winding.**

In addition to these, armature winding of alternator can also integral slot winding and fractional slot winding.

Single Phase Armature Winding

Single phase armature winding can be either concentrated or distributed type.

Concentrated Armature Winding

The concentrated winding is employed where the number of slots on the armature is equal to the number of poles in the machine. This armature winding of alternator gives maximum output voltage but not exactly sinusoidal.

The most simple single-phase winding is shown below in the figure-1. Here, number poles = the number of slots = number of coil sides. Here, one coil side is inside one slot under one pole and the other coil side inside other slots under next pole. The emf induced in one coil side gets added to that of adjacent coil side.

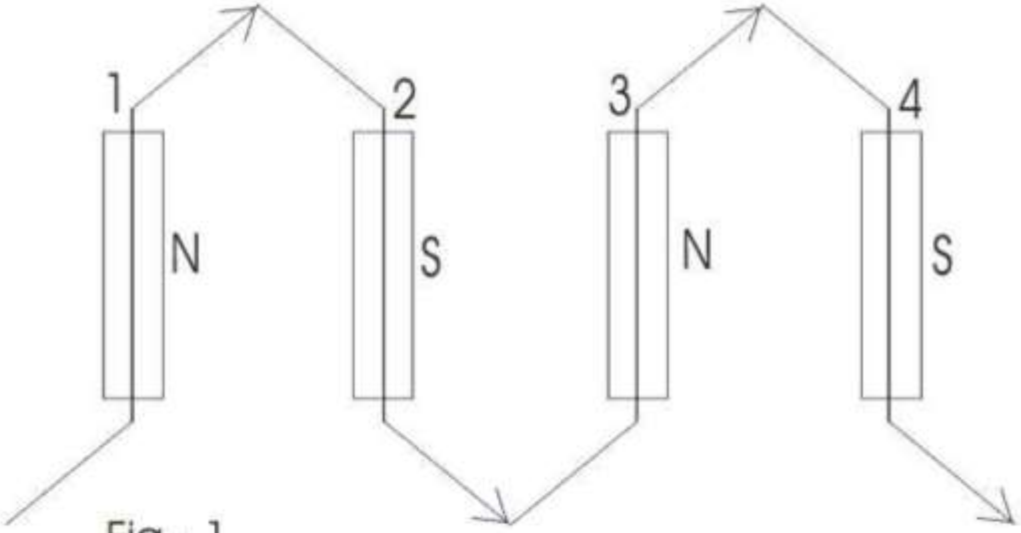


Fig - 1

This arrangement of an armature winding in an alternator is known as skeleton wave winding. As per the fig-1, coil side-1 under N-pole is connected to coil side-2 under S-pole at the back and coil side-3 at the front and so on.

The direction of induced emf of coil side-1 is upward and emf induced in coil side-2 is downward. Again as coil side-3 is under N-pole, it will have emf in the upward direction and so on. Hence total emf is the summation of emf of all coil sides. This form of armature winding is quite simple but rarely used as this requires considerable space for end connection of every coil side or conductor. We can overcome this problem, some extent by using multi turns coil. We use the multi-turn half coiled winding to get higher emf. Since the coils cover only one half of the armature periphery thus, we refer this winding as Half coiled or Hemi tropic winding. Figure 2 shows this. If we distribute the all coils over the whole armature periphery, then the armature winding is referred as whole coiled winding.

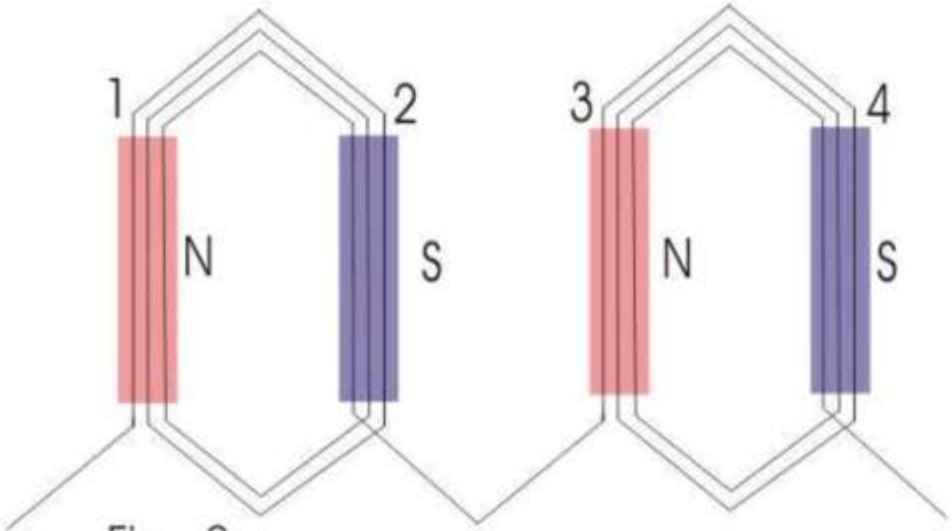


Fig - 2

Figure 3 shows a double layer winding, where we place one side of each coil on the top of armature slot, and another side in the bottom of the slot. (Represented by dotted lines).

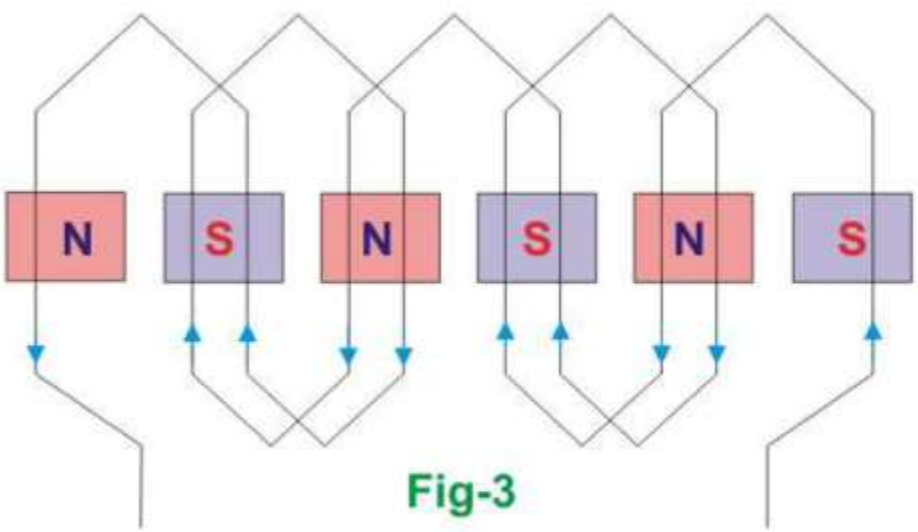


Fig-3

Distributed Armature Winding of Alternator

For obtaining smooth sinusoidal emf wave from, conductors are placed is several slots under single pole. This armature winding is known as distributed winding. Although distributed armature winding in alternator reduces emf, still it is very much usable due to following reason.

1. **It also reduces harmonic emf and so waveform is improved.**
2. **It also diminishes armature reaction.**
3. **Even distribution of conductors, helps for better cooling.**
4. **The core is fully utilized as the conductors are distributed over the slots on the armature periphery.**

Lap Winding of Alternator

Full pitched lap winding of 4 poles, 12 slots, 12 conductors (one conductor per slot) alternator is shown below. The back pitch of the winding is equal to the number of conductors per pole, i.e., = 3 and the front pitch is equal to back pitch minus one. The winding is completed per pair of the pole and then connected in series as

shown in figure 4 below.

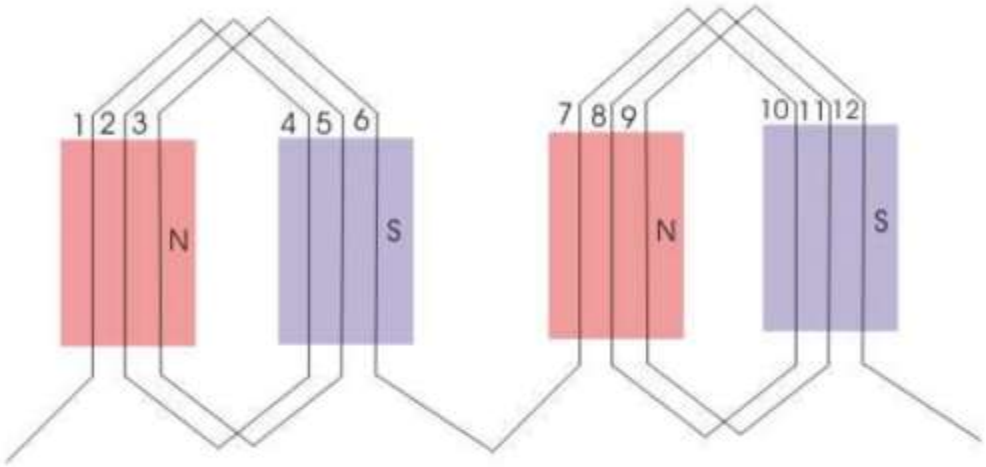


Fig - 4

Wave Winding of Alternator

Wave winding of the same machine, i.e., four poles, 12 slots, 12 conductors is shown in the figure-e below. Here, back pitch and front pitch both equal to some conductor per pole.

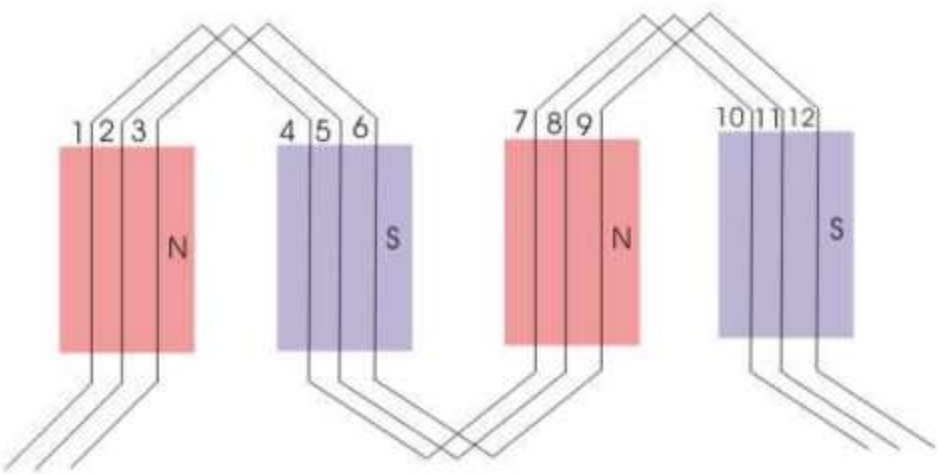


Fig - 5

Concentric or Spiral Winding

This winding for the same machine, i.e., four poles 12 slots 12 conductors alternator is shown in the figure-f below. In this winding, the coils are of different pitches. The outer coil pitch is 5, the middle coil pitch is 3,

and inner coil pitch is one.

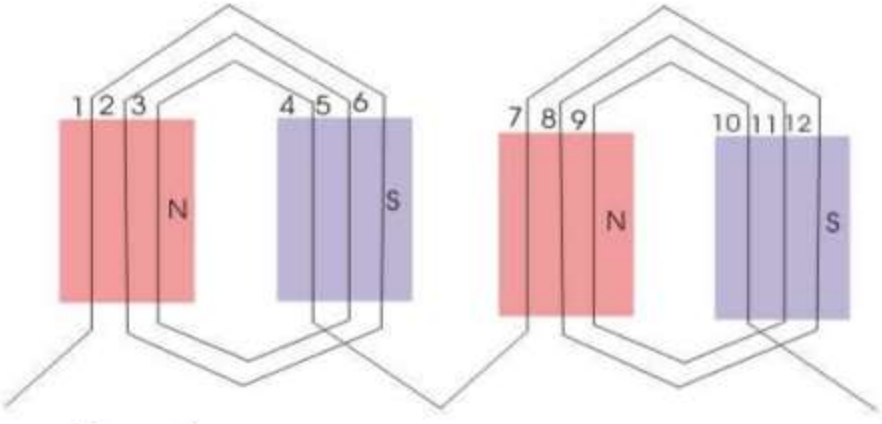


Fig - 6

Poly Phase Armature Winding of Alternator

Before discussing poly phase armature winding of alternator, we should go through some of the related terms for better understanding.

Coil Group

It is product of number of phases and number of poles in a rotating machine.
Coil group = number of poles × the number of phases.

Balanced Winding

If under each pole face, there are an equal number of coils of different phases, then the winding is said to be balanced winding. In balanced winding, coil group should be an even number.

Unbalanced Winding

If the number of coils per coil group is not a whole number, the winding is known as unbalanced winding. In such case, each pole face contains unequal of coils of different phase. In two-phase alternator, two single-phase windings are placed on the armature by 90 electrical degrees apart from each other.
In case of three phase alternator, three single-phase windings are placed on the armature, by 60 degrees (electrical) apart from each other.
The figure below represents, a Skelton 2 phase 4 pole winding two slots per pole. The electrical phase difference between adjacent slots = 180/2 = 90 degree electrical).

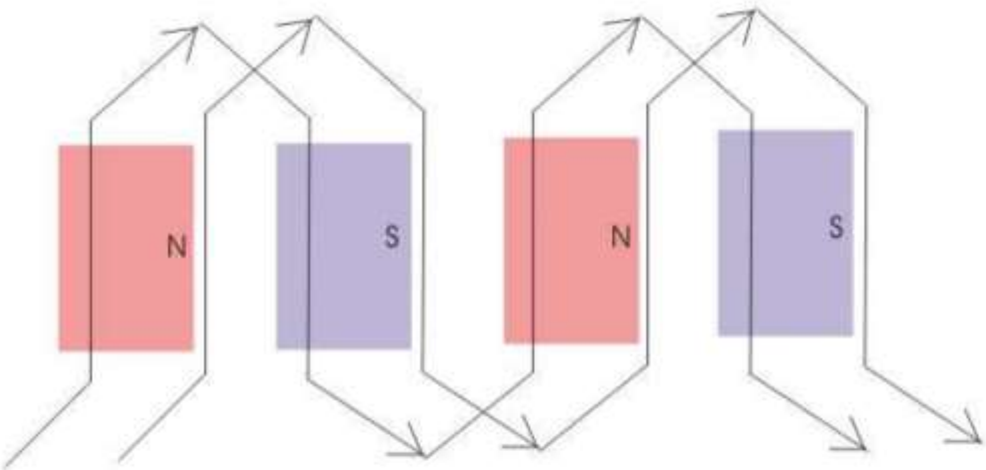


Fig - 7

Point a and b are starting point of the first and second phase winding of two phase alternator a’ and b’ are finishing point of first and second phase wining of the two-phase alternator, respectively. The figure below represents a Skelton 3 phase 4 pole winding, three slots per pole. The electrical phase difference between, adjacent slots is 180/ 3 = 60 degree (electrical) a, b and c are starting point of Red, Yellow, and blue phases and a’ b’ and c’ are the finishing points of same Red Yellow and Blue phases of the three-phase winding.

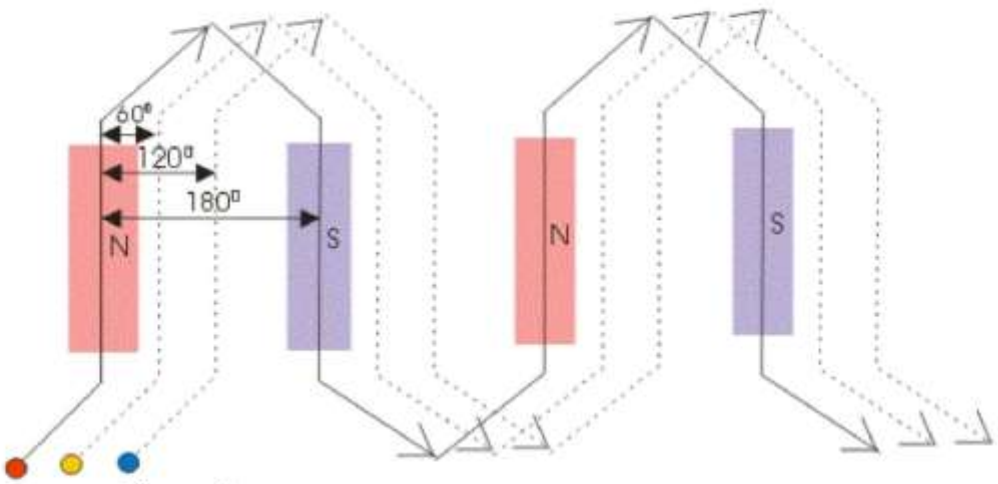


Fig - 8

Say red phase winding starts at slot no 1 and ends over slot no 10. Then yellow winding or second winding starts at slot no 2 and ends over slot no 11. Third or blue phase winding starts at slot no 3 and ends at slot no 12. The phase difference of induced emfs, in red phase and yellow, yellow phase and blue phase and blue phase and red phase winding respectively by 60 degrees, 60 degree and 240 degrees (electrical respectively). Since in three phase system, the phase difference between red, yellow and blue phase is 120 degree (electrical). This can be achieved by revering yellow phase (second winding) winding as shown in the figure above. Figure- below represents 4 pole, 24 slot, single layer, full pitched 3 phases distributed winding. No of slot per pole per phase

____

The phase difference between emfs induced in the conductors, of two adjacent slots is __________
Hence,

Slots No: 1, 2, 7, 8, 13, 14, 19, and 20 for R phase
Slots No: 5, 6, 11, 12, 17, 18, 23 and 24 for Y phase
Slots No: 3, 4, 9, 10, 15, 16, 21 and 22 for B phase

The figure below shows three phase full pitched double layer lap winding. Each winding is spaced 120 electrical degrees from two adjacent winding. This winding has 12 slots per pole per phase. Since the winding is the full pitched coil, so the pitch of each. The coil is 12 slots. Since one pole presents 180 electrical space degrees, so the slots pitch corresponding to 180/12, i.e., 15° (electrical).

In a fractional pitch winding, we make the coil span less than 180 degrees electrical space degrees. In the figure above a coil instead of having a pitch of 12 slots now has a pitch of 10 slots so that its spread is no longer equal to pole pitch.

There are two types of coil span. The first one is full pitched coil where two sides of the coil are 180 degrees (electrical) apart. In full pitched coil when one side of the coil is under N pole, the other side is in the corresponding position, under S pole. The induced emfs on two opposite side of coil differ by 180 degrees (electrical). Hence the resultant, emf of the coil, is just arithmetic sum of these two emfs.

The second one is the short-pitched coil, where, two opposite side of a coil is not exactly 180 degree (electrical) it is less than that. In this case, the phase difference between emf of two coil side is also less than 180 degree (electrical). Hence, the resultant emf of the coil is not a simple arithmetic sum of two emfs, but it is the vector sum of two emfs. Hence, resultant emf of a short-pitched coil is always less than that of a full pitched coil. But still, we preferably use short pitched coil because short pitched coil reduces or elements harmonics from waveforms.

Integral Slot and Fractional Slot Winding

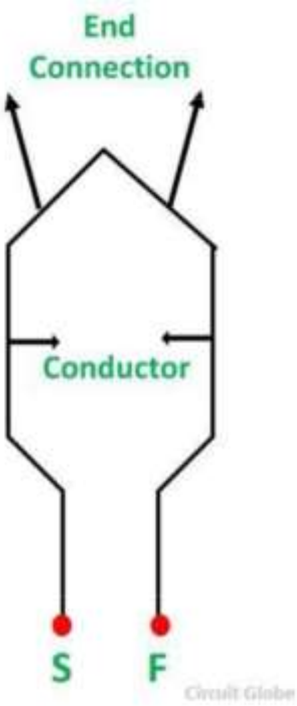
When the number of slots per pole per phase is an integer, the winding is the integer slot winding but when the number slots per pole per phase is fractional number the winding we refer as fractional slot winding. Fractional slot winding is practicable only with the double layered winding. It limits the number of parallel circuits available because phase group under several poles must be connected in series before a unit is formed and the widening respects the pattern to give the second unit that can be put in parallel with the first.

Terminology Of Armature Winding

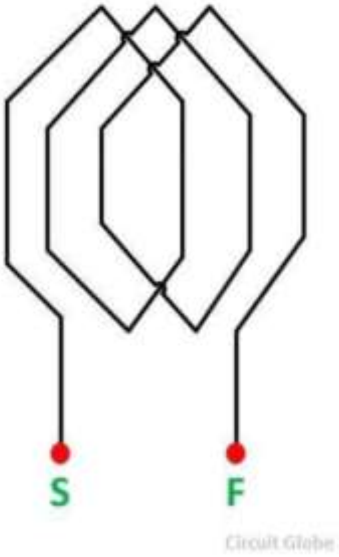
Armature Winding is the windings, in which voltage is induced.The Field Winding is the winding in which the main field flux is produced when the current through the winding is passed. Some of the basic terms related to the Armature Winding are defined as follows:

- **Turn: A turn consists of two conductors connected to one end by an end connector.**
- **Coil: A coil is formed by connecting several turns in the series.**
- **Winding: A winding is formed by connecting several coils in series.**

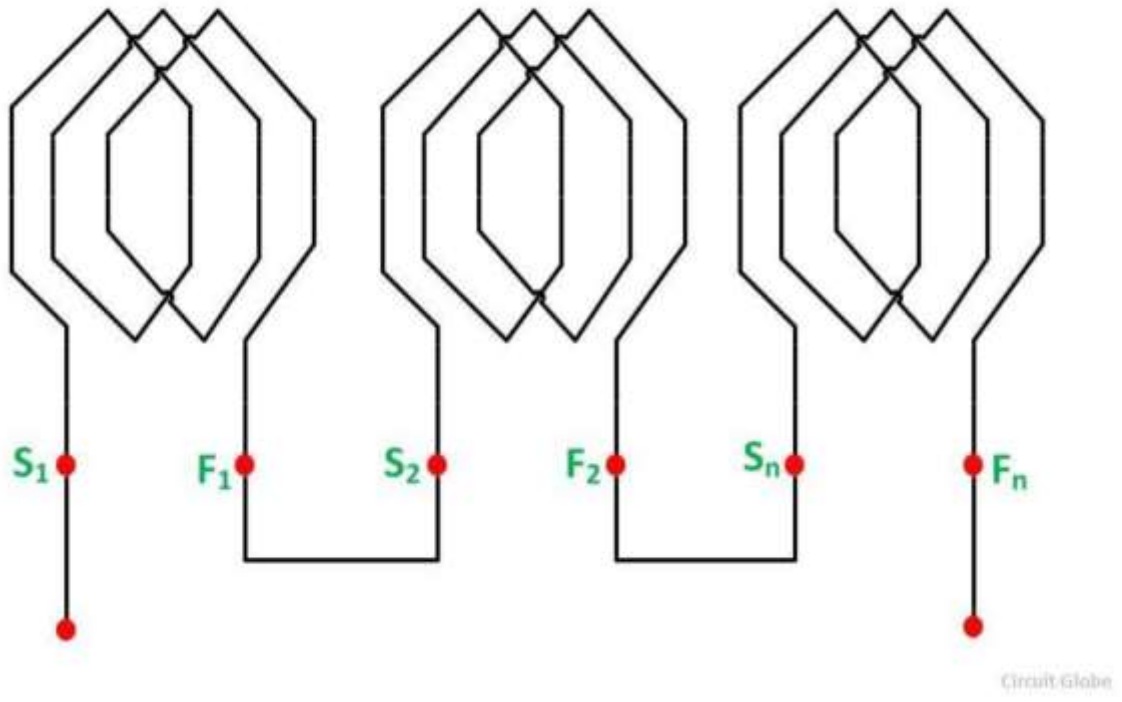
The figure of the turn is shown below.



- The figure of the coil is shown below.



The figure of the winding is shown below



the turn or coil is represented by the symbol (F) meaning Finish.

The concept of electrical degree is very important in the study of the machine.

For a (P) pole The beginning of the turn or coil is identified by the symbol (S) meaning Start, and the end of machine, the electrical degree is defined as given below.

$$\theta_{ed} \triangleq \frac{P}{2}\,\theta_{md} \;\dots\dots\dots (1)$$

Where,

$?_{md}$ is the mechanical degrees or an angular measure in space.

$?_{ed}$ is the electrical degrees or an angular measure in cycles.

The advantage of this notation is that the expressions written in terms of electrical angles apply to the machine any number of poles.

The angular distance between the centers of two adjacent poles on a machine is known as pole pitch or pole span.

$$\text{One pole pitch} = 180^{\circ}_{ed} = \frac{360^{\circ}_{md}}{P} \;\dots\dots. (2)$$

The pole pitch is always 180 degrees electrical regardless of the number of poles in a machine.

The two sides of a coil are placed in two slots on the stator surface. The distance between the two sides of a coil is called the coil-pitch. If the coil pitch is one pole pitch, it is called the Full Pitch Coil. If the coil pitch is less than one pole pitch, the coil is called the Short Pitch or Fractional Pitch coil.

Winding Factor | Pitch Factor | Distribution Factor

Before knowing about, winding factor, we should know about pitch factor and distribution factor, since winding factor is the product of pitch factor and distribution factor.

If we denote winding factor with K_w, pitch factor with K_p and distribution factor with K_d, we can write

$$K_w = K_p \times K_d$$

The pitch factor and distribution factor are explained below one by one.

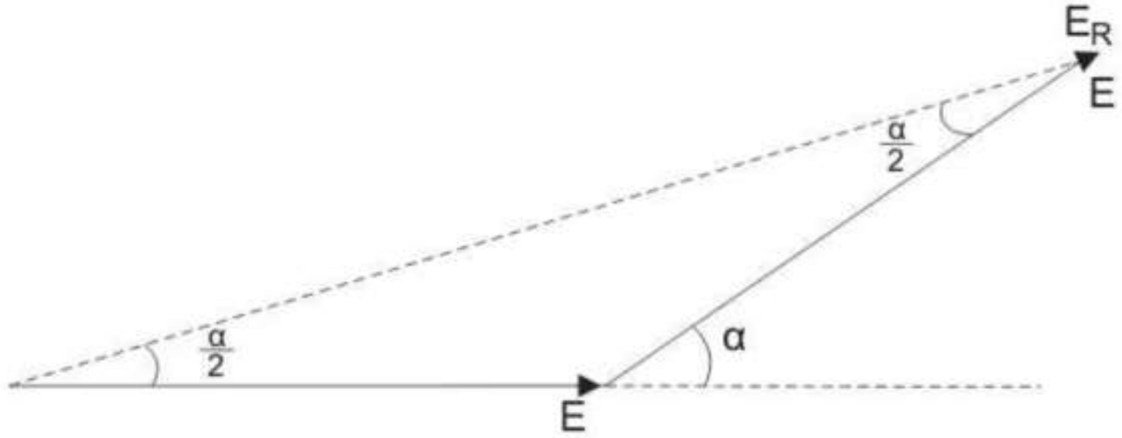
Pitch Factor

In short pitched coil, the induced emf of two coil sides get vectorially added and give resultant emf of the loop. In short pitched coil, the phase angle between the induced emf of two opposite coil sides is less than 180^o (electrical). But we know that, in full pitched coil, the phase angle between the induced emf of two coil sides is exactly 180^o (electrical). Hence, the resultant emf of a full pitched coil is just the arithmetic sum of the emfs induced on both sides of the loop. We well know that vector sum or phasor sum of two quantities is always less than their arithmetic sum. The pitch factor is the measure of resultant emf of a short-pitched coil in comparison with resultant emf of a full pitched coil.

Hence, it must be the ratio of phasor sum of induced emfs per coil to the arithmetic sum of induced emfs per coil. Therefore, it must be less than unity.

Let us assume that, a coil is short pitched by an angle α (electrical degree). Emf induced per coil side is E. The arithmetic sum of induced emfs is 2E. That means, 2E, is the induced voltage across the coil terminals, if the coil would have been full pitched.

Now, come to the short pitched coil. From the figure below it is clear that, resultant emf of the short pitched coil



$$E_R = 2E\cos\frac{\alpha}{2}$$

Now, as per definition of pitched factor,

$$K_p = \frac{Resultant\ emf\ of\ short\ pitched\ coil}{Resultant\ emf\ of\ full\ pitched\ coil}$$
$$= \frac{Phasor\ sum\ of\ coil\ side\ emfs}{Arithmetic\ sum\ of\ coil\ side\ emfs}$$
$$= \frac{2E\cos\frac{\alpha}{2}}{2E} = \cos\frac{\alpha}{2}$$

This pitch factor is the fundamental component of emf. The flux wave may consist of space field harmonics also, which give rise to the corresponding time harmonics in the generated voltage waveform. A 3rd harmonic component of the flux wave, may be imagined as produced by three poles as compared to one pole for the fundamental component.

In the view of this, the chording angle for the rth harmonic becomes r times the chording angle for the fundamental component and pitch factor for the rth harmonic is given as,

$$K_{pr} = cos\frac{r\alpha}{2}$$

The rth harmonic becomes zero, if,

$$cos\frac{r\alpha}{2} = 0 \; or \; \frac{r\alpha}{2} = 90^o$$

In 3 phase alternator, the 3rd harmonic is suppressed by star or delta connection as in the case of 3 phase transformer. Total attention is given for designing a 3 phase alternator winding design, for 5th and 7th harmonics.

For 5th harmonic

$$\frac{5\alpha}{2} = 90^\circ \Rightarrow \alpha = \frac{180^\circ}{5} = 36^\circ$$

For 7th harmonic

$$\frac{7\alpha}{2} = 90^\circ \Rightarrow \alpha = \frac{180^\circ}{7} = 25.7^\circ$$

Hence, by adopting a suitable chording angle of $\alpha = 30^o$, **we make most optimized design armature winding of alternator.**

Distribution Factor

If all the coil sides of any one phase under one pole are bunched in one slot, the winding obtained is known as concentrated winding and the total emf induced is equal to the arithmetic sum of the emfs induced in all the coils of one phase under one pole.

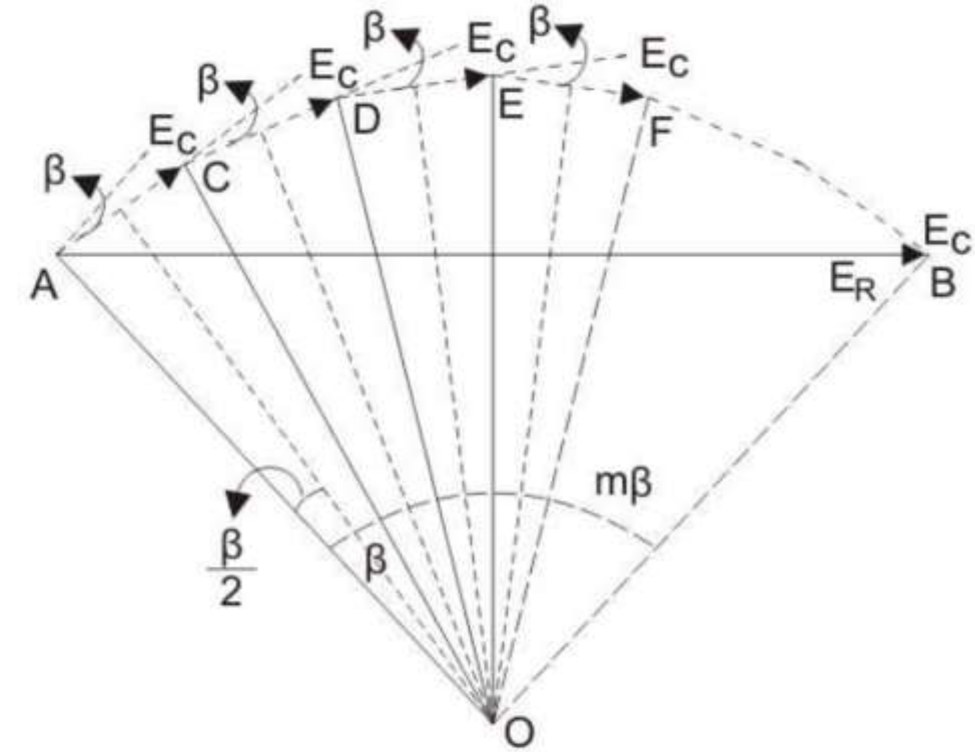
But in practical cases, for obtaining smooth sinusoidal voltage waveform, armature winding of alternator is not concentrated but distributed among the different slots to form polar groups under each pole. In distributed winding, coil sides per phase are displaced from each other by an angle equal to the angular displacement of the adjacent slots. Hence, the induced emf per coil side is not an angle equal to the angular displacement of the slots.

So, the resultant emf of the winding is the phasor sum of the induced emf per coil side. As it is phasor sum, must be less than the arithmetic sum of these induced emfs. Resultant emf would be an arithmetic sum if the winding would have been a concentrated one. As per definition, distribution factor is a measure of resultant emf of a distributed winding in compared to a concentrated winding.

We express it as the ratio of the phasor sum of the emfs induced in all the coils distributed in some slots under one pole to the arithmetic sum of the emfs induced. Distribution factor is,

$$k_d = \frac{EMF \; induced \; in \; distributed \; winding}{EMF \; induced \; if \; the \; winding \; would \; have \; been \; concentrated}$$

$$= \frac{Phasor \; sum \; of \; component \; emfs}{Arithmetic \; sum \; of \; component \; emfs}$$



As pitch factor, distribution factor is also always less than unity.
Let the number of slots per pole is n.
The number of slots per pole per phase is m.
Induced emf per coil side is Ec.
Angular displacement between the slots,

$$\beta = \frac{180^o}{n}$$

Let us represent the emfs induced in different coils of one phase under one pole as AC, DC, DE, EF and so on.

They are equal in magnitude, but they differ from each other by an angle β.

If we draw bisectors on AC, CD, DE, ——. They would meet at common point O.
EF Emf induced in each coil side,

$$E = AC = 2 \cdot OAsin\frac{\beta}{2}$$

As the slot per pole per phase is m, the total arithmetic sum of all induced emfs per coil sides per pole per phase,

$$Arithmetic\ sum = m \times 2 \times OAsin\frac{\beta}{2}$$

The resultant emf would be AB, as represented by the figure, Hence, the resultant emf

$$E_R = AB = 2 \times OA\sin\frac{\angle AOB}{2} = 2 \times OA\sin\frac{m\beta}{2}$$

$$Therefore,\ Distribution\ Factor$$

$$K_d = \frac{Phasor\ sum\ of\ component\ emfs}{Arithmetic\ sum\ of\ component\ emfs}$$

$$= \frac{2 \times OA\sin\frac{m\beta}{2}}{m \times 2 \times OA\sin\frac{\beta}{2}} = \frac{\sin\frac{m\beta}{2}}{m\sin\frac{\beta}{2}}$$

mβ is also known as the phase spread in electrical degree.

The distribution factor K_d given by equation is for the fundamental component of emf. distribution contains space harmonics the slot angular pitch β on the fundamental scale would **become** rβ for the r^{th} **harmonic component and thus the distribution factor for the r^{th} harmonic would be.**

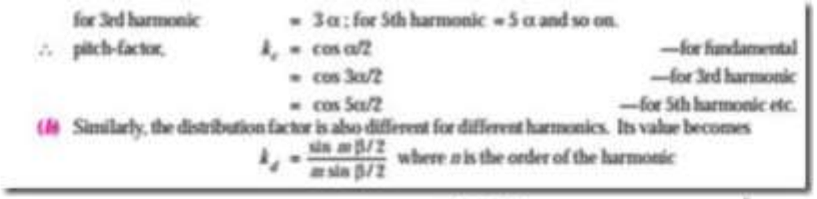
$$K_{dr} = \frac{\sin \frac{rm\beta}{2}}{m \sin \frac{r\beta}{2}}$$

$$Therefore,\ Winding\ Factor$$

$$K_w = K_p \times K_d = \cos \frac{\alpha}{2} \times \frac{\sin \frac{m\beta}{2}}{m \sin \frac{\beta}{2}}$$

Effect of Harmonics on Pitch and Distribution Factors

(a) If the short-pitch angle or chording angle is a degrees (electrical) for the fundamental flux wave, then its values for different harmonics are



for 3rd harmonic $= 3\alpha$; for 5th harmonic $= 5\alpha$ and so on.

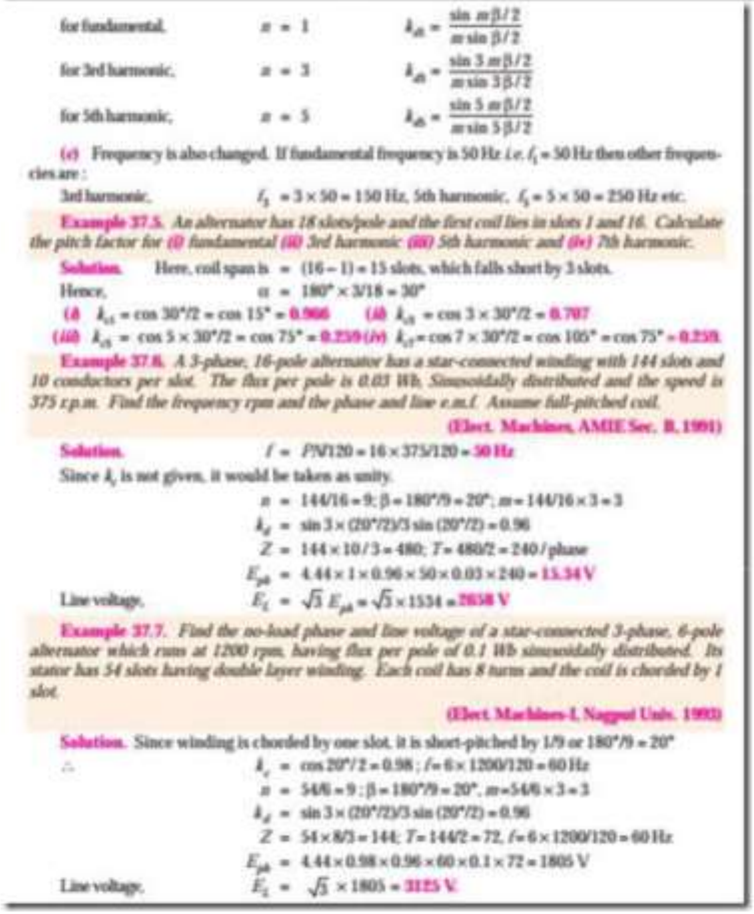
∴ pitch-factor, $k_c = \cos \alpha/2$ —for fundamental

$= \cos 3\alpha/2$ —for 3rd harmonic

$= \cos 5\alpha/2$ —for 5th harmonic etc.

(*b*) Similarly, the distribution factor is also different for different harmonics. Its value becomes

$k_d = \frac{\sin n m\beta/2}{m \sin \beta/2}$ where *n* is the order of the harmonic



for fundamental, $n = 1$ $k_{d1} = \frac{\sin m\beta/2}{m \sin \beta/2}$

for 3rd harmonic, $n = 3$ $k_{d3} = \frac{\sin 3\, m\beta/2}{m \sin 3\beta/2}$

for 5th harmonic, $n = 5$ $k_{d5} = \frac{\sin 5\, m\beta/2}{m \sin 5\beta/2}$

(*c*) Frequency is also changed. If fundamental frequency is 50 Hz *i.e.* $f_1 = 50$ Hz then other frequencies are :

3rd harmonic, $f_3 = 3 \times 50 = 150$ Hz, 5th harmonic, $f_5 = 5 \times 50 = 250$ Hz etc.

Example 37.5. *An alternator has 18 slots/pole and the first coil lies in slots 1 and 16. Calculate the pitch factor for (i) fundamental (ii) 3rd harmonic (iii) 5th harmonic and (iv) 7th harmonic.*

Solution. Here, coil span is $= (16 - 1) = 15$ slots, which falls short by 3 slots.

Hence, $\alpha = 180° \times 3/18 = 30°$

(*i*) $k_{c1} = \cos 30°/2 = \cos 15° = 0.966$ (*ii*) $k_{c3} = \cos 3 \times 30°/2 = 0.707$

(*iii*) $k_{c5} = \cos 5 \times 30°/2 = \cos 75° = 0.259$ (*iv*) $k_{c7} = \cos 7 \times 30°/2 = \cos 105° = \cos 75° = 0.259$

Example 37.6. *A 3-phase, 16-pole alternator has a star-connected winding with 144 slots and 10 conductors per slot. The flux per pole is 0.03 Wb, Sinusoidally distributed and the speed is 375 r.p.m. Find the frequency rpm and the phase and line e.m.f. Assume full-pitched coil.*

(Elect. Machines, AMIE Sec. B, 1991)

Solution. $f = PN/120 = 16 \times 375/120 = 50$ Hz

Since k_c is not given, it would be taken as unity.

$n = 144/16 = 9;\ \beta = 180°/9 = 20°;\ m = 144/16 \times 3 = 3$

$k_d = \sin 3 \times (20°/2)/3 \sin (20°/2) = 0.96$

$Z = 144 \times 10/3 = 480;\ T = 480/2 = 240$ / phase

$E_{ph} = 4.44 \times 1 \times 0.96 \times 50 \times 0.03 \times 240 = 15.34$ V

Line voltage, $E_L = \sqrt{3}\, E_{ph} = \sqrt{3} \times 1534 = 2658$ V

Example 37.7. *Find the no-load phase and line voltage of a star-connected 3-phase, 6-pole alternator which runs at 1200 rpm, having flux per pole of 0.1 Wb sinusoidally distributed. Its stator has 54 slots having double layer winding. Each coil has 8 turns and the coil is chorded by 1 slot.*

(Elect. Machines-I, Nagpur Univ. 1993)

Solution. Since winding is chorded by one slot, it is short-pitched by 1/9 or 180°/9 = 20°

∴ $k_c = \cos 20°/2 = 0.98$; $f = 6 \times 1200/120 = 60$ Hz

$n = 54/6 = 9$; $\beta = 180°/9 = 20°$, $m = 54/6 \times 3 = 3$

$k_d = \sin 3 \times (20°/2)/3 \sin (20°/2) = 0.96$

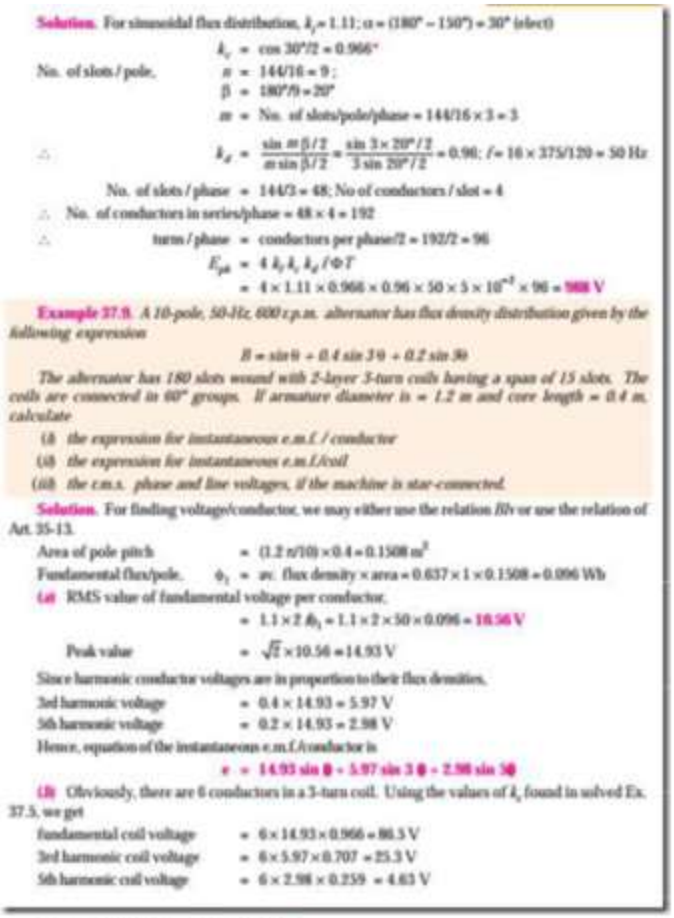
$Z = 54 \times 8/3 = 144;\ T = 144/2 = 72,\ f = 6 \times 1200/120 = 60$ Hz

$E_{ph} = 4.44 \times 0.98 \times 0.96 \times 60 \times 0.1 \times 72 = 1805$ V

Line voltage, $E_L = \sqrt{3} \times 1805 = 3125$ V

Example 37.8. The stator of a 3-phase, 16-pole alternator has 144 slots and there are 4 conductors per slot connected in two layers and the conductors of each phase are connected in series. If the speed of the alternator is 375 r.p.m., calculate the e.m.f. inducted per phase. Result- ant flux in the air-gap is 5 ´ 10 2– webers per pole sinusoidally distributed. Assume the coil span as 150° electrical.

(Elect. Machine, Nagpur Univ. 1993)



Solution. For sinusoidal flux distribution, $k_f = 1.11$; $\alpha = (180° - 150°) = 30°$ (elect)

$k_c = \cos 30°/2 = 0.966$*

No. of slots / pole, $n = 144/16 = 9$;

$\beta = 180°/9 = 20°$

m = No. of slots/pole/phase = $144/16 \times 3 = 3$

$\therefore \quad k_d = \dfrac{\sin m\beta/2}{m \sin \beta/2} = \dfrac{\sin 3 \times 20°/2}{3 \sin 20°/2} = 0.96$; $f = 16 \times 375/120 = 50$ Hz

No. of slots / phase = $144/3 = 48$; No of conductors / slot = 4

$\therefore$ No. of conductors in series/phase = $48 \times 4 = 192$

$\therefore$ turns / phase = conductors per phase/2 = $192/2 = 96$

$E_{ph} = 4\, k_f k_c k_d\, f \Phi T$

$= 4 \times 1.11 \times 0.966 \times 0.96 \times 50 \times 5 \times 10^{-2} \times 96 =$ **908 V**

Example 37.9. *A 10-pole, 50-Hz, 600 r.p.m. alternator has flux density distribution given by the following expression*

$$B = \sin\theta + 0.4 \sin 3\theta + 0.2 \sin 5\theta$$

The alternator has 180 slots wound with 2-layer 3-turn coils having a span of 15 slots. The coils are connected in 60° groups. If armature diameter is = 1.2 m and core length = 0.4 m, calculate

(i) the expression for instantaneous e.m.f. / conductor

(ii) the expression for instantaneous e.m.f./coil

(iii) the r.m.s. phase and line voltages, if the machine is star-connected.

Solution. For finding voltage/conductor, we may either use the relation Blv or use the relation of Art. 35-13.

Area of pole pitch $= (1.2\,\pi/10) \times 0.4 = 0.1508\ m^2$

Fundamental flux/pole, ϕ_1 = av. flux density × area $= 0.637 \times 1 \times 0.1508 = 0.096$ Wb

(a) RMS value of fundamental voltage per conductor,

$= 1.1 \times 2 f\phi_1 = 1.1 \times 2 \times 50 \times 0.096 =$ **10.56 V**

Peak value $= \sqrt{2} \times 10.56 = 14.93$ V

Since harmonic conductor voltages are in proportion to their flux densities,

3rd harmonic voltage $= 0.4 \times 14.93 = 5.97$ V

5th harmonic voltage $= 0.2 \times 14.93 = 2.98$ V

Hence, equation of the instantaneous e.m.f./conductor is

$$e = 14.93 \sin\theta + 5.97 \sin 3\theta + 2.98 \sin 5\theta$$

(b) Obviously, there are 6 conductors in a 3-turn coil. Using the values of k_c found in solved Ex. 37.5, we get

fundamental coil voltage $= 6 \times 14.93 \times 0.966 = 86.5$ V

3rd harmonic coil voltage $= 6 \times 5.97 \times 0.707 = 25.3$ V

5th harmonic coil voltage $= 6 \times 2.98 \times 0.259 = 4.63$ V

Hence, coil voltage expression is*

$$e = 86.5 \sin\theta + 25.3 \sin 3\theta + 4.63 \sin 5\theta$$

(c) Here, $m = 6$, $\beta = 180°/18 = 10°$; $\quad k_{d1} = \dfrac{\sin 6 \times 10°/2}{6 \sin 10°/2} = 0.956$

$k_{d3} = \dfrac{\sin 3 \times 6 \times 10°/2}{6 \sin 3 \times 10°/2} = 0.644 \quad k_{d5} = \dfrac{\sin 5 \times 6 \times 10°/2}{6 \sin 5 \times 10°/2} = 0.197$

It should be noted that number of coils per phase = 180/3 = 60

Fundamental phase e.m.f. $= (86.5/\sqrt{2}) \times 60 \times 0.956 = 3510$ V

3rd harmonic phase e.m.f. $= (25.3/\sqrt{2}) \times 60 \times 0.644 = 691$ V

5th harmonic phase e.m.f. $= (4.63/\sqrt{2}) \times 60 \times 0.197 = 39$ V

RMS value of phase voltage $= (3510^2 + 691^2 + 39^2)^{1/2} =$ **3577 V**

RMS value of line voltage $= \sqrt{3} \times (3510^2 + 39^2)^{1/2} =$ **6080 V**

Example 37.10. *A 4-pole, 3-phase, 50-Hz, star-connected alternator has 60 slots, with 4 conductors per slot. Coils are short-pitched by 3 slots. If the phase spread is 60°, find the line voltage induced for a flux per pole of 0.943 Wb distributed sinusoidally in space. All the turns per phase are in series.* **(Electrical Machinery, Mysore Univ. 1987)**

Solution. As explained in Art. 37.12, phase spread $= m\beta = 60°$ —given

Now, $m = 60/4 \times 3 = 5 \quad \therefore \quad 5\beta = 60°, \beta = 12°$

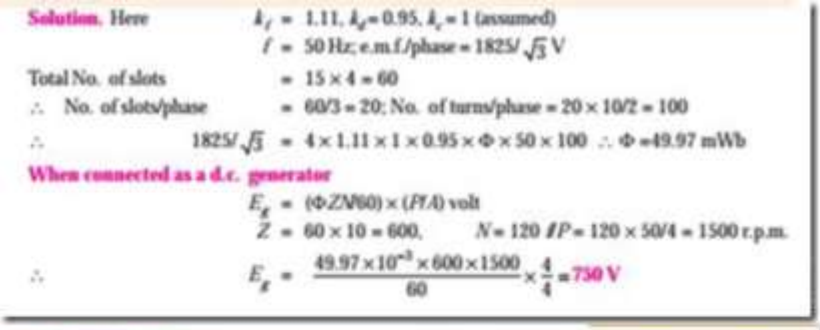
$k_d = \dfrac{\sin 5 \times 12°/2}{5 \sin 12°/2} = 0.957$; $\alpha = (3/15) \times 180° = 36°$; $k_c = \cos 18° = 0.95$

$Z = 60 \times 4/3 = 80$; $T = 80/2 = 40$; $\Phi = 0.943$ Wb; $k_f = 1.11$

$\therefore \quad E_{ph} = 4 \times 1.11 \times 0.95 \times 0.975 \times 50 \times 0.943 \times 40 = 7613$ V

$E_L = \sqrt{3} \times 7613 =$ **13,185 V**

Example 37.11. A 4-pole, 50-Hz, star-connected alternator has 15 slots per pole and each slot has 10 *conductors. All the conductors of each phase are connected in series' the winding factor being 0.95. When* **running on no-load for a certain flux per pole, the terminal e.m.f. was 1825 volt. If the windings are lap-connected as in a d.c. machine, what would be the e.m.f. between the brushes for the same speed and the same flux/pole. Assume sinusoidal distribution of flux.**



Solution. Here $k_f = 1.11, k_d = 0.95, k_c = 1$ (assumed)

$f = 50$ Hz; e.m.f./phase $= 1825/\sqrt{3}$ V

Total No. of slots $= 15 \times 4 = 60$

$\therefore$ No. of slots/phase $= 60/3 = 20$; No. of turns/phase $= 20 \times 10/2 = 100$

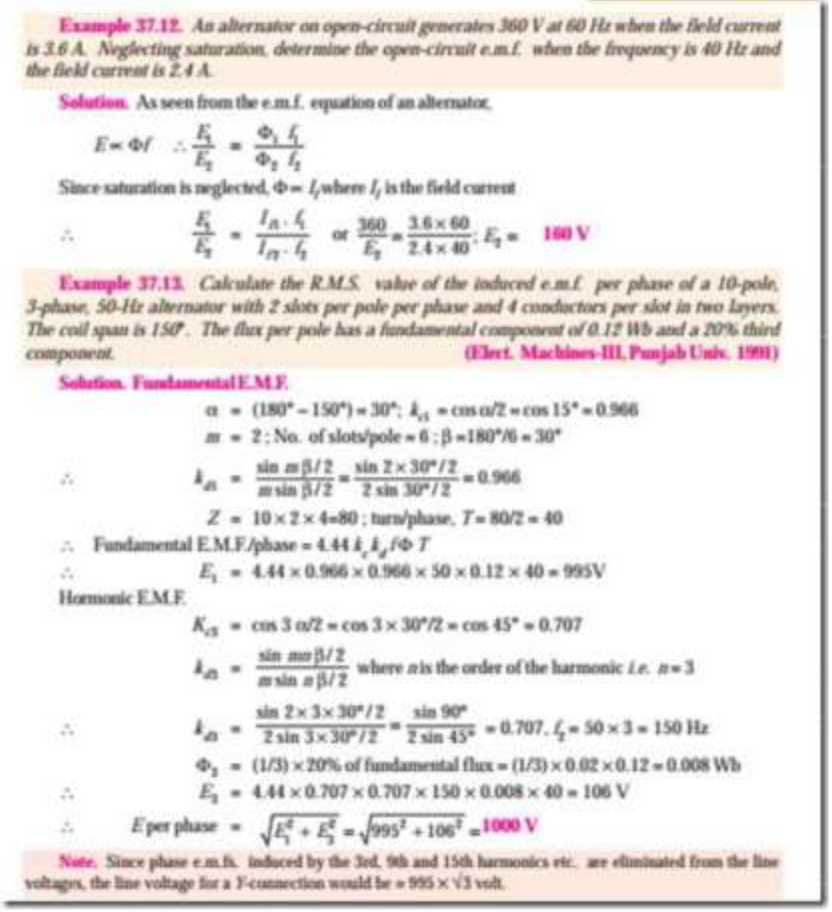
$\therefore$ $1825/\sqrt{3} = 4 \times 1.11 \times 1 \times 0.95 \times \Phi \times 50 \times 100$ $\therefore$ $\Phi = 49.97$ mWb

When connected as a d.c. generator

$$E_g = (\Phi ZN/60) \times (P/A) \text{ volt}$$

$$Z = 60 \times 10 = 600, \qquad N = 120\ f/P = 120 \times 50/4 = 1500 \text{ r.p.m.}$$

$$\therefore \quad E_g = \frac{49.97 \times 10^{-3} \times 600 \times 1500}{60} \times \frac{4}{4} = 750 \text{ V}$$



Example 37.12. *An alternator on open-circuit generates 360 V at 60 Hz when the field current is 3.6 A. Neglecting saturation, determine the open-circuit e.m.f. when the frequency is 40 Hz and the field current is 2.4 A.*

Solution. As seen from the e.m.f. equation of an alternator,

$$E \propto \Phi f \quad \therefore \frac{E_1}{E_2} = \frac{\Phi_1}{\Phi_2}\frac{f_1}{f_2}$$

Since saturation is neglected, $\Phi \propto I_f$ where I_f is the field current

$$\therefore \quad \frac{E_1}{E_2} = \frac{I_{f1} \cdot f_1}{I_{f2} \cdot f_2} \quad \text{or} \quad \frac{360}{E_2} = \frac{3.6 \times 60}{2.4 \times 40}; \; E_2 = 160 \text{ V}$$

Example 37.13. *Calculate the R.M.S. value of the induced e.m.f. per phase of a 10-pole, 3-phase, 50-Hz alternator with 2 slots per pole per phase and 4 conductors per slot in two layers. The coil span is 150°. The flux per pole has a fundamental component of 0.12 Wb and a 20% third component.* **(Elect. Machines-III, Punjab Univ. 1991)**

Solution. Fundamental E.M.F.

$$\alpha = (180° - 150°) = 30°; \; k_{c1} = \cos \alpha/2 = \cos 15° = 0.966$$

$$m = 2; \text{ No. of slots/pole} = 6; \; \beta = 180°/6 = 30°$$

$$\therefore \quad k_{d1} = \frac{\sin m\beta/2}{m \sin \beta/2} = \frac{\sin 2 \times 30°/2}{2 \sin 30°/2} = 0.966$$

$$Z = 10 \times 2 \times 4 = 80; \text{ turn/phase, } T = 80/2 = 40$$

$\therefore$ Fundamental E.M.F./phase $= 4.44\, k_c k_d f \Phi T$

$$\therefore \quad E_1 = 4.44 \times 0.966 \times 0.966 \times 50 \times 0.12 \times 40 = 995 \text{V}$$

Harmonic E.M.F.

$$K_{c3} = \cos 3\,\alpha/2 = \cos 3 \times 30°/2 = \cos 45° = 0.707$$

$$k_{d3} = \frac{\sin mn\beta/2}{m \sin n\beta/2} \text{ where } n \text{ is the order of the harmonic } i.e. \; n = 3$$

$$\therefore \quad k_{d3} = \frac{\sin 2 \times 3 \times 30°/2}{2 \sin 3 \times 30°/2} = \frac{\sin 90°}{2 \sin 45°} = 0.707, \; f_3 = 50 \times 3 = 150 \text{ Hz}$$

$$\Phi_3 = (1/3) \times 20\% \text{ of fundamental flux} = (1/3) \times 0.02 \times 0.12 = 0.008 \text{ Wb}$$

$$\therefore \quad E_3 = 4.44 \times 0.707 \times 0.707 \times 150 \times 0.008 \times 40 = 106 \text{ V}$$

$$\therefore \quad E \text{ per phase} = \sqrt{E_1^2 + E_3^2} = \sqrt{995^2 + 106^2} = 1000 \text{ V}$$

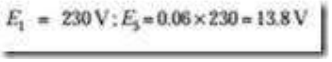
Note. Since phase e.m.fs. induced by the 3rd, 9th and 15th harmonics etc. are eliminated from the line voltages, the line voltage for a Y-connection would be $= 995 \times \sqrt{3}$ volt.

Example 37.14. A 3-phase alternator has generated e.m.f. per phase of 230 V with 10 per cent third harmonic and 6 per cent fifth harmonic content. Calculate the r.m.s. line voltage for (a) star connection (b) delta-connection. Find also the circulating current in delta connection if the reactance per phase of the machine at 50-Hz is 10 W .

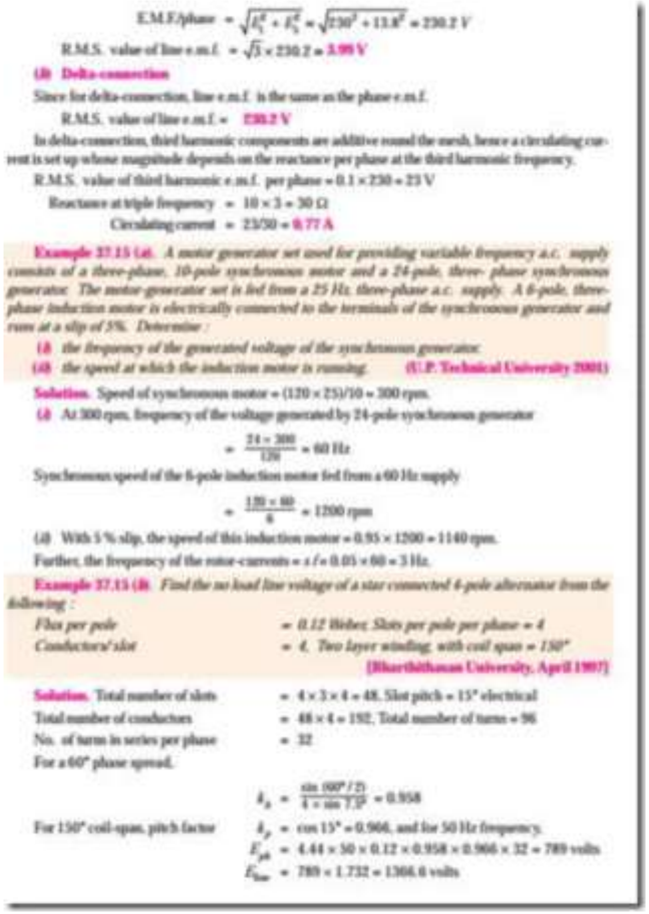
(Elect. Machines-III, Osmania Univ. 1988)

Solution. It should be noted that in both star and delta-connections, the third harmonic components of the three phases cancel out at the line terminals because they are co-phased. Hence, the line is composed of the fundamental and the fifth harmonic only.

(a) Star-connection



$$E_1 = 230 \text{ V}; E_5 = 0.06 \times 230 = 13.8 \text{ V}$$



$$\text{E.M.F./phase} = \sqrt{E_1^2 + E_3^2} = \sqrt{230^2 + 13.8^2} = 230.2\ V$$

$$\text{R.M.S. value of line e.m.f.} = \sqrt{3} \times 230.2 = \mathbf{398\ V}$$

(ii) Delta-connection

Since for delta-connection, line e.m.f. is the same as the phase e.m.f.

R.M.S. value of line e.m.f. = **230.2 V**

In delta-connection, third harmonic components are additive round the mesh, hence a circulating current is set up whose magnitude depends on the reactance per phase at the third harmonic frequency.

R.M.S. value of third harmonic e.m.f. per phase = 0.1 × 230 = 23 V

Reactance at triple frequency = 10 × 3 = 30 Ω

Circulating current = 23/30 = **0.77 A**

Example 37.15 (a). *A motor generator set used for providing variable frequency a.c. supply consists of a three-phase, 10-pole synchronous motor and a 24-pole, three- phase synchronous generator. The motor-generator set is fed from a 25 Hz, three-phase a.c. supply. A 6-pole, three-phase induction motor is electrically connected to the terminals of the synchronous generator and runs at a slip of 5%. Determine :*

(i) the frequency of the generated voltage of the synchronous generator.

(ii) the speed at which the induction motor is running. **(U.P. Technical University 2001)**

Solution. Speed of synchronous motor = (120 × 25)/10 = 300 rpm.

(i) At 300 rpm, frequency of the voltage generated by 24-pole synchronous generator

$$= \frac{24 \times 300}{120} = 60\ \text{Hz}$$

Synchronous speed of the 6-pole induction motor fed from a 60 Hz supply

$$= \frac{120 \times 60}{6} = 1200\ \text{rpm}$$

(ii) With 5 % slip, the speed of this induction motor = 0.95 × 1200 = 1140 rpm.

Further, the frequency of the rotor-currents = $s\,f$ = 0.05 × 60 = 3 Hz.

Example 37.15 (b). *Find the no load line voltage of a star connected 4-pole alternator from the following :*

Flux per pole = 0.12 Weber. Slots per pole per phase = 4

Conductors/slot = 4. Two layer winding, with coil span = 150°

(Bharathidhasan University, April 1997)

Solution. Total number of slots = 4 × 3 × 4 = 48. Slot pitch = 15° electrical

Total number of conductors = 48 × 4 = 192. Total number of turns = 96

No. of turns in series per phase = 32

For a 60° phase spread,

$$k_d = \frac{\sin (60°/2)}{4 \times \sin 7.5°} = 0.958$$

For 150° coil-span, pitch factor k_p = cos 15° = 0.966, and for 50 Hz frequency,

$$E_{ph} = 4.44 \times 50 \times 0.12 \times 0.958 \times 0.966 \times 32 = 789\ \text{volts}$$

$$E_{line} = 789 \times 1.732 = 1366.6\ \text{volts}$$

Derivation of EMF Equation of Synchronous Generator or Alternator

EMF Equation of Synchronous Generator or Alternator:

We know that Synchronous Generator or Alternator will generate an EMF. The following is the derivation of emf equation of Synchronous Generator or Alternator.

Let Φ = Flux per pole, in Wb

P = Number of poles

N = Synchronous speed in r.p.m

f = Frequency of induced emf in Hz

Z = Total number of conductors

Zph = Conductors per phase connected in series

Zph = Z/3 as number of phases = 3

Consider a single conductor placed in a slot.

The average value of emf induced in a conductor = $d\Phi/dt$

For one revolution of a conductor,

eavg per conductor = (Flux cut in one revolution/Time taken for one revolution)

Total flux cut in one revolution is Φ x P.

Time taken for one revolution is 60/Ns seconds.

$$\therefore \quad e_{avg} \text{ per conductor } = \frac{\phi P}{\left(\frac{60}{N_s}\right)} = \phi \frac{PN_s}{60}$$

$$\text{But} \qquad f = \frac{PN_s}{120}$$

$$\therefore \qquad \frac{PN_s}{60} = 2f$$

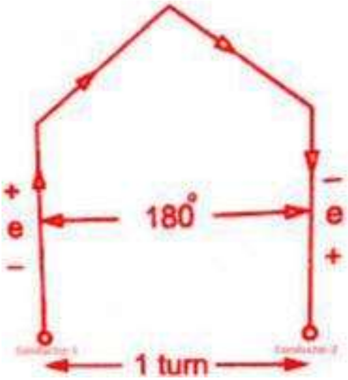
Substituting in above equation

$$\text{eavg per conductor} = 2\ f\ \Phi \text{ volts}$$

Assume full pitch winding for simplicity i.e. this conductor is connected to a conductor which is 180° electrical apart. So these two emf's will try to set up a current in the same direction i.e. the two emf are helping each other and hence resultant emf per turn will be twice the emf induced in a conductor.

$$\text{emf per turn} = 2 \times (\text{emf per conductor}) = 2 \times (2\ f\ \Phi)$$

$$= 4\ f\ \Phi \text{ volts.}$$



Turn of full pitch coil

Let Tph be the total number of turns per phase connected in series. Assuming concentrated winding, we can say that a are placed in single slot per pole per phase (So induced emf's in all turns will be in phase as placed in a single slot. Hence net emf per phase will be algebraic sum of the emf's per turn.

$$\text{Average Eph} = \text{Tph} \times (\text{Average emf per turn})$$

$$\text{Average Eph} = \text{Tph} \times 4\ f\ \Phi$$

But in ac circuits, RMS value of an alternating quantity is used for the analysis. The form factor is 1.11 of sinusoidal emf.

$$K_f = \frac{\text{R.M.S.}}{\text{Average}} = 1.11$$

$$\therefore \text{R.M.S. value of } E_{ph} = K_f \times \text{Average value}$$

$$\therefore \quad E_{ph} = 1.11 \times 4 f \phi T_{ph}$$

$$\boxed{E_{ph} = 4.44 f \phi T_{ph} \text{ volts}}$$

Key point: This is the general emf equation for an induced emf per phase for full pitch, concentrated type of winding.

where Tph = Number of turns per phase

Tph = Zph/2 --->As 2 conductors constitute 1 turn

But as mentioned earlier, the winding used for the alternators is distributed and short pitch hence emf induced slightly gets affected.

In general the emf equation of an alternator is given as

Eph = 4.44 Kp Kd f Φ Tph volts

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^{o} to + 90^{o}

If this angle is θ then,

$$-90^{o} \geq \theta \geq +90^{o}$$

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

1. When $\theta = 0$
2. When $\theta = 90^{o}$
3. When $\theta = -90^{o}$

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

$$\phi_f = \phi_{fm} sin\omega t \cdots\cdots\cdots(1)$$

Then induced emf E across the armature is proportional to $d\varphi_f/dt$.

$$Now, \frac{d\phi_f}{dt} = -\omega\phi_{fm}cos\omega t \cdots\cdots\cdots(2)$$

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-magnetising 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,

$$\phi_f = \phi_{fm} sin\omega t$$

$$Therefore, induced\ emf\ E \propto -\frac{d\phi_f}{dt}$$

$$\Rightarrow E \propto -\omega\phi_{fm}cos\omega t$$

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^o. Again, we have shown just, field flux φ_f leads, induced emf E by 90^o.

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^o as I leads E by 90^o.

As in this case both armature flux and field flux lead, induced emf E by 90^o, 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

1. The armature reaction flux is constant in magnitude and rotates at synchronous speed.
2. The armature reaction is cross magnetising when the generator supplies a load at unity power factor.(This is for resistive load)
3. When the generator supplies a load at leading power factor the armature reaction is partly demagnetising and partly cross-magnetising.
4. armature reaction of alternator due to a purely leading electrical power factor is the magnetizing type.
5. armature reaction of the alternator at lagging zero power factor is a purely demagnetising type.
6. Armature flux acts independently of main field flux.

Alternator on Load

As the load on an alternator is varied, its terminal voltage is also found to vary as in d.c. generators. This variation in terminal voltage V is due to the following reasons:

1. voltage drop due to armature resistance R
2. voltage drop due to armature leakage reactance X
3. voltage drop due to armature reaction

(a) Armature Resistance The armature resistance/phase Ra causes a voltage drop/phase of IR which is in phase with the armature current I. However, this voltage drop is practically negligible.

(b) Armature Leakage Reactance When current flows through the armature conductors, fluxes are set up which do not cross the air-gap, but take different paths. Such fluxes are known as leakage fluxes.

The leakage flux is practically independent of saturation, but is dependent on I and its phase angle with terminal voltage V. This leakage flux sets up an e.m.f. of self-inductance which is known as reactance e.m.f. and which is ahead of I by 90°. Hence, armature winding is assumed to possess leakage reactance X (also known as Potier rectance X) such that voltage drop due to this equals IX . A part of the generated e.m.f. is used up in overcoming this reactance e.m.f.

$\therefore E = V\ I\ (R\ jX)$.

(c) Armature Reaction

As in d.c. generators, armature reaction is the effect of armature flux on the main field flux. In the case of alternators, the power factor of the load has a considerable effect on the armature reaction. We will consider three cases : (i) when load of p.f. is unity (ii) when p.f. is zero lagging and (iii) when p.f. is zero leading.

Synchronous Impedance

The actual generated voltage consists of the summation of two component voltages. One of these components voltages is the voltage that would be generated if there were no armature reaction. it is the voltage that would be generated because of only field excitation. This component of the generated voltage is called the excitation voltage, Eexc.

The other component of the generated voltage is called armature reaction voltage , EAR. This is the voltage that must be added to the excitation voltage to take care of the effect of armature reaction upon the generated voltage .

$$Ea = Eexc + EAR$$

Since armature reaction results, in a voltage effect in circuit caused bu change in flux by current in the same circuit, its effect is of the nature of an inductive reactance .therefore EAR is equivalent to a voltage of inductive reactance and

$$EAR = - j\, XAR\, Ia$$

The inductive Reactance XAR is a fictitious reactance which will result in a voltage in armature circuit to account for the effect of armature reaction upon the voltage relations of the armature circuit. Therefore armature reaction voltage can be modelled as in inductor in series with internal generated voltage .

In additionato the effect of armature reaction , the stator winding also has a self inductance and resistance.

Let La = self inductance of stator winding.

Xa = self reactance of stator winding.

Ra = armature (stator) resistance.

The terminal voltage V is given by

$$V = E_a - jX_{AR}I_a - jX_aI_a - R_aI_a$$

where

R_aI_a = armature resistance drop

X_aI_a = armature leakage reactance drop

$X_{AR}I_a$ = armature reaction voltage

the armature reaction effect and the leakage flux effect in the machine are both represented by inductive reactance . therefore, it is customary to combine them into a single reactance, is called the synchronous reactance of the machine, Xs.

$$X_s = X_a + X_{AR}$$

$$V = E_a - jX_sI_a - R_aI_a$$

$$V = E_a - (R_a + jX_s)I_a$$

$$V = E_a - Z_sI_a$$

$$Z_s = R_a + jX_s$$

The impedance Zs is called synchronous impedance.

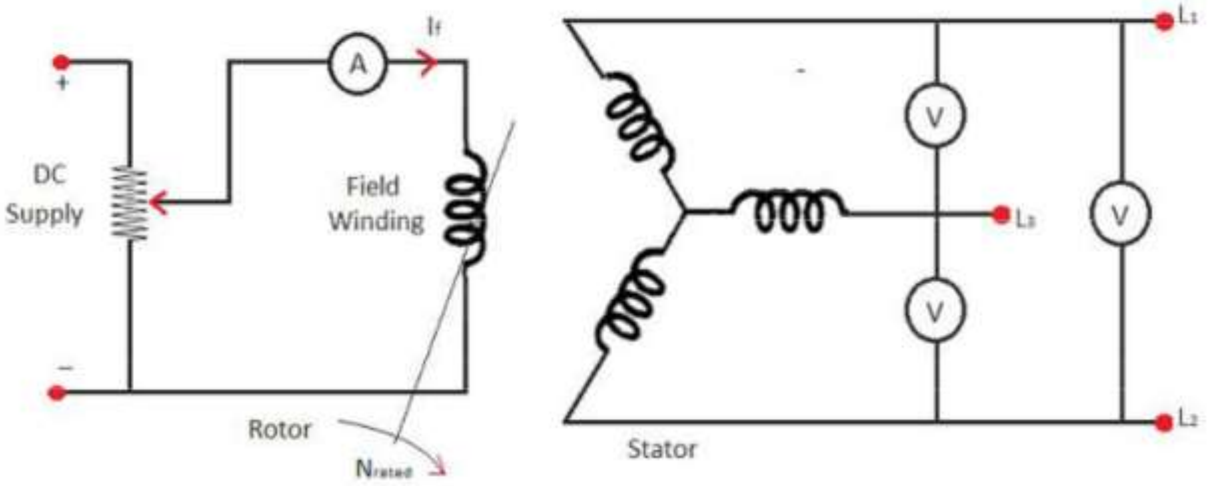
The synchronous Reactance Xs is the fictitious reactance employed to account for voltage effects in the armature circuit produced by the actual armature leakage reactance and by the change in air gap flux caused by the armature reaction.

Open Circuit Test and Short Circuit Test of Synchronous generator

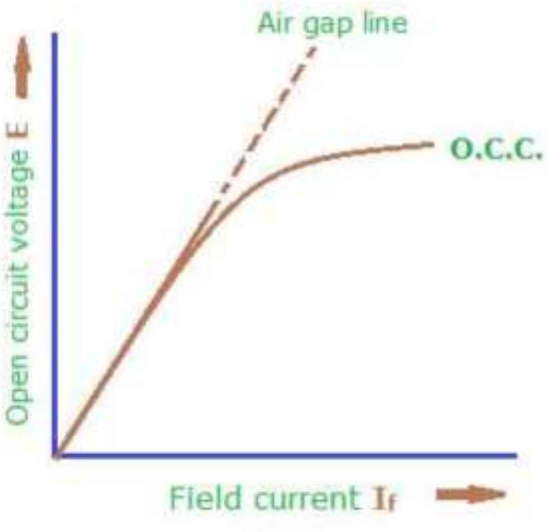
Open Circuit Test and Short Circuit Test are performed on a Synchronous Machine to find out the Synchronous impedance For Large Machine to Determine the Voltage regulation.

Open Circuit Test

the alternator is run at rated synchronous speed and the load terminals are kept open. That is, all the loads are disconnected. the field current is set to zero,this condition is called open circuit test condition.



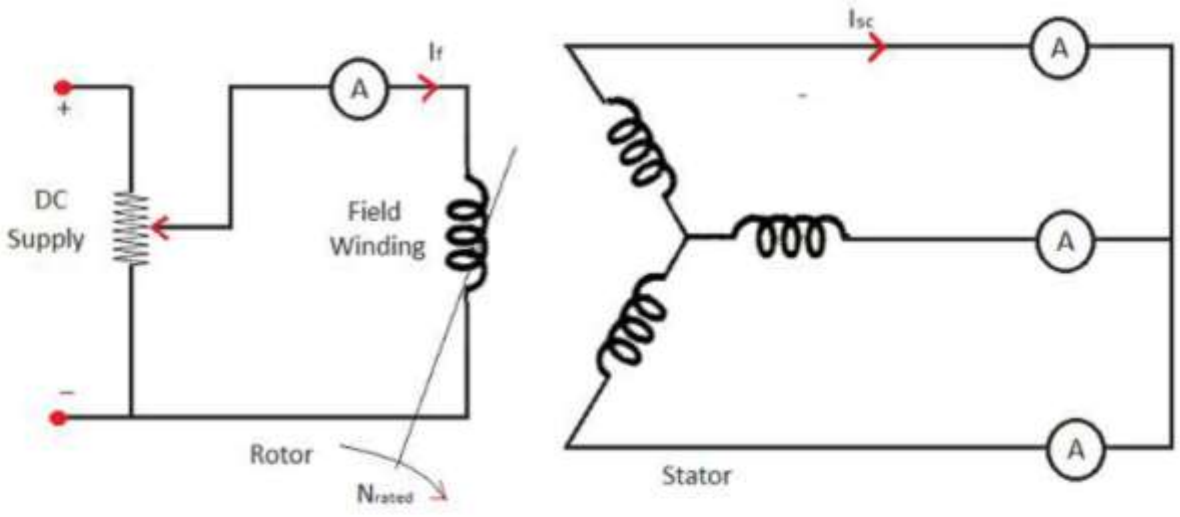
The field current is gradually increase in steps, and the terminal voltage Et is measure at each step, The excitation current may be increased to get 25% more than rated voltage of the alternator. A graph is plotted between the open circuit test voltage Ep and field excitation current If.



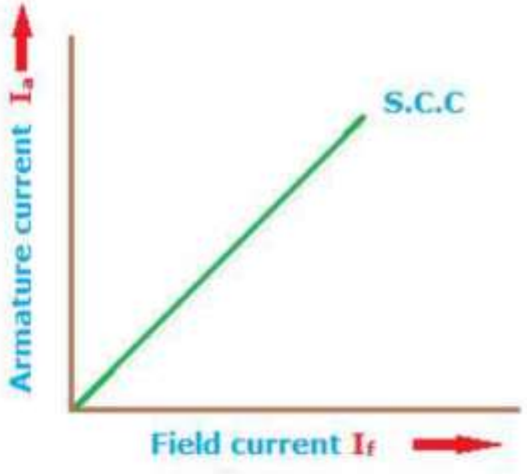
the characteristic curve so obtain is called open circuit characteristic (O.C.C.). it take the shape of a normal magnetization curve. the extension of linear portion of an O.C.C. is called the air gap line are show in figure.

Short Circuit Test

The armature terminals are shorted through three ammeter.Care should we taken performing this test, and the field current should first decreased to zero before starting the alternator. Each ammeter should have range greater than the full rated value. the alternator run at synchronous speed. then the field current gradually increased in step, and the armature current is measured at each step.



The field current may be increased to get armature current upto 150% of the rated value.The field current If and the average of three ammeter reading at each step is taken.



A graph is plotted between the armature current Ia and field current If. The characteristic so obtained is called short-circuit characteristic (SCC). the characteristic is a straight line as shown in figure.

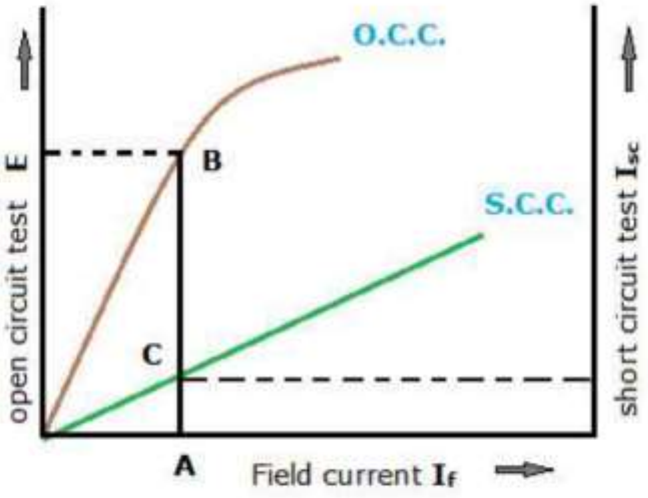
Calculation of Zs

The open circuit characteristic (O.C.C.) and short circuit characteristic (S.C.C.) are drawn on the same curve sheet. Determine the value of Isc and field current that gives the rated alternator voltage per phase. the synchronous impedance Zs will then be equal to the open circuit voltage divided by the short circuit current at the field current which gives the rated e.m.f. per phase.

$$Z_s = \frac{\text{Open-circuit voltage per phase}}{\text{short-circuit armature current}}$$

For the same value of field current.
The synchronous reactance is found as follows.

$$X_s = \sqrt{Z_s^2 - R_a^2}$$



In figure , consider the field current If = OA that the produces rated alternator voltage per phase. corresponding to this field current the open circuit voltage is AB.

$$Z_s = \frac{AB \text{ (in volts)}}{AC \text{ (in amperes)}}$$

Short Circuit Ratio (SCR)

Short circuit ratio or SCR is a measure of the stability ~~of an electromechanical~~ generator.[1] It is the ratio of field current required to produce rated armature voltage at open circuit to the field current required to produce the rated armature current at short circuit.

SCR

$$= \frac{AB}{AC} \Rightarrow \frac{1}{\left(\frac{AC}{AB}\right)} \Rightarrow \frac{1}{\frac{\text{open ckt voltage}}{\text{short ckt. current}}}$$

$$= \frac{1}{\text{Synchro Impedance}}$$

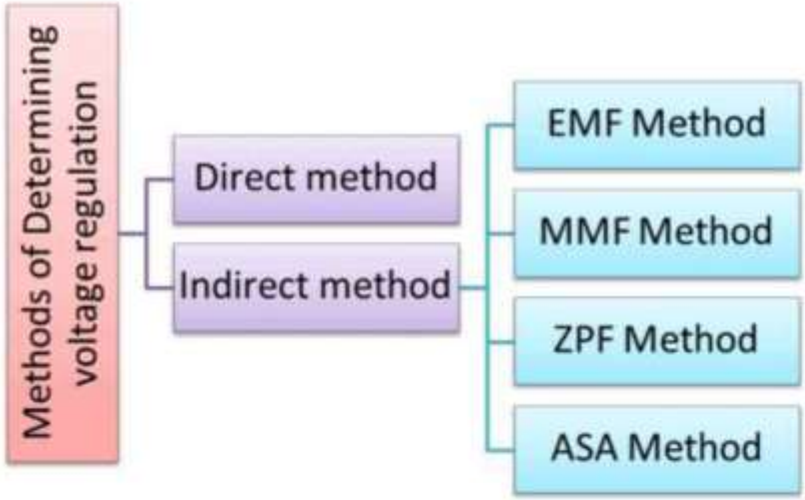
$$= \frac{1}{Z_s} = \frac{1}{X_s} \Rightarrow \text{Neglecting } R_a$$

Voltage Regulation of Alternator

The voltage regulation of an alternator is defined as "the rise in voltage at the terminals, when the load is reduced from full load rated value to zero, speed and field current remaining constant".
With the change in load, there is a change in terminal voltage of an alternator or synchronous generator. The magnitude of this change not only depends on the load but also on the load power factor.

It is also defined as "the rise in voltage when full load is removed **divided by the rated terminal voltage, when** speed and field excitation remains the same." It is given by the formula,

$$Percentage\ Voltage\ Regulation = \frac{E_0 - V}{V} * 100$$



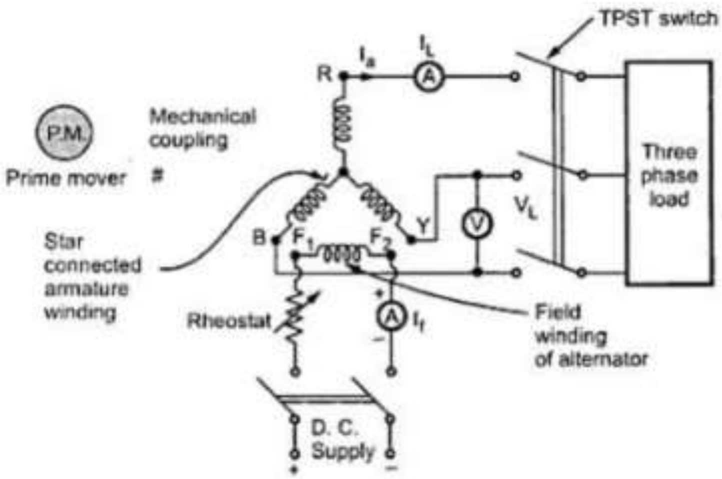
Direct method of determining the voltage regulation is employed for smaller machines.

In this direct method, a three phase load is connected to star connected alternator with the help of Triple Pole Single Throw switch. The field winding of alternator is excited using an external DC supply. A rheostat is connected in series with the field winding, to control the flux produced in the field winding.

Direct load test method for calculating voltage regulation of synchronous machine:

Now let's see how to calculate **voltage regulation of synchronous machine by using direct load test method:**

Circuit diagram for calculating Voltage regulation of synchronous machine by direct load test:



Circuit connections for calculating voltage regulation of synchronous machine by direct load test:

1.Firstly connections are to be made as given in the circuit diagram:

2. Armature which is star connected is connected to the three-phase load with the help of TPST. TPST is a switch and it means triple pole single through.

3. A rheostat is connected in series with the field winding.

4. The field winding is excited by using D.C supply and flux is adjusted by adjusting the rheostat. Flux adjustment is nothing but adjusts the current flow through field winding.

Procedure for calculating voltage regulation of synchronous machine by direct load test:

1. Adjust the prime mover such that the alternator rotates at synchronous speed Ns.

we know Eph αΦ from emf equation

2. Now DC supply is given to the field winding and the current flow through the field is adjusted so that the flux is adjusted such that the rated voltage is obtained at its terminals which can be seen on the voltmeter connected across the lines.

3. Now load is connected to the alternator with the help of TPST switch.

4.The load is then increased such that the ammeter reads rated current. This is full load condition of the alternator. Now as the load is connected due to armature reaction there is a loss of voltage so let the induced voltage be V.

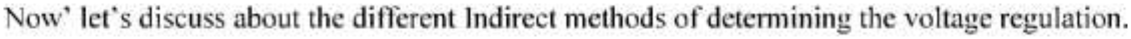
5.Now again adjust the rheostat of the field winding to get rated voltage at alternator terminals.

6.Now remove the load by opening TPST switch and the excitation, speed should not be changed it should be same as before removing the load.

7. As there is no load there is no armature reaction the induced emf is equal to the terminal voltage which is E. Now we can calculate voltage regulation of synchronous machine by

Voltage regulation% =(E V / V) × 100 at a specific power factor.

But in the case of large machines, it becomes very difficult to determine the voltage regulation by direct loading method. So it is very important to switch over to the indirect methods of determination.



Now' let's discuss about the different Indirect methods of determining the voltage regulation.

1. **Synchronous Impedance method or EMF method**
2. **Ampere turns method or MMF method**
3. **Potier method or Zero Power Factor(ZPF) method**
4. **American Standard Association(ASA) of Modified MMF method.**

Synchronous Impedance Method or EMF method:

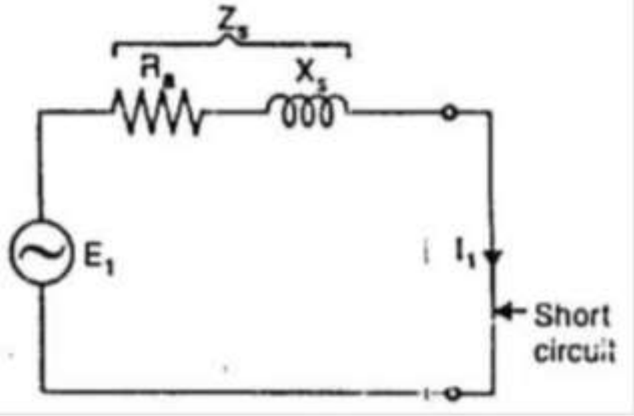
In this method of finding the voltage regulation of an alternator, we find the synchronous impedance Z (and hence synchronous reactance X) of the alternator from the O.C.C. and S.S.C. For this reason, it is called synchronous impedance method. The method involves the following steps:

(i) Plot the O.C.C. and S.S.C. on the same field current base as shown in Fig. (1).

(ii) Consider a field current If. The open-circuit voltage corresponding to this field current is E . The short-circuit armature current corresponding to field current If is I . On shortcircuit p.d. = 0 and voltage E is being used to circulate the snort-circuit armature current I against the synchronous impedance Z . This is illustrated in Fig. (2).

$$\therefore \quad E_1 = I_1 Z_s \quad \text{or} \quad Z_s = \frac{E_1\ (\text{Open - circu}}{I_1\ (\text{Short - circui}}$$

Note that E_1 is the phase value and so is I_1.



(i) The armature resistance can be found as

$$\therefore \quad \text{Synchronous reactance,}\ X_s = \sqrt{Z_s^2 - R_a^2}$$

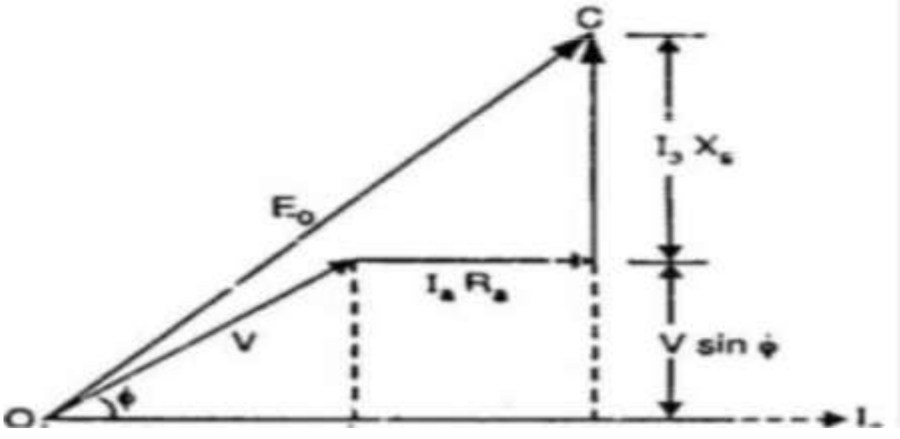


diagram can be drawn for any load and any p.f.

Fig. (3) shows the phasor diagram for the usual case of inductive load; the load p.f. being cos Φ lagging. Note that in drawing the phasor diagram current I_a has been taken as the reference phasor. The I_aR_a drop is in phase with I_a while I_aX_s drop leads I_a by 90°. The phasor sum of V, I_aR_a and I_aX_s gives the no- load e.m.f. E_0.

$$E_0 = \sqrt{(OB)^2 + (BC)^2}$$

$$\text{Now} \quad OB = V\cos\phi + I_aR_a$$

$$\text{and} \quad BC = V\sin\phi + I_aX_s$$

$$\boxed{E_{ph} = \sqrt{(V_{ph}\ \cos\phi + I_a\ R_a)^2 + (V_{ph}\ \sin\phi \pm I_a\ X_s)^2}}$$

$$\therefore \quad \%\ \text{voltage regulation} = \frac{E_0 - V}{V} \times 100$$

Drawback of EMF method:

This method if easy but it gives approximate results. The reason is simple. The combined effect of XL (armature leakage reactance) and X_{AR} (reactance of armature reaction) is measured on short-circuit. Since the current in this condition is almost lagging 90°, the armature reaction will provide its worst demagnetizing effect. It follows that under any normal operation at, say 0.8 or 0.9 lagging power factors will produce error in calculations. This method gives a value higher than the value obtained from an actual load test. For this reason, it is called pessimistic method.

Synchronization of Generators

Often electrical generators are removed from the service and connected back to the power system during variations of the load, emergency outages, maintenance, etc.

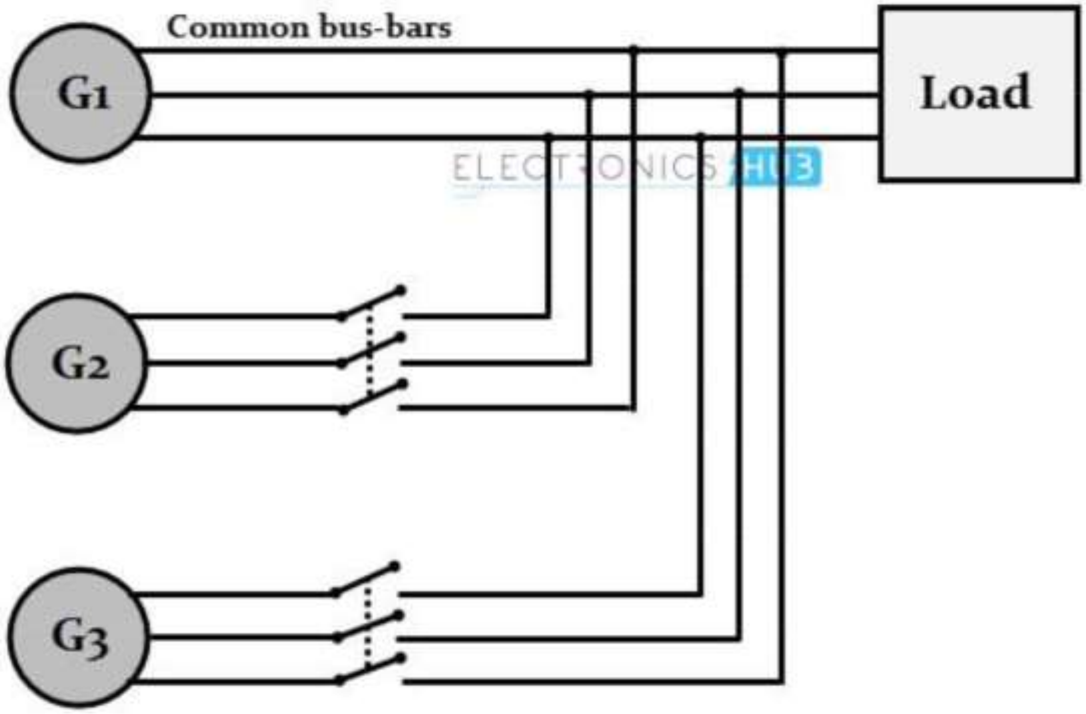
Before reconnecting the generator to the system in each time, it must be synchronized with parameters of the power system network.

An improper synchronization can affect the healthy power system and results in electrical and mechanical transients that can damage the prime mover, generator, transformers and other power system components.

What is Synchronization of Generators?

The process of matching parameters such as voltage, frequency, phase angle, phase sequence and waveform of alternator (generator) or other source with a healthy or running power system is called synchronization.

Generator cannot deliver power to electric power system unless its voltage, frequency and other parameters are exactly matched with the network. Synchronization is accomplished by controlling the exciter current and the engine speed of the generator.



The need for synchronization arrives, particularly when two or more alternators are working together to supply the power to the load. This is because electrical loads are not constant and they vary with time and hence they necessitate the interconnection of two or more alternators operating in parallel to supply larger loads.

Synchronization matches various parameters of one alternator (or generator) to another alternator or to the bus bar. The process of synchronization is also called as paralleling of alternators.

Need of Paralleling of Generators

In most commercial power plants, several small units supply the power rather than single large unit. This is called as parallel operation of generators. The reasons for preferring this practice are enumerated below.

Reliability

Several small units are more reliable than single large unit. This is because, if one alternator is failed, other alternators are still active and hence the whole system will not be shutdown.

Continuity of Service

In case of periodic maintenance, break-down, or repairs of one alternator, it must be shutdown and removed from service. Since the other machines are operating in parallel, the interruption to supply the load is prevented.

Load Requirements

The load requirements in the central station changes continuously. During light-load periods only one or two generators are operated to supply the load demands. During peak-load demands, other alternators are connected in parallel to meet the demand.

High Efficiency

Generators run most efficiently when they are loaded at their rated values. Due to the operation of few generators at light-loads and more generators at high peak loads efficiently loads the generators.

Expanded Capacity

As the demand for electric power is increasing continuously, utility companies have been increasing the physical size of the generating plants by adding more alternators. So these alternators have to be connected in parallel with the existing generator equipment.

Conditions for Synchronization or Paralleling of Generators

There are certain requirements that must be met for successful paralleling of alternators. The following conditions must be met in order to synchronize a generator to the grid or with other generators.

Phase Sequence

The phase sequence of the three phases of the alternator which is being connected to the power system bus must be same as the phase sequence of the three phases of the bus bar (or electric grid). This problem comes mainly in the event of initial installation or after maintenance.

TERMINAL Voltage Magnitude

The RMS voltage of the incoming alternator should be same as the RMS voltage of the bus bar or electric grid. If the incoming alternator voltage is more than the bus bar voltage, there will be a high reactive power that flows from the generator into the grid.

If the incoming alternator voltage is lower than the bus bar voltage, generator absorbs the high reactive power from the bus bar.

Frequency

The frequency of the incoming generator must be equal to the frequency of the bus bar. Improper matching of frequency results high acceleration and deceleration in the prime mover that increases the transient torque.

Phase Angle

The phase angle between the incoming generator voltage and voltage of the bus bar should be zero. This can be observed by comparing the occurrence of zero crossing or peaks of the voltage waveforms.

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.

Procedure for Connecting Alternators in Parallel

When the above stated methods are fulfilled, the alternators are said to be in synchronism. The actual process of synchronization or paralleling generators includes the following steps.

- Consider that alternator-1 is supplying power to the bus bars at rated voltage and frequency. Now, an incoming alternator-2 is to be connected in parallel with alternator-1 for the first time. By increasing the speed of the alternator, its frequency is varied and hence the speed is adjusted till it matches with bus bar frequency (or the frequency of alternator-1). Also by varying the field rheostat, the voltage of the alternator-2 is varied and hence it is adjusted till the voltage matches with bus bar voltage.
- The three voltages generated by the alternator-2 must be in phase with the respective voltages of the bus bar (or alternator-1). This is achieved by maintaining the same phase sequence and frequency of alternator-2 with bus bar or alternator-1. For achieving these relationships, synchronizing lamps technique is used.

Techniques for Synchronization

There are different techniques being available for the synchronization of alternators. The primary purpose of these techniques is to check all four conditions discussed above. The common methods used for synchronizing the alternators are given below.

1. Three Dark Lamps Method

2. Two Bright, One Dark Method

3. Synchroscope Method

Three Dark Lamps Method

The figure below shows the circuit for bright lamp method used to synchronize the alternators. Assume that alternator is connected to the load supplying rated voltage and frequency to it. Now the alternator-2 is to be connected in parallel with alternator-1.

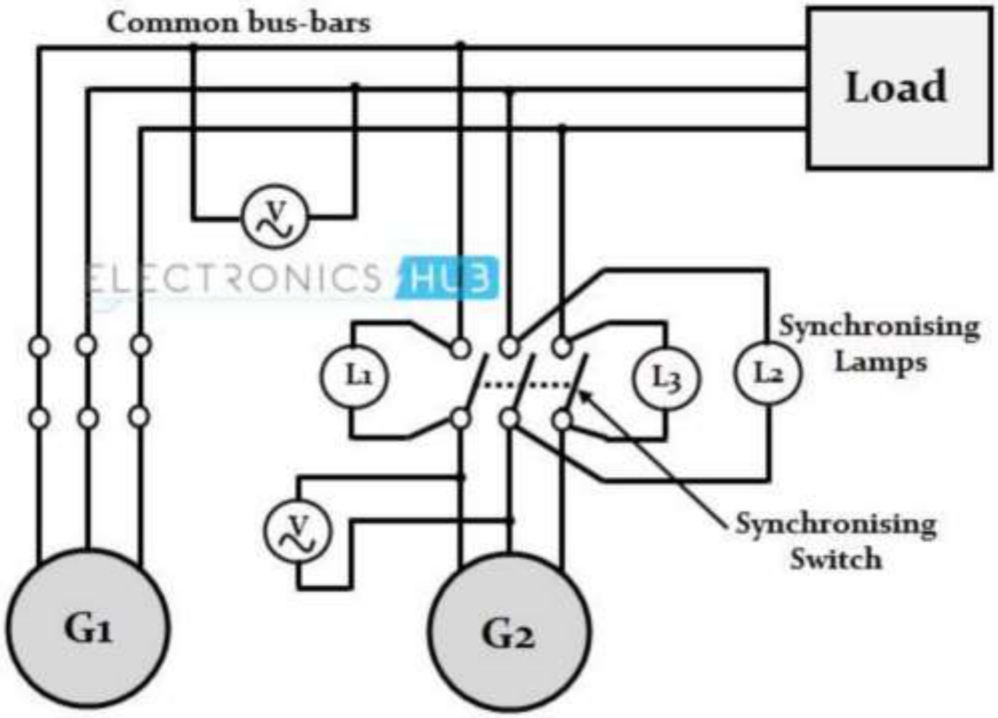
Three lamps (each of which is rated for alternator terminal voltage) are connected across the switches of the alternator-2. From the figure it is clear that the moment when all the conditions of parallel operation are satisfied, the lamps should be more or less dark.

To synchronize the alternator-2 with bus bar, the prime mover of the alternator-2 is driven at speed close to the synchronous speed decided by the bus bar frequency and number of poles of the alternator.

Now the field current of the generator-2 is increased till voltage across the machine terminals is equal to the bus bar voltage (by observing the readings on voltmeters).

If lamps go ON and OFF concurrently , indicating that the phase sequence of alternator-2 matches with bus bar. On the other hand, if they ON and OFF one after another, it resembles the incorrect phase sequence.

By changing the connections of any two leads of alternator-2 after shutting down the machine, the phase sequence can be changed.



Depending on the frequency difference between alternator-2 voltage and bus bar voltage, ON and OFF rate of these lamps is decided. Hence, the rate of flickering has to be reduced to match the frequency. This is possible by adjusting the speed of alternator by its prime mover control.

When all these parameters are set, the lamps become dark and then the synchronizing switch can be closed to synchronize alternator-2 with alternator-1.

The main disadvantage of this method is that rate of flickering only indicates the difference between the alternator-2 and the bus bar. But the information of alternator frequency in relation to bus bar frequency is not available in this method.

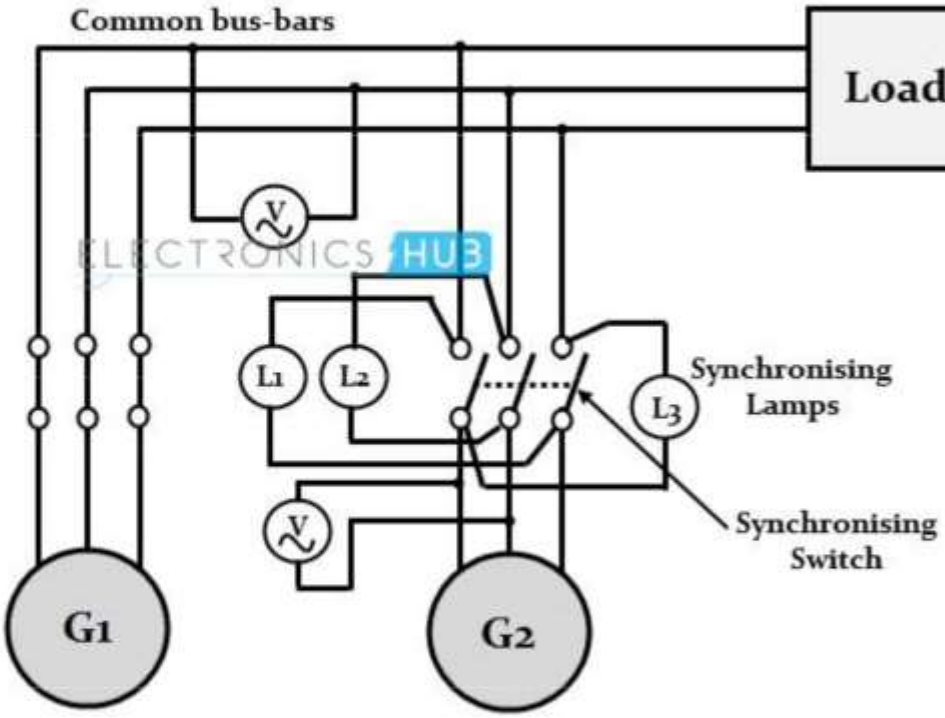
Suppose, if the bus bar frequency is 50Hz, the rate of flickering of lamps is same when the frequency of the alternator is either 51 or 49 Hz, as the difference in these two cases is 1Hz.

Two Bright and One Dark Lamp Method

The connections for this method are shown in figure below and it is useful in finding whether the alternator frequency is lower or higher than the bus bar frequency.

Here, the lamp L2 is connected across the pole in the middle line of synchronizing switch as similar to the dark lamp method, whereas the lamps L1 and L3 are connected in a transposed manner.

The voltage condition checking is similar to the previous method and after it, the lamps glow bright and dark one after another. The lower or higher value of alternator frequency in comparison with bus bar frequency is determined by the sequence in which the lamps become dark and bright.



The sequence of becoming bright and dark L1- L2-L3 indicates that the incoming generator frequency is higher than the bus bar frequency. Hence, the alternator speed has to be reduced by prime mover control till the flickering rate is brought down to a small.

On the other hand, the sequence flickering L1- L3 L2 indicates that incoming alternator frequency is less than that of bus bar.

Hence, the speed of the alternator is increased by the prime mover till the rate of flickering is brought down to as small as possible. The synchronizing switch is then closed at the instant when lamps L1 and L3 are equally bright and lamp L2 is dark.

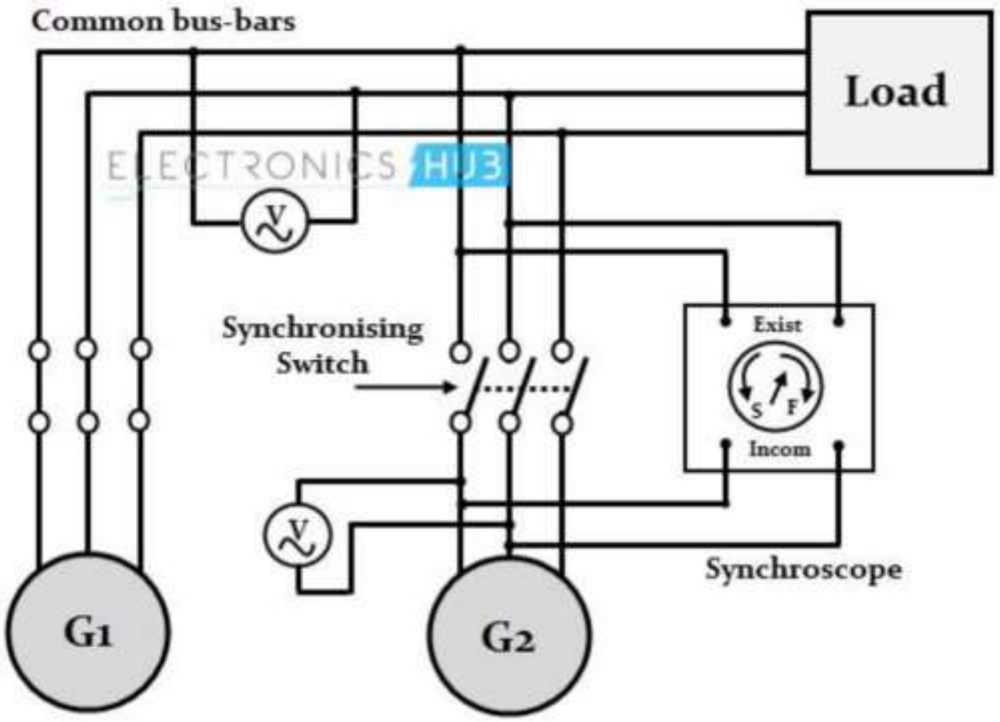
The disadvantage of this method is that the correctness of phase sequence cannot be checked. However, this requirement is unnecessary for permanently connected alternators where checking of phase sequence is enough to be carried out for the first time of operation alone.

Synchroscope Method

It is similar to the two bright and one dark lamp method and indicates whether the alternator frequency is higher or lower than the bus bar frequency. A synchroscope is used for better accuracy of synchronization and it consists of two pairs of terminals.

One pair of terminals marked as 'existing' has to be connected across the bus bar terminals or to the existing alternator and other pair of terminals marked as 'incoming' has to be connected across the terminals of incoming alternator.

The synchroscope has circular dial over which a pointer is hinged that is capable of rotating in clockwise and anticlockwise directions.



After the voltage condition is checked, the operator has to check the synchroscope. The rate at which the pointer rotates indicates the difference of frequency between the incoming alternator and the bus bar.

Also, the direction to which the pointer rotates (to either fast or slow) gives the information, whether the incoming alternator frequency is higher or lower than the bus bar frequency and hence the pointer moves either fast or slow.

The appropriate correction has to be made to control the speed of the alternator so as to bring the rate of rotation of pointer as small as possible.Therefore, synchroscope along with voltmeters are enough for synchronization process. However, in most of the cases a set of lights along with synchroscope is used as a double-check system.

These are the methods of synchronizing the generators. This process must be done carefully to prevent the disturbances in the power system as well as to avoid a serious damage to the machine. Only three lamps methods are not preferred today due to less accuracy and manual operation.

These processes need a skilled and experienced person to handle the equipment while synchronizing. In most cases synchroscope method with set of lamps is used as mentioned above.

Modern synchronization equipments automate the whole synchronization process with the use of microprocessor based systems that avoids manual lamps and synchroscope observations. These methods are easier to manage and more reliable.

DISTRIBUTION OF LOAD BY PARALLEL CONNECTED ALTERNATORS :

Load Sharing

When several alternators are required to run in parallel, it probably happens that their rated outputs differ. In such cases it is usual to divide the total load between them in such a way that each alternator takes the load in the same proportion of its rated load in total rated outputs. The total load is not divided equally. Alternatively, it may be desired to run one large alternator permanently on full load, the fluctuations in load being borne by one or more of the others. If the alternators are sharing the load equally the power triangles are as shown in Fig.2.9a

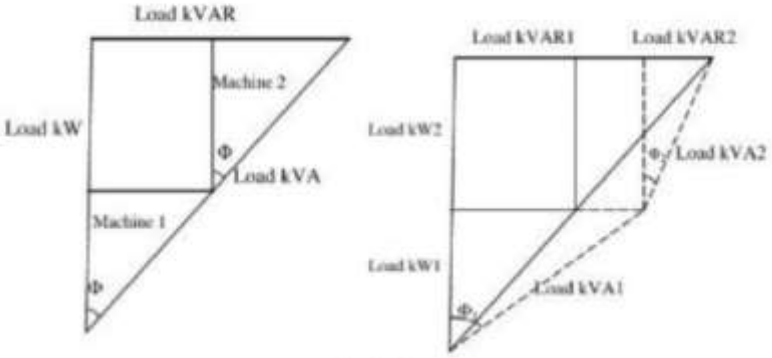
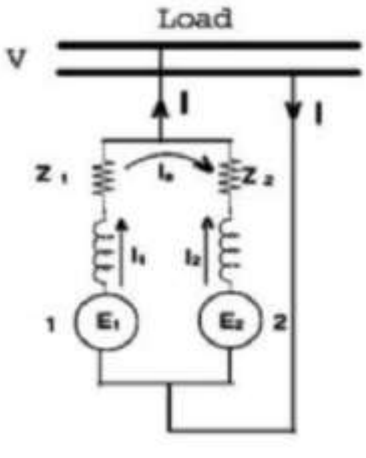


Fig 2.9

Fig.2.9a **Fig.2.9b**

Sharing of load when two alternators are in parallel

Consider two alternators with identical speed load characteristics connected in parallel as shown in Fig:



Fig

Let E1, E2 be the induced emf per phase,

Z1, Z2 be the impedances per phase,

I1, I2 be the current supplied by each machine per phase

Z be the load impedance per phase,

V be the terminal voltage per phase

From the circuit we have $V = E1 - I1Z1 = E2 - I2Z2$ and hence, $I1 = E1 - V/Z1$ and $I2 = E2 - V/Z2$

and also $V = (I1 + I2) Z = IZ$ solving above equations

$$I1 = [(E1 - E2) Z + E1 Z2] / [Z(Z1 + Z2) + Z1Z2]$$

$$I2 = [(E2 - E1) Z + E2 Z1] / [Z(Z1 + Z2) + Z1Z2]$$

The total current $I = I1 + I2 = [E1Z2 + E2Z1] / [Z(Z1 + Z2) + Z1Z2]$

And the circulating current or synchronizing current $I_s = (E1 - E2) / (Z1 + Z2)$

- If the power input to one alternator let machine' 1' is increased then the real power(KW) delivered by **machine 1 is increased where as the KW of machine 2 is decreased without change in KVAR i.e the reactive power of both the machines.**
- **If the excitation of machine1 is increased then KVAR of machine1 increases and KVAR of machine2 decreases without change in KW of both the machines.**

Three Phase Induction Motor

The most common type of AC motor being used throughout the work today is the "Induction Motor". Applications of three-phase induction motors of size varying from half a kilowatt to thousands of kilowatts are numerous. They are found everywhere from a small workshop to a large manufacturing industry.

The advantages of three-phase AC induction motor are listed below:

- **Simple design**
- **Rugged construction**
- **Reliable operation**

- Low initial cost
- Easy operation and simple maintenance
- Simple control gear for starting and speed control
- High efficiency.

Induction motor is originated in the year 1891 with crude construction (The induction machine principle was invented by NIKOLA TESLA in 1888.). Then an improved construction with distributed stator windings and a cage rotor was built.

The slip ring rotor was developed after a decade or so. Since then a lot of improvement has taken place on the design of these two types of induction motors. Lot of research work has been carried out to improve its power factor and to achieve suitable methods of speed control.

Types and Construction of Three Phase Induction Motor

Three phase induction motors are constructed into two major types:

1. Squirrel cage Induction Motors
2. Slip ring Induction Motors

Squirrel cage Induction Motors

(a) Stator Construction

The induction motor stator resembles the stator of a revolving field, three phase alternator. The stator or the stationary part consists of three phase winding held in place in the slots of a laminated steel core which is enclosed and supported by a cast iron or a steel frame as shown in Fig: 3.1(a).

The phase windings are placed 120 electrical degrees apart and may be connected in either star or delta externally, for which six leads are brought out to a terminal box mounted on the frame of the motor. When the stator is energized from a three phase voltage it will produce a rotating magnetic field in the stator core.

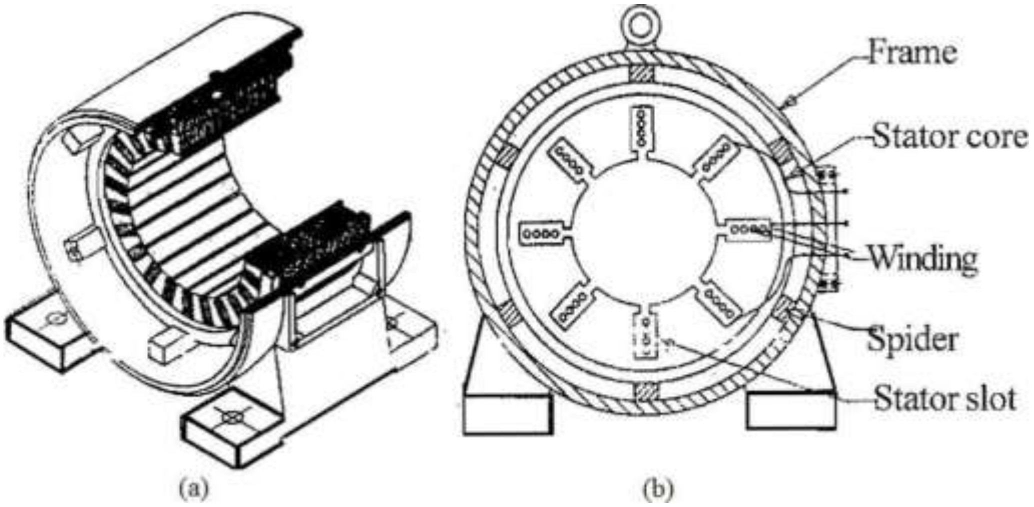


Fig: 3.1

(b) Rotor Construction

The rotor of the squirrel cage motor shown in Fig: 3.1(b) contains no windings. Instead it is a cylindrical core constructed of steel laminations with conductor bars mounted parallel to the shaft and embedded near the surface of the rotor core.

These conductor bars are short circuited by an end rings at both end of the rotor core. In large machines, these conductor bars and the end rings are made up of copper with the bars brazed or welded to the end rings shown in Fig: 3.1(b).In small machines the conductor bars and end rings are sometimes made of aluminium with the bars and rings cast in as part of the rotor core. Actually the entire construction (bars and end-rings) resembles a squirrel cage, from which the name is derived.

The rotor or rotating part is not connected electrically to the power supply but has voltage induced in it by transformer action from the stator. For this reason, the stator is sometimes called the primary and the rotor is referred to as the secondary of the motor since the motor operates on the principle of induction and as the construction of the rotor with the bars and end rings resembles a squirrel cage, the squirrel cage induction motor is used.

The rotor bars are not insulated from the rotor core because they are made of metals having less resistance than the core. The induced current will flow mainly in them. Also the rotor bars are usually not quite parallel to the rotor shaft but are mounted in a slightly skewed position. This feature tends to produce a more uniform rotor field and torque. Also it helps to reduce some of the internal magnetic noise when the motor is running.

(c) End Shields

The function of the two end shields is to support the rotor shaft. They are fitted with bearings and attached to the stator frame with the help of studs or bolts attention.

Slip ring Induction Motors

(a) Stator Construction

The construction of the slip ring induction motor is exactly similar to the construction of squirrel cage induction motor. There is no difference between squirrel cage and slip ring motors.

(b) Rotor Construction

The rotor of the slip ring induction motor is also cylindrical or constructed of lamination.

Squirrel cage motors have a rotor with short circuited bars whereas slip ring motors have wound rotors having "three windings" each connected in star.

The winding is made of copper wire. The terminals of the rotor windings of the slip ring motors are brought out through slip rings which are in contact with stationary brushes as shown in Fig: 3.2.

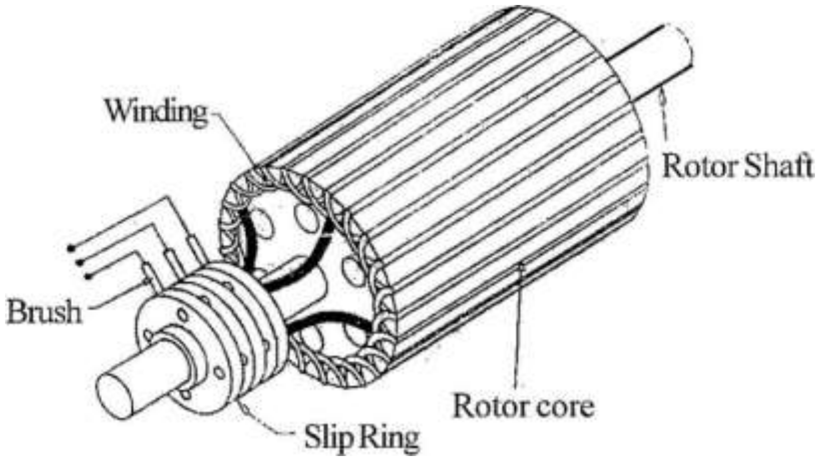


Fig: 3.2

THE ADVANTAGES OF THE SLIPRING MOTOR ARE

- **It has susceptibility to speed control by regulating rotor resistance.**
- **High starting torque of 200 to 250% of full load value.**
- **Low starting current of the order of 250 to 350% of the full load current.**

Hence slip ring motors are used where one or more of the above requirements are to be met.

Comparison of Squirrel Cage and Slip Ring Motor

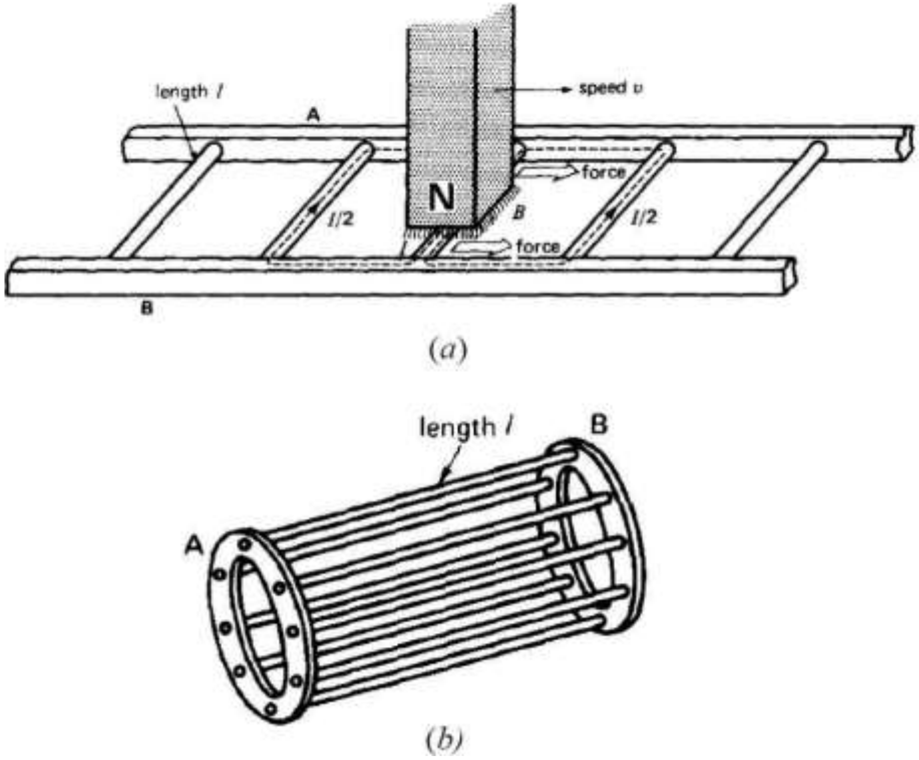
Sl.No.	Property	Squirrel cage motor	Slip ring motor
1.	Rotor Construction	Bars are used in rotor. Squirrel cage motor is very simple, rugged and long lasting. No slip rings and brushes	Winding wire is to be used. Wound rotor required attention. Slip ring and brushes are needed also need frequent maintenance.
2.	Starting	Can be started by D.O.L., star-delta, auto transformer starters	Rotor resistance starter is required.
3.	Starting torque	Low	Very high
4.	Starting Current	High	Low
5.	Speed variation	Not easy, but could be varied in large steps by pole changing or through smaller incremental steps through thyristors or by frequency variation.	Easy to vary speed. Speed change is possible by inserting rotor resistance using thyristors or by using frequency variation injecting emf in the rotor circuit cascading.
6.	Maintenance	Almost ZERO maintenance	Requires frequent maintenance
7.	Cost	Low	High

Principle of Operation

The operation of a 3-phase induction motor is based upon the application of Faraday Law and the Lorentz force on a conductor. The behaviour can readily be understood by means of the following example.

Consider a series of conductors of length l, whose extremities are short-circuited by two bars A and B (Fig.3.3 a). A permanent magnet placed above this conducting ladder, moves rapidly to the right at a speed v, so that its magnetic field B sweeps across the conductors. The following sequence of events then takes place:

1. **A voltage E = Blv is induced in each conductor while it is being cut by the flux (Faraday law).**
2. **The induced voltage immediately produces a current I, which flows down the conductor underneath the pole face, through the end-bars, and back through the other conductors.**
3. **Because the current carrying conductor lies in the magnetic field of the permanent magnet, it experiences a mechanical force (Lorentz force).**
4. **The force always acts in a direction to drag the conductor along with the magnetic field. If the conducting ladder is free to move, it will accelerate toward the right. However, as it picks up speed, the conductors will be cut less rapidly by the moving magnet, with the result that the induced voltage E and the current I will diminish. Consequently, the force acting on the conductors wilt also decreases. If the ladder were to move at the same speed as the magnetic field, the induced voltage E, the current I, and the force dragging the ladder along would all become zero.**



(a)

(b)

Fig: 3.3

In an induction motor the ladder is closed upon itself to form a squirrel-cage (Fig.3.3b) and the moving magnet is replaced by a rotating field. The field is produced by the 3-phase currents that flow in the stator windings.

Rotating Magnetic Field and Induced Voltages

Consider a simple stator having 6 salient poles, each of which carries a coil having 5 turns (Fig.3.4). Coils that are diametrically opposite are connected in series by means of three jumpers

that respectively connect terminals a-a, b-b, and c-c. This creates three identical sets of windings AN, BN, CN, which are mechanically spaced at 120 degrees to each other. The two coils in each winding produce magneto motive forces that act in the same direction.

The three sets of windings are connected in wye, thus forming a common neutral N. Owing to the perfectly symmetrical arrangement, the line to neutral impedances are identical. In other words, as regards terminals A, B, C, the windings constitute a balanced 3-phase system.

For a two-pole machine, rotating in the air gap, the magnetic field (i.e., flux density) being sinusoidally distributed with the peak along the centre of the magnetic poles. The result is illustrated in Fig.3.5. The rotating field will induce voltages in the phase coils aa', bb', and cc'. Expressions for the induced voltages can be obtained by using Faraday laws of induction.

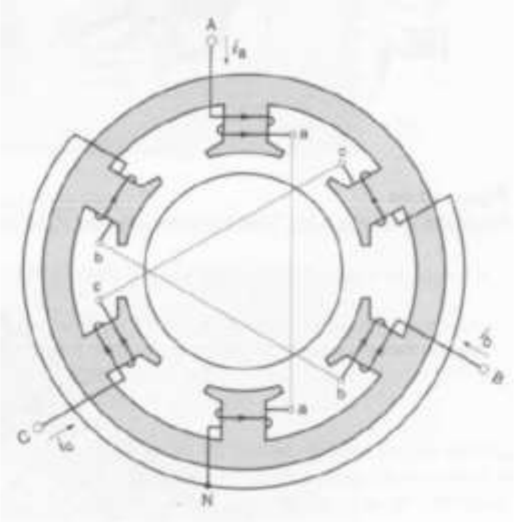


Fig: 3.4 Elementary stator having terminals A, B, C connected to a 3-phase source (not shown). Currents flowing from line to neutral are considered to be positive.

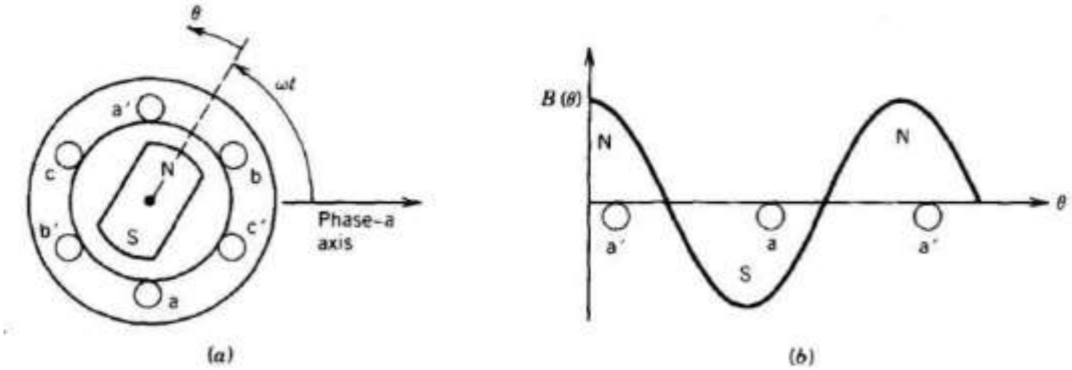


Fig: 3.5 Air gap flux density distribution.

The flux density distribution in the air gap can be expressed as:

$$B(\theta) = B_{\max} \cos \theta$$

The air gap flux per pole, ϕ_P, is:

$$\phi_p = \int_{-\pi/2}^{\pi/2} B(\theta) lr d\theta = 2B_{\max} lr$$

Where,

l is the axial length of the stator.

r is the radius of the stator at the air gap.

Let us consider that the phase coils are full-pitch coils of N turns (the coil sides of each phase are 180 electrical degrees apart as shown in Fig.3.5). It is obvious that as the rotating field moves (or the magnetic poles rotate) the flux linkage of a coil will vary. The flux linkage for coil aa' will be maximum.

$(= N\phi_P \ at \ \omega t = 0^o)$ (Fig.3.5a) and zero at $\omega t = 90^o$. The flux linkage $\lambda_a(\omega t)$ will vary as the cosine of the angle ωt.

Hence,

$$\lambda_a(\omega t) = N\phi_p \cos \omega t$$

Therefore, the voltage induced in phase coil **aa'** is obtained from *Faraday law* as:

$$e_a = -\frac{d\lambda_a(\omega t)}{dt} = \omega N\phi_p \sin \omega t = E_{\max} \sin \omega t$$

The voltages induced in the other phase coils are also sinusoidal, but phase-shifted from each other by 120 electrical degrees. Thus,

$$e_b = E_{\max} \sin(\omega t - 120)$$

$$e_c = E_{\max} \sin(\omega t + 120).$$

the *rms* value of the induced voltage is:

$$E_{rms} = \frac{\omega N\phi_p}{\sqrt{2}} = \frac{2\pi f}{\sqrt{2}} N\phi_p = 4.44 fN\phi_p$$

Where f is the frequency in hertz. Above equation has the same form as that for the induced voltage in transformers. However, Ø$_P$ represents the flux per pole of the machine.

The above equation also shows the rms voltage per phase. The N is the total number of series turns per phase with the turns forming a concentrated full-pitch winding. In an actual AC machine each phase winding is distributed in a number of slots for better use of the iron and copper and to improve the waveform. For such a distributed winding, the EMF induced in various coils placed in different slots are not in time phase, and therefore the phasor sum of the EMF is less than their numerical sum when they are connected in series for the phase winding. A reduction factor K$_W$, called the winding factor, must therefore be applied. For most three-phase machine windings K$_W$ is about 0.85

to 0.95.

Therefore, for a distributed phase winding, the rms voltage per phase is

$$E_{rms} = 4.44fN_{ph}\varphi_pK_W$$

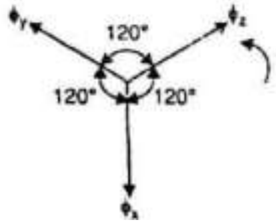
Where N_{ph} is the number of turns in series per phase.

Alternate Analysis for Rotating Magnetic Field

When a 3-phase winding is energized from a 3-phase supply, a rotating magnetic field is produced. This field is such that its poles do no remain in a fixed position on the stator but go on shifting their positions around the stator. For this reason, it is called a rotating Held. It can be shown that magnitude of this rotating field is constant and is equal to 1.5 m where m is the maximum flux due to any phase.

To see how rotating field is produced, consider a 2-pole, 3-phase winding as shown in Fig. 3.6 (i). The three phases X, Y and Z are energized from a 3-phase source and currents in these phases are indicated as Ix, Iy and Iz [See Fig. 3.6 (ii)]. Referring to Fig. 3.6 (ii), the fluxes produced by these currents are given by:

$$\phi_x = \phi_m \sin \omega t$$
$$\phi_y = \phi_m \sin (\omega t - 120^\circ)$$
$$\phi_z = \phi_m \sin (\omega t - 240^\circ)$$



Here ϕ_m is the maximum flux due to any phase. Above figure shows the phasor diagram of the three fluxes. We shall now prove that this 3-phase supply produces a rotating field of constant magnitude equal to 1.5 ϕ_m.

At instant 1 [See Fig. 3.6 (ii) and Fig. 3.6 (iii)], the current in phase X is zero and currents in phases Y and Z are equal and opposite. The currents are flowing outward in the top conductors and inward

in the bottom conductors. This establishes a resultant flux towards right. The magnitude of the resultant flux is constant and is equal to 1.5 ϕ_m as proved under:

At instant 1, ωt = 0°. Therefore, the three fluxes are given by;

$$\phi_x = 0; \qquad \phi_y = \phi_m \sin(-120°) = -\frac{\sqrt{3}}{2}\phi_m;$$

$$\phi_z = \phi_m \sin(-240°) = \frac{\sqrt{3}}{2}\phi_m$$

The phasor sum of $-\phi_y$ and ϕ_z is the resultant flux ϕ_r

So,

$$\text{Resultant flux, } \phi_r = 2 \times \frac{\sqrt{3}}{2}\phi_m \cos\frac{60°}{2} = 2 \times \frac{\sqrt{3}}{2}\phi_m \times \frac{\sqrt{3}}{2} = 1.5\ \phi_m$$

At instant 2 [Fig: 3.7 (ii)], the current is maximum (negative) in ϕ_y phase Y and 0.5 maximum (positive) in phases X and Y. The magnitude of resultant flux is 1.5 ϕ_m as proved under:

At instant 2, ωt = 30°. Therefore, the three fluxes are given by;

$$\phi_x = \phi_m \sin 30° = \frac{\phi_m}{2}$$

$$\phi_y = \phi_m \sin(-90°) = -\phi_m$$

$$\phi_z = \phi_m \sin(-210°) = \frac{\phi_m}{2}$$

The phasor sum of ϕ_x, $-\phi_y$ and ϕ_z is the resultant flux ϕ_r

Phasor sum of ϕ_x and ϕ_z, $\phi'_r = 2 \times \frac{\phi_m}{2} \cos\frac{120°}{2} = \frac{\phi_m}{2}$

Phasor sum of ϕ'_r and $-\phi_y$, $\phi_r = \frac{\phi_m}{2} + \phi_m = 1.5\ \phi_m$

Note that resultant flux is displaced 30° clockwise from position 1.

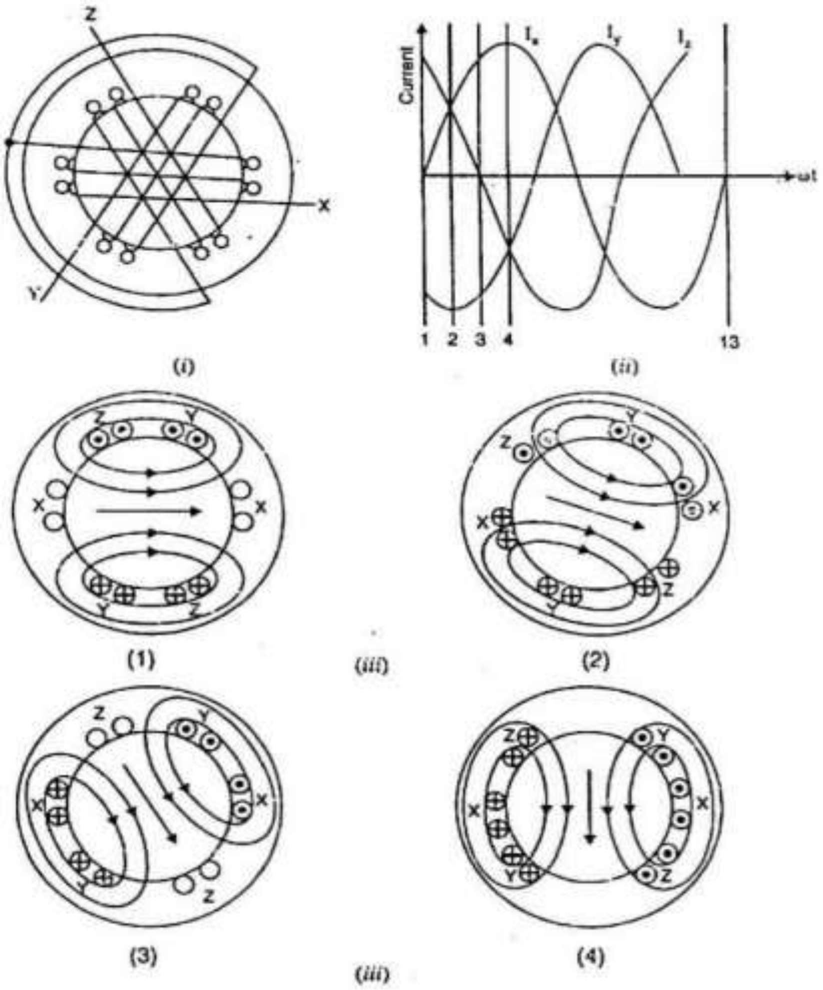
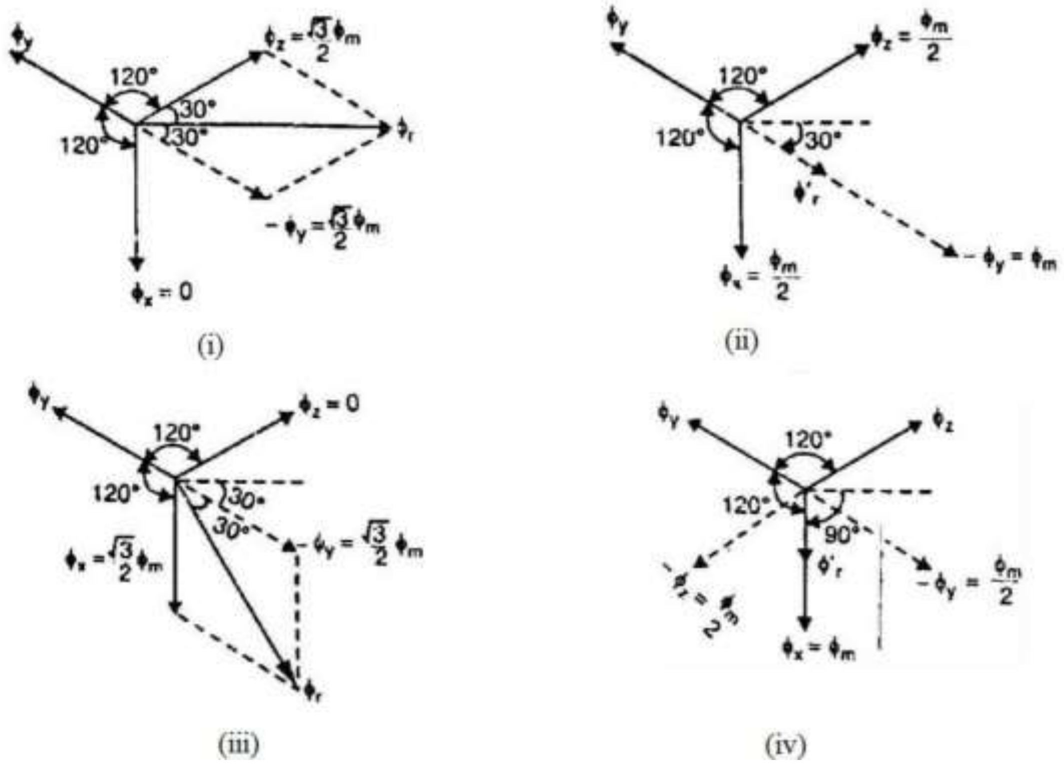


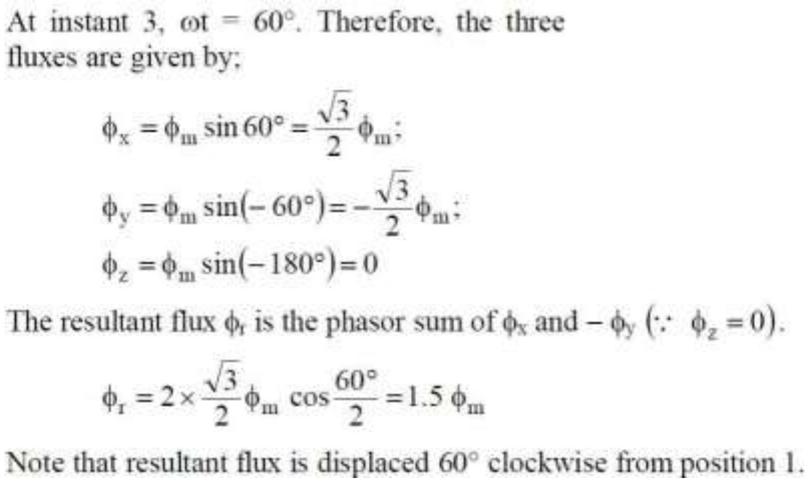
Fig: 3.6

At instant 3[Fig: 3.7 (iii)], current in phase Z is zero and the currents in phases X and Y are equal and opposite (currents in phases X and Y arc 0.866 × max. value). The magnitude of resultant flux is $1.5\ \phi_m$ as proved under:



(i) (ii) (iii) (iv)

Fig: 3.7



At instant 3, ωt = 60°. Therefore, the three fluxes are given by;

$$\phi_x = \phi_m \sin 60° = \frac{\sqrt{3}}{2}\phi_m;$$

$$\phi_y = \phi_m \sin(-60°) = -\frac{\sqrt{3}}{2}\phi_m;$$

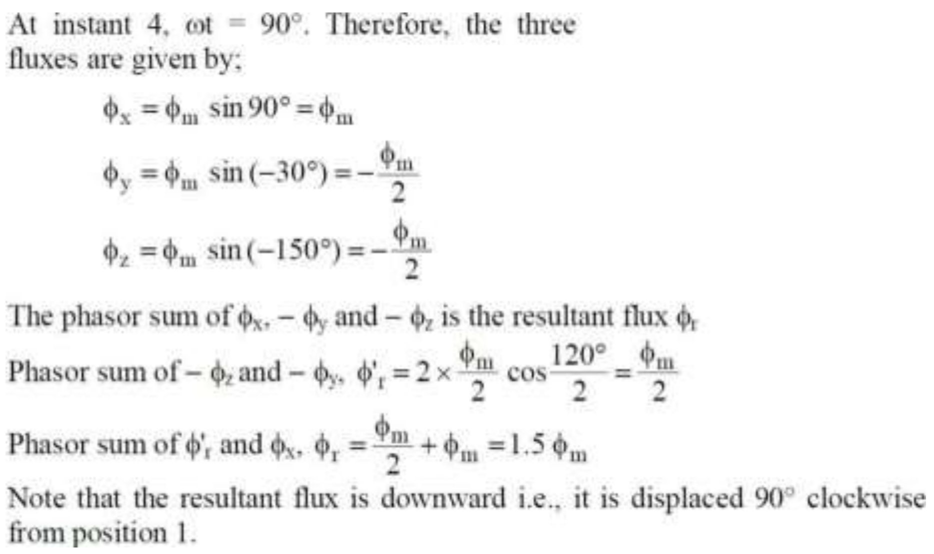
$$\phi_z = \phi_m \sin(-180°) = 0$$

The resultant flux ϕ_r is the phasor sum of ϕ_x and $-\phi_y$ $(\because\ \phi_z = 0)$.

$$\phi_r = 2 \times \frac{\sqrt{3}}{2}\phi_m \cos\frac{60°}{2} = 1.5\ \phi_m$$

Note that resultant flux is displaced 60° clockwise from position 1.

At instant 4 [Fig: 3.7 (iv)], the current in phase X is maximum (positive) and the currents in phases V and Z are equal and negative (currents in phases V and Z are 0.5 × max. value). This establishes a resultant flux downward as shown under:



At instant 4, ωt = 90°. Therefore, the three fluxes are given by;

$$\phi_x = \phi_m \sin 90° = \phi_m$$

$$\phi_y = \phi_m \sin(-30°) = -\frac{\phi_m}{2}$$

$$\phi_z = \phi_m \sin(-150°) = -\frac{\phi_m}{2}$$

The phasor sum of ϕ_x, $-\phi_y$ and $-\phi_z$ is the resultant flux ϕ_r

Phasor sum of $-\phi_z$ and $-\phi_y$, $\phi'_r = 2 \times \frac{\phi_m}{2} \cos\frac{120°}{2} = \frac{\phi_m}{2}$

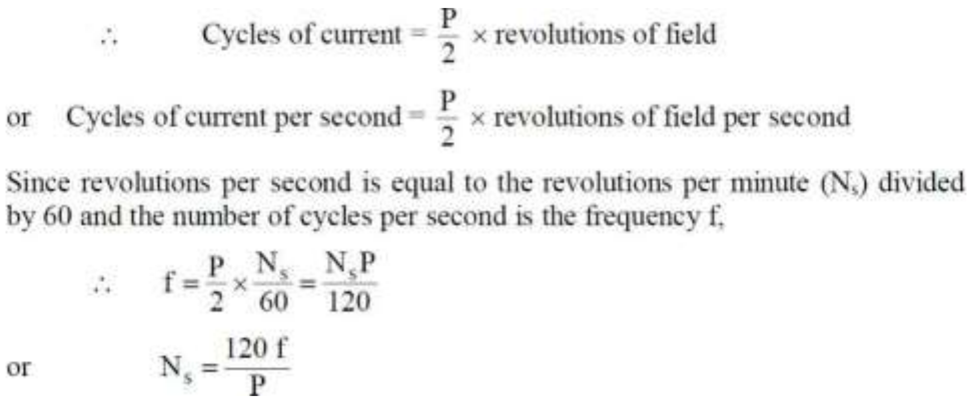
Phasor sum of ϕ'_r and ϕ_x, $\phi_r = \frac{\phi_m}{2} + \phi_m = 1.5\,\phi_m$

Note that the resultant flux is downward i.e., it is displaced 90° clockwise from position 1.

It follows from the above discussion that a 3-phase supply produces a rotating field of constant value (= 1.5 ϕ_m, where ϕ_m is the maximum flux due to any phase).

Speed of rotating magnetic field

The speed at which the rotating magnetic field revolves is called the synchronous speed (Ns). Referring to Fig. 3.6 (ii), the time instant 4 represents the completion of one-quarter cycle of alternating current Ix from the time instant 1. During this one quarter cycle, the field has rotated through 90°. At a time instant represented by 13 [Fig. 3.6 (ii)] or one complete cycle of current Ix from the origin, the field has completed one revolution. Therefore, for a 2-pole stator winding, the field makes one revolution in one cycle of current. In a 4-pole stator winding, it can be shown that the rotating field makes one revolution in two cycles of current. In general, fur P poles, the rotating field makes one revolution in P/2 cycles of current.



$$\therefore \quad \text{Cycles of current} = \frac{P}{2} \times \text{revolutions of field}$$

$$\text{or} \quad \text{Cycles of current per second} = \frac{P}{2} \times \text{revolutions of field per second}$$

Since revolutions per second is equal to the revolutions per minute (N_s) divided by 60 and the number of cycles per second is the frequency f,

$$\therefore \quad f = \frac{P}{2} \times \frac{N_s}{60} = \frac{N_s P}{120}$$

$$\text{or} \quad N_s = \frac{120\,f}{P}$$

The speed of the rotating magnetic field is the same as the speed of the alternator that is supplying power to the motor if the two have the same number of poles. Hence the magnetic flux is said to rotate at synchronous speed.

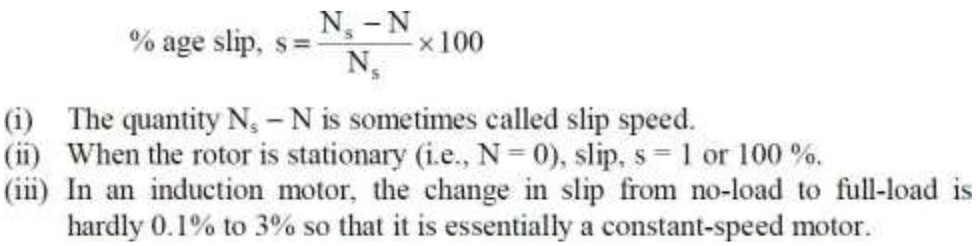
Direction of rotating magnetic field

The phase sequence of the three-phase voltage applied to the stator winding in Fig. 3.6 (ii) is X-Y-Z. If this sequence is changed to X-Z-Y, it is observed that direction of rotation of the field is reversed i.e., the field rotates counter clockwise rather than clockwise. However, the number of poles and the speed at which the magnetic field rotates remain unchanged. Thus it is necessary only to change the phase sequence in order to change the direction of rotation of

the magnetic field. For a three-phase supply, this can be done by interchanging any two of the three lines. As we shall see, the rotor in a 3-phase induction motor runs in the same direction as the rotating magnetic field. Therefore, the direction of rotation of a 3-phase induction motor can be reversed by interchanging any two of the three motor supply lines.

Slip

We have seen above that rotor rapidly accelerates in the direction of rotating field. In practice, the rotor can never reach the speed of stator flux. If it did, there would be no relative speed between the stator field and rotor conductors, no induced rotor currents and, therefore, no torque to drive the rotor. The friction and windage would immediately cause the rotor to slow down. Hence, the rotor speed (N) is always less than the suitor field speed (Ns). This difference in speed depends upon load on the motor. The difference between the synchronous speed Ns of the rotating stator field and the actual rotor speed N is called slip. It is usually expressed as a percentage of synchronous speed i.e.



$$\%\text{ age slip, } s = \frac{N_s - N}{N_s} \times 100$$

(i) The quantity $N_s - N$ is sometimes called slip speed.
(ii) When the rotor is stationary (i.e., $N = 0$), slip, $s = 1$ or 100 %.
(iii) In an induction motor, the change in slip from no-load to full-load is hardly 0.1% to 3% so that it is essentially a constant-speed motor.

Rotor Current Frequency

The frequency of a voltage or current induced due to the relative speed between a vending and a magnetic field is given by the general formula;

$$\text{Frequency} = \frac{NP}{120}$$

where N = Relative speed between magnetic field and the winding
P = Number of poles

For a rotor speed N, the relative speed between the rotating flux and the rotor is $N_s - N$. Consequently, the rotor current frequency f' is given by;

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

$$= \frac{sN_sP}{120} \qquad \left(\because s = \frac{N_s - N}{N_s}\right)$$

$$= sf \qquad \left(\because f = \frac{N_sP}{120}\right)$$

i.e., Rotor current frequency = Fractional slip x Supply frequency

(i) When the rotor is at standstill or stationary (i.e., $s = 1$), the frequency of rotor current is the same as that of supply frequency ($f' = sf = 1 \times f = f$).

(ii) As the rotor picks up speed, the relative speed between the rotating flux and the rotor decreases. Consequently, the slip s and hence rotor current frequency decreases.

Phasor Diagram of Three Phase Induction Motor

In a 3-phase induction motor, the stator winding is connected to 3-phase supply and the rotor winding is short-circuited. The energy is transferred magnetically from the stator winding to the short-circuited, rotor winding. Therefore, an induction motor may be considered to be a transformer with a rotating secondary (short-circuited). The stator winding corresponds to transformer primary and the rotor finding corresponds to transformer secondary. In view of the similarity of the flux and voltage conditions to those in a transformer, one can expect that the equivalent circuit of an induction motor will be similar to that of a transformer. Fig. 3.8 shows the equivalent circuit per phase for an induction motor. Let discuss the stator and rotor circuits separately.

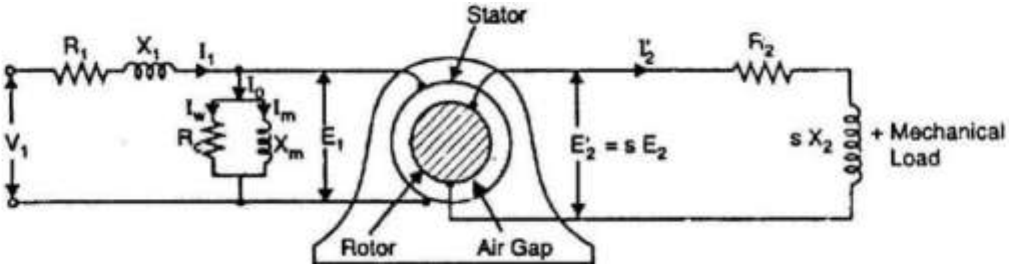


Fig: 3.8

Stator circuit. In the stator, the events are very similar to those in the transformer primary. The applied voltage per phase to the stator is V1 and R1and X1 are the stator resistance and leakage reactance per phase respectively. The applied voltage V1 produces a magnetic flux which links the stator winding (i.e., primary) as well as the rotor winding (i.e., secondary). As a result, self- induced e.m.f. E1 is induced in the stator winding and mutually induced e.m.f.

E'2(= s E_2 = s K E1 where K is transformation ratio) is induced in the rotor winding. The flow of stator current I_1 causes voltage drops in R_1 and X_1.

$\therefore V_1 - \_E_1 + I_1 (R_1 + j X_1)$ **...phasor sum**

When the motor is at no-load, the stator winding draws a current I0. It has two components viz., (i) which supplies the no-load motor losses and (ii) magnetizing component Im which sets up magnetic flux in the core and the air gap. The parallel combination of Rc and Xm, therefore, represents the no-load motor losses and the production of magnetic flux respectively.

$\therefore I_0 = I_w + I_m$

Rotor circuit. Here R2 and X2 represent the rotor resistance and standstill rotor reactance per phase respectively. At any slip s, the rotor reactance will be X_2 .The induced voltage/phase in the rotor is E'_2 = s E2 = s K E_1. Since the rotor winding is short-circuited, the whole of e.m.f. E'_2 is used up in circulating the rotor current I'_2.

$\therefore E'_2 - I'_2 (R_2 + j s X_2)$

The rotor current I'2 is reflected as I''_2 (= K I'_2) in the stator. The phasor sum of I''_2 and I_0 gives the stator current I_1.

It is important to note that input to the primary and output from the secondary of a transformer are electrical. However, in an induction motor, the inputs to the stator and rotor are electrical but the output from the rotor is mechanical. To facilitate calculations, it is desirable and necessary to replace the mechanical load by an equivalent electrical load. We then have the transformer equivalent circuit of the induction motor.

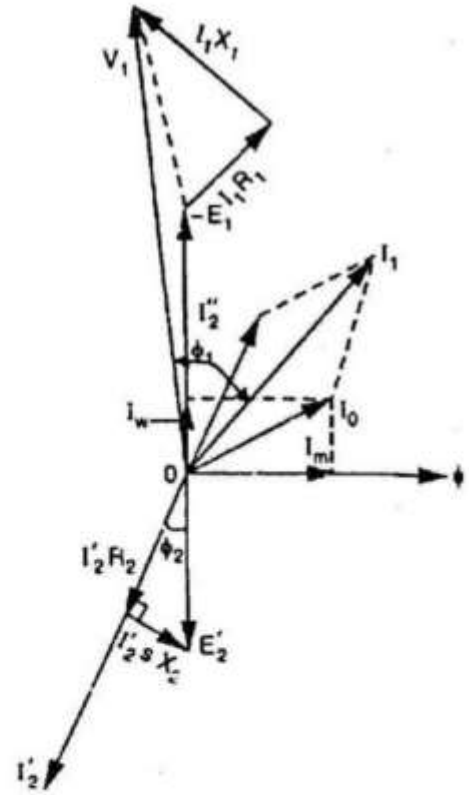


Fig: 3.9

It may be noted that even though the frequencies of stator and rotor currents are different, yet the magnetic fields due to them rotate at synchronous speed Ns. The stator currents produce a magnetic flux which rotates at a speed Ns. At slip s, the speed of rotation of the rotor field relative to the rotor surface in the direction of rotation of the rotor is

$$= \frac{120\,f'}{P} = \frac{120\,s\,f}{P} = s\,N_s$$

But the rotor is revolving at a speed of N relative to the stator core. Therefore, the speed of rotor field relative to stator core

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

Thus no matter what the value of slip s, the stator and rotor magnetic fields are synchronous with each other when seen by an observer stationed in space. Consequently, the 3-phase induction motor can be regarded as being equivalent to a transformer having an air-gap separating the iron portions of the magnetic circuit carrying the primary and secondary windings. Fig. 3.9 shows the phasor diagram of induction motor.

Equivalent Circuit of Three Phase Induction Motor

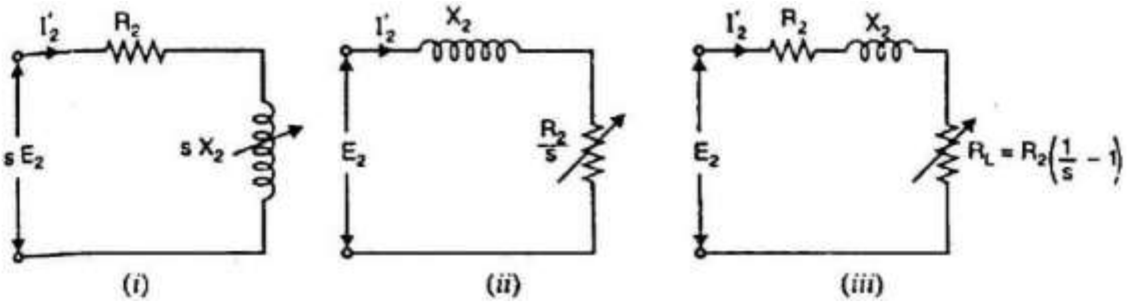
Fig. 3.10 (i) shows the equivalent circuit per phase of the rotor at slip s. The rotor phase current is given by;

$$I'_2 = \frac{s\,E_2}{\sqrt{R_2^2 + (s\,X_2)^2}}$$

Mathematically, this value is unaltered by writing it as:

$$I'_2 = \frac{E_2}{\sqrt{(R_2/s)^2 + (X_2)^2}}$$

As shown in Fig. 3.10 (ii), we now have a rotor circuit that has a fixed reactance X_2 connected in series with a variable resistance R2/s and supplied with constant voltage E_2. Note that Fig. 3.10 (ii) transfers the variable to the resistance without altering power or power factor conditions.



(i) *(ii)* *(iii)*

Fig: 3.10

The quantity R_2/s is greater than R_2 since s is a fraction. Therefore, R_2/s can be divided into a fixed part R_2 and a variable part $(R_2/s - R_2)$ i.e.,

$$\frac{R_2}{s} = R_2 + R_2\left(\frac{1}{s} - 1\right)$$

(i) The first part R_2 is the rotor resistance/phase, and represents the rotor Cu loss.

(ii) The second part $R_2\left(\frac{1}{s}-1\right)$ is a variable-resistance load. The power delivered to this load represents the total mechanical power developed in the rotor. Thus mechanical load on the induction motor can be replaced by a variable-resistance load of value $R_2\left(\frac{1}{s}-1\right)$. This is

$$\therefore \quad R_L = R_2\left(\frac{1}{s}-1\right)$$

Fig. 3.10 (iii) shows the equivalent rotor circuit along with load resistance R_L.

Now Fig: 3.11 shows the equivalent circuit per phase of a 3-phase induction motor. Note that mechanical load on the motor has been replaced by an equivalent electrical resistance R_L given by;

$$R_L = R_2\left(\frac{1}{s}-1\right) \qquad \text{......- (i)}$$

The circuit shown in Fig. 3.11 is similar to the equivalent circuit of a transformer with secondary load equal to R_2 given by eq. (i). The rotor e.m.f. in the equivalent circuit now depends only on the transformation ratio K (= E_2/E_1).

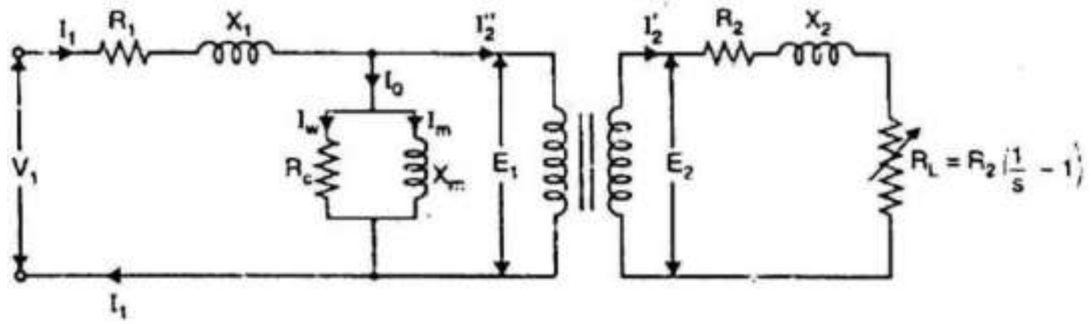


Fig: 3.11

Therefore; induction motor can be represented as an equivalent transformer connected to a variable-resistance load R_L given by eq. (i). The power delivered to R_L represents the total mechanical power developed in the rotor. Since the equivalent circuit of Fig. 3.11 is that of a transformer, the secondary (i.e., rotor) values can be transferred to primary (i.e., stator) through the appropriate use of transformation ratio K. Recall that when shifting resistance/reactance from secondary to primary, it should be divided by K2 whereas current should be multiplied by K. The equivalent circuit of an induction motor referred to primary is shown in Fig. 3.12.

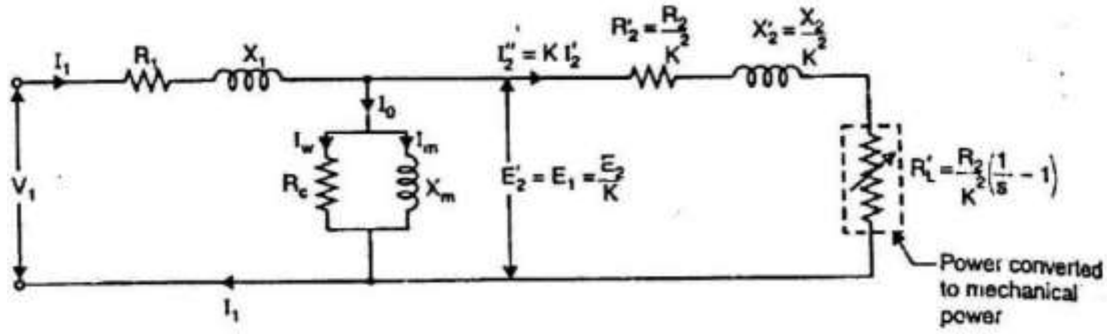


Fig: 3.12

Note that the element (i.e., R'_L) enclosed in the dotted box is the equivalent electrical resistance related to the mechanical load on the motor. The following points may be noted from the equivalent circuit of the induction motor:

(i) At no-load, the slip is practically zero and the load R'_L is infinite. This condition resembles that in a transformer whose secondary winding is open-circuited.

(ii) At standstill, the slip is unity and the load R'_L is zero. This condition resembles that in a transformer whose secondary winding is short-circuited.

(iii) When the motor is running under load, the value of R'_L will depend upon the value of the slip s. This condition resembles that in a transformer whose secondary is supplying variable and purely resistive load.

(iv) The equivalent electrical resistance R'_L related to mechanical load is slip or speed dependent. If the slip s increases, the load R'_L decreases and the rotor current increases and motor will develop more mechanical power. This is expected because the slip of the motor increases with the increase of load on the motor shaft.

Power and Torque Relations of Three Phase Induction Motor

The transformer equivalent circuit of an induction motor is quite helpful in analyzing the various power relations in the motor. Fig. 3.13 shows the equivalent circuit per phase of an induction motor where all values have been referred to primary (i.e., stator).

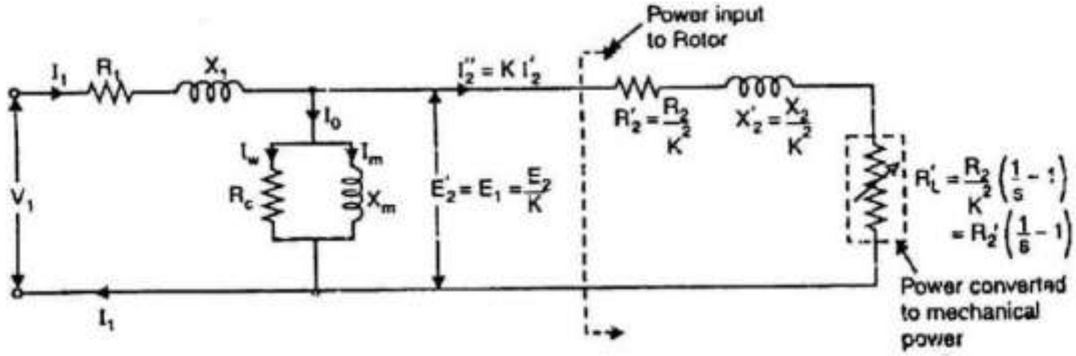


Fig: 3.13

(i) Total electrical load $= R'_2\left(\frac{1}{s}-1\right) + R'_2 = \frac{R'_2}{s}$

Power input to stator $= 3V_1\,I_1\cos\phi_1$

There will be stator core loss and stator Cu loss. The remaining power will be the power transferred across the air-gap i.e., input to the rotor.

(ii) Rotor input $= \frac{3(I''_2)^2 R'_2}{s}$

Rotor Cu loss $= 3(I''_2)^2 R'_2$

Total mechanical power developed by the rotor is

$$P_m = \text{Rotor input} - \text{Rotor Cu loss}$$

$$= \frac{3(I''_2)^2 R'_2}{s} 3(I''_2)^2 R'_2 = 3(I''_2)^2 R'_2\left(\frac{1}{s}-1\right)$$

This is quite apparent from the equivalent circuit shown in Fig: 3.13.

(iii) If T_g is the gross torque developed by the rotor, then,

$$P_m = \frac{2\pi N\ T_g}{60}$$

$$\text{or} \qquad 3(I''_2)^2 R'_2\left(\frac{1}{s}-1\right) = \frac{2\pi N\ T_g}{60}$$

$$\text{or} \qquad 3(I''_2)^2 R'_2\left(\frac{1-s}{s}\right) = \frac{2\pi N\ T_g}{60}$$

$$\text{or} \qquad 3(I''_2)^2 R'_2\left(\frac{1-s}{s}\right) = \frac{2\pi N_s(1-s)\ T_g}{60} \qquad [\because N = N_s(1-s)]$$

$$\therefore \qquad T_g = \frac{3(I''_2)^2 R'_2/s}{2\pi N_s/60} \quad \text{N - m}$$

$$\text{or} \qquad T_g = 9.55\frac{3(I''_2)^2 R'_2/s}{N_s} \quad \text{N - m}$$

Note that shaft torque T_{sh} will be less than T_g by the torque required to meet windage and frictional losses.

Induction Motor Torque

The mechanical power P available from any electric motor can be expressed as:

$$P = \frac{2\pi NT}{60} \quad \text{watts}$$

where N = speed of the motor in r.p.m.
T = torque developed in N-m

$$\therefore \qquad T = \frac{60}{2\pi}\frac{P}{N} = 9.55\frac{P}{N} \quad \text{N - m}$$

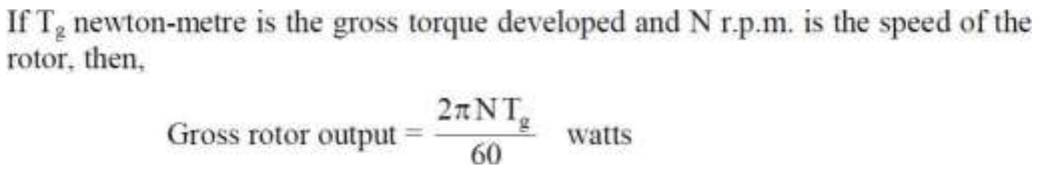
If the gross output of the rotor of an induction motor is P_m and its speed is N r.p.m., then gross torque T developed is given by:

$$T_g = 9.55\frac{P_m}{N} \quad \text{N - m}$$

$$\text{Similarly,} \qquad T_{sh} = 9.55\frac{P_{out}}{N} \quad \text{N - m}$$

Note. Since windage and friction loss is small, $T_g = T_{sh}$,. This assumption hardly leads to any significant error.

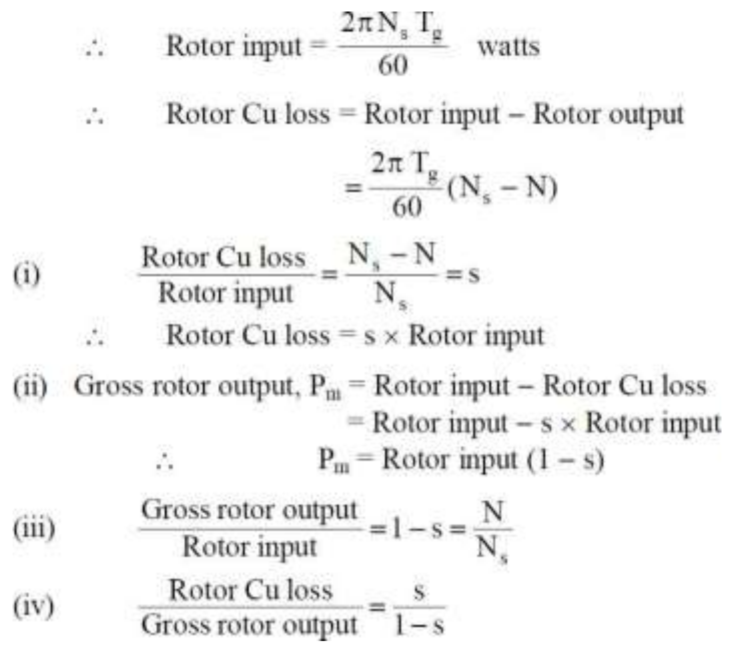
Rotor Output



If T_g newton-metre is the gross torque developed and N r.p.m. is the speed of the rotor, then,

$$\text{Gross rotor output} = \frac{2\pi N T_g}{60} \quad \text{watts}$$

If there were no copper losses in the rotor, the output would equal rotor input and the rotor would run at synchronous speed Ns.



$$\therefore \quad \text{Rotor input} = \frac{2\pi N_s T_g}{60} \quad \text{watts}$$

$$\therefore \quad \text{Rotor Cu loss} = \text{Rotor input} - \text{Rotor output}$$

$$= \frac{2\pi T_g}{60}(N_s - N)$$

$$\text{(i)} \quad \frac{\text{Rotor Cu loss}}{\text{Rotor input}} = \frac{N_s - N}{N_s} = s$$

$$\therefore \quad \text{Rotor Cu loss} = s \times \text{Rotor input}$$

$$\text{(ii)} \quad \text{Gross rotor output, } P_m = \text{Rotor input} - \text{Rotor Cu loss}$$

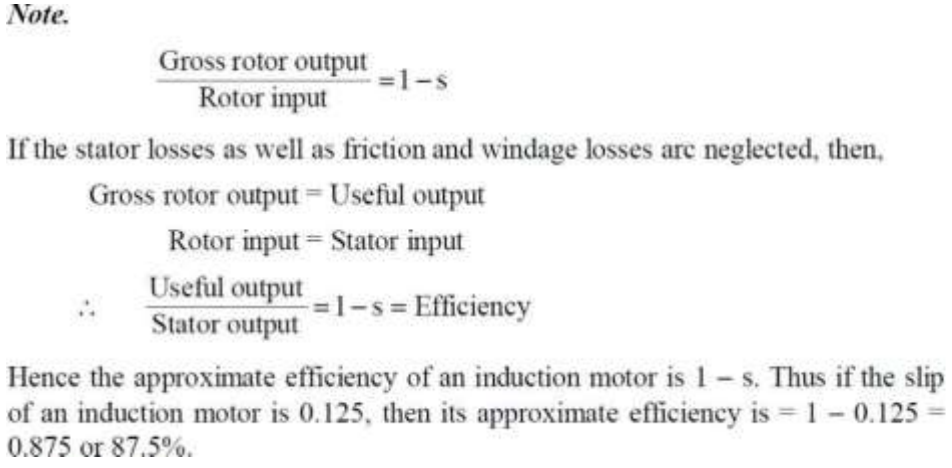
$$= \text{Rotor input} - s \times \text{Rotor input}$$

$$\therefore \quad P_m = \text{Rotor input } (1 - s)$$

$$\text{(iii)} \quad \frac{\text{Gross rotor output}}{\text{Rotor input}} = 1 - s = \frac{N}{N_s}$$

$$\text{(iv)} \quad \frac{\text{Rotor Cu loss}}{\text{Gross rotor output}} = \frac{s}{1-s}$$

It is clear that if the input power to rotor is Pr then sPr is lost as rotor Cu loss and the remaining (1 - s) Pr is converted into mechanical power. Consequently, induction motor operating at high slip has poor efficiency.



Note.

$$\frac{\text{Gross rotor output}}{\text{Rotor input}} = 1 - s$$

If the stator losses as well as friction and windage losses are neglected, then,

$$\text{Gross rotor output} = \text{Useful output}$$

$$\text{Rotor input} = \text{Stator input}$$

$$\therefore \quad \frac{\text{Useful output}}{\text{Stator output}} = 1 - s = \text{Efficiency}$$

Hence the approximate efficiency of an induction motor is 1 – s. Thus if the slip of an induction motor is 0.125, then its approximate efficiency is = 1 – 0.125 = 0.875 or 87.5%.

Torque Equations

The gross torque Tg developed by an induction motor is given by;

$$T_g = \frac{\text{Rotor input}}{2\pi\ N_s} \qquad \ldots N_s \text{ is r.p.s.}$$

$$= \frac{60 \times \text{Rotor input}}{2\pi\ N_s} \qquad \ldots N_s \text{ is r.p.s.}$$

Now $\quad \text{Rotor input} = \frac{\text{Rotor Cu loss}}{s} = \frac{3(I'_2)^2 R_2}{s} \qquad$ (i)

As shown in Sec. 8.16, under running conditions,

$$I'_2 = \frac{s\ E_2}{\sqrt{R_2^2 + (s\ X_2)^2}} = \frac{s\ K\ E_1}{\sqrt{R_2^2 + (s\ X_2)^2}}$$

where $\quad K = \text{Transformation ratio} = \frac{\text{Rotor turns/phase}}{\text{Stator turns/phase}}$

$$\therefore \quad \text{Rotor input} = 3 \times \frac{s^2\ E_2^2 R_2}{R_2^2 + (s\ X_2)^2} \times \frac{1}{s} = \frac{3\ s\ E_2^2 R_2}{R_2^2 + (s\ X_2)^2}$$

(Putting me value of I'_2 in eq.(i))

Also $\quad \text{Rotor input} = 3 \times \frac{s^2\ K^2\ E_1^2 R_2}{R_2^2 + (s\ X_2)^2} \times \frac{1}{s} = \frac{3\ s\ K^2\ E_1^2 R_2}{R_2^2 + (s\ X_2)^2}$

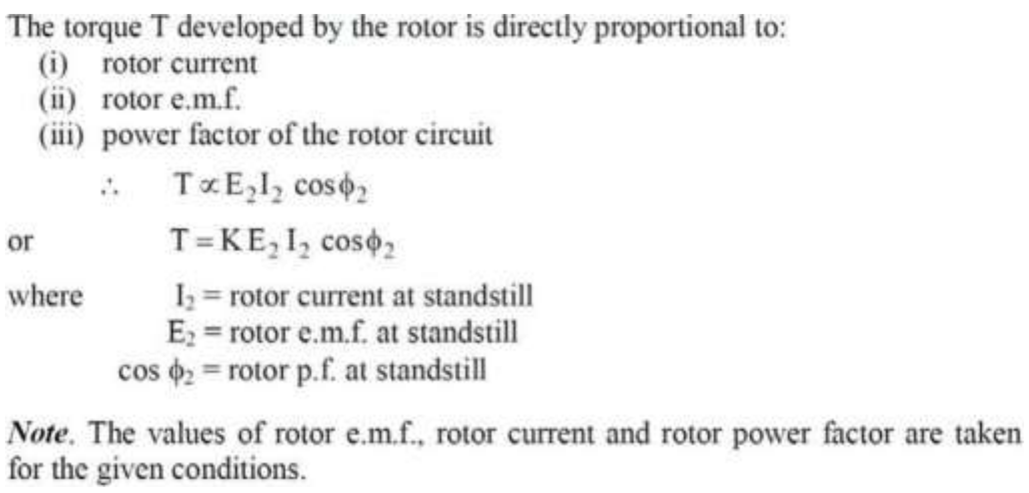
(Putting me value of I'_2 in eq.(i))

$$\therefore \quad T_g = \frac{\text{Rotor input}}{2\pi\ N_s} = \frac{3}{2\pi\ N_s} \times \frac{s\ E_2^2 R_2}{R_2^2 + (s\ X_2)^2} \qquad \ldots\text{in terms of } E_2$$

$$= \frac{3}{2\pi\ N_s} \times \frac{s\ K^2\ E_1^2 R_2}{R_2^2 + (s\ X_2)^2} \qquad \ldots\text{in terms of } E_1$$

Note that in the above expressions of T_g, the values E_1, E_2, R_2 and X_2 represent the phase values.

Rotor Torque



The torque T developed by the rotor is directly proportional to:

(i) rotor current
(ii) rotor e.m.f.
(iii) power factor of the rotor circuit

$$\therefore \quad T \propto E_2 I_2 \cos\phi_2$$

or
$$T = K E_2 I_2 \cos\phi_2$$

where
I_2 = rotor current at standstill
E_2 = rotor e.m.f. at standstill
$\cos\phi_2$ = rotor p.f. at standstill

Note. The values of rotor e.m.f., rotor current and rotor power factor are taken for the given conditions.

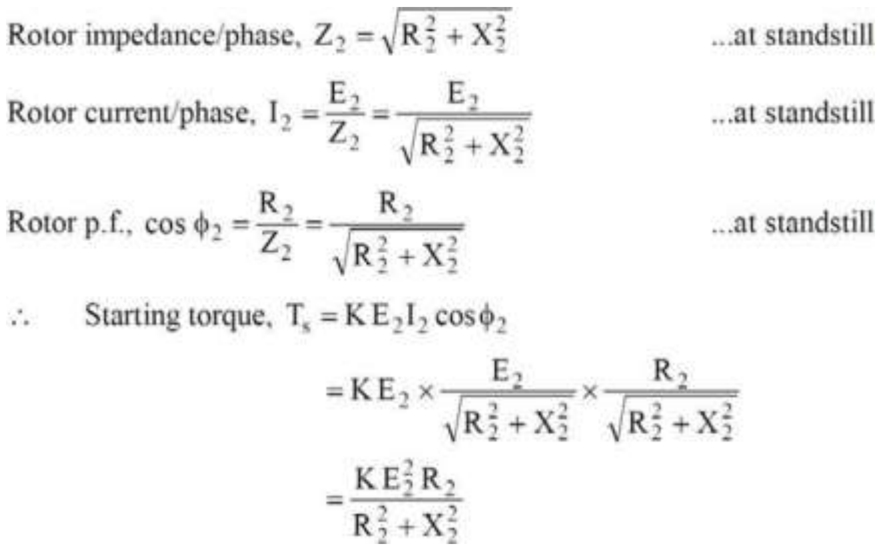
Starting Torque (Ts)

Let,

E_2 = rotor e.m.f. per phase at standstill

X_2 = rotor reactance per phase at standstill R_2

= rotor resistance per phase



Rotor impedance/phase, $Z_2 = \sqrt{R_2^2 + X_2^2}$ ...at standstill

Rotor current/phase, $I_2 = \dfrac{E_2}{Z_2} = \dfrac{E_2}{\sqrt{R_2^2 + X_2^2}}$ ...at standstill

Rotor p.f., $\cos\phi_2 = \dfrac{R_2}{Z_2} = \dfrac{R_2}{\sqrt{R_2^2 + X_2^2}}$ ...at standstill

$$\therefore \quad \text{Starting torque, } T_s = K E_2 I_2 \cos\phi_2$$

$$= K E_2 \times \frac{E_2}{\sqrt{R_2^2 + X_2^2}} \times \frac{R_2}{\sqrt{R_2^2 + X_2^2}}$$

$$= \frac{K E_2^2 R_2}{R_2^2 + X_2^2}$$

Generally, the stator supply voltage V is constant so that flux per pole ϕ set up by the stator is also fixed. This in turn means that e.m.f. E_2 induced in the rotor will be constant.

$$\therefore \qquad T_s = \frac{K_1 R_2}{R_2^2 + X_2^2} = \frac{K_1 R_2}{Z_2^2}$$

where K_1 is another constant.

It is clear that the magnitude of starting torque would depend upon the relative values of R_2 and X_2 i.e., rotor resistance/phase and standstill rotor reactance/phase.

It can be shown that $K = 3/2\, \pi\, N_s$.

$$\therefore \qquad T_s = \frac{3}{2\pi N_s} \cdot \frac{E_2^2 R_2}{R_2^2 + X_2^2}$$

Note that here N_s is in r.p.s.

Condition for Maximum Starting Torque

It can be proved that starting torque will be maximum when rotor resistance/phase is equal to standstill rotor reactance/phase.

Now $$T_s = \frac{K_1 R_2}{R_2^2 + X_2^2} \qquad \text{(i)}$$

Differentiating eq. (i) w.r.t. R_2 and equating the result to zero, we get,

$$\frac{dT_s}{dR_2} = K_1 \left[\frac{1}{R_2^2 + X_2^2} - \frac{R_2(2R_2)}{\left(R_2^2 + X_2^2\right)^2} \right] = 0$$

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

or $$R_2 = X_2$$

Hence starting torque will be maximum when:

Rotor resistance/phase = Standstill rotor reactance/phase

Under the condition of maximum starting torque, ϕ_2 = 45° and rotor power factor is 0.707 lagging.

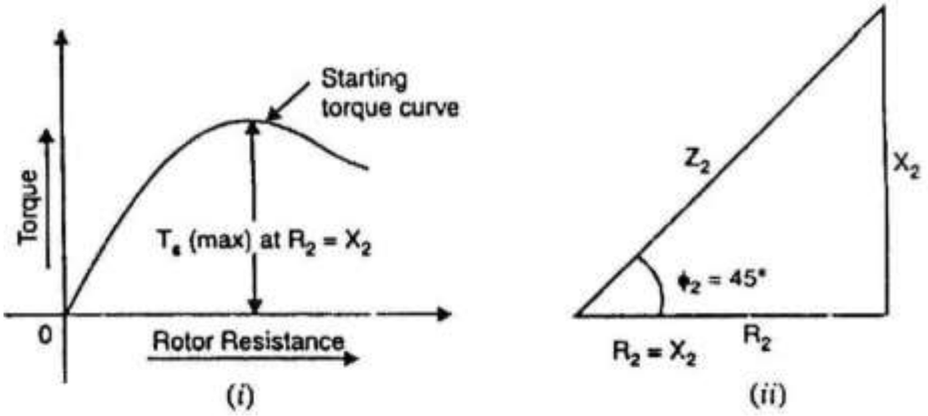


Fig: 3.14

Fig. 3.14 shows the variation of starting torque with rotor resistance. As the rotor resistance is increased from a relatively low value, the starting torque increases until it becomes maximum when $R_2 = X_2$. If the rotor resistance is increased beyond this optimum value, the starting torque will decrease.

Effect of Change of Supply Voltage

$$T_s = \frac{K E_2^2 R_2}{R_2^2 + X_2^2}$$

Since $E_2 \propto$ Supply voltage V

$$\therefore \quad T_s = \frac{K_2 V^2 R_2}{R_2^2 + X_2^2}$$

where K_2 is another constant.

$$\therefore \quad T_s \propto V^2$$

Therefore, the starting torque is very sensitive to changes in the value of supply voltage. For example, a drop of 10% in supply voltage will decrease the starting torque by about 20%. This could mean the motor failing to start if it cannot produce a torque greater than the load torque plus friction torque.

Circle Diagram

To analyse the three phase induction motor performance using circle diagram we need to determine the equivalent circuit parameters of the machine.

Approximate Equivalent Circuit of Induction Motor

As in case of a transformer, the approximate equivalent circuit of an induction motor is obtained by shifting the shunt branch (Rc - Xm) to the input terminals as shown in Fig. 3.15. This step has been taken on the assumption that voltage drop in R_1 and X_1 is small and the terminal voltage V_1 does not appreciably differ from the induced voltage E1. Fig. 3.15 shows the approximate equivalent circuit per phase of an induction motor where all values have been referred to primary (i.e., stator).

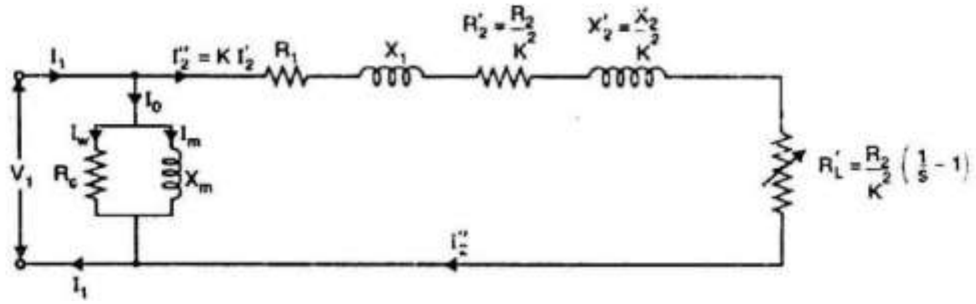


Fig: 3.15

The above approximate circuit of induction motor is not so readily justified as with the transformer. This is due to the following reasons:

(i) Unlike that of a power transformer, the magnetic circuit of the induction motor has an air-gap. Therefore, the exciting current of induction motor (30 to 40% of full-load current) is much higher than that of the power transformer. Consequently, the exact equivalent circuit must be used for accurate results.

(ii) The relative values of X_1 and X_2 in an induction motor are larger than the corresponding ones to be found in the transformer. This fact does not justify the use of approximate equivalent circuit

(iii) In a transformer, the windings are concentrated whereas in an induction motor, the windings are distributed. This affects the transformation ratio.

In spite of the above drawbacks of approximate equivalent circuit, it yields results that are satisfactory for large motors. However, approximate equivalent circuit is not justified for small motors.

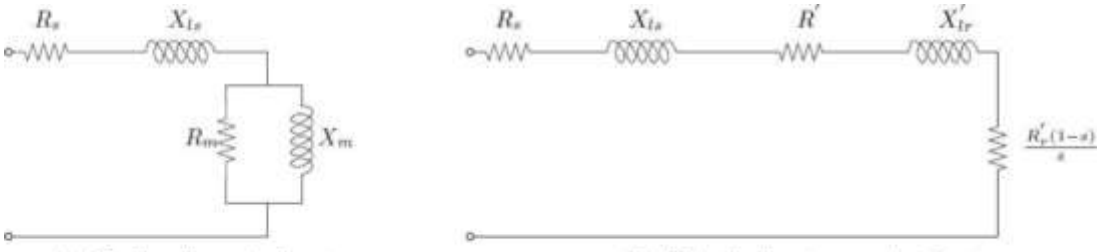
Tests to Determine the Equivalent Circuit Parameters

In order to find values for the various elements of the equivalent circuit, tests must be conducted on a particular machine, which is to be represented by the equivalent circuit. In order to do this, we note the following.

1. When the machine is run on no-load, there is very little torque developed by it. In an ideal case where there is no mechanical losses, there is no mechanical power developed at no-load. Recalling the explanations in the section on torque production, the flow of current in the rotor is indicative of the torque that is produced. If no torque is produced, one may conclude that no current would be flowing in the rotor either. The rotor branch acts like an open circuit. This conclusion may also be reached by reasoning that when there is no load, an ideal machine will run up to its synchronous speed where the slip is zero resulting in an infinite impedance in the rotor branch.

2. When the machine is prevented from rotation, and supply is given, the slip remains at unity. The elements representing the magnetizing branch Rm & Xm are high impedances much larger than R'_r & X'_{lr} in series. Thus, in the exact equivalent circuit of the induction machine, the magnetizing branch may be neglected.

From these considerations, we may reduce the induction machine equivalent circuit of Fig.3.13 & Fig: 3.15 to those shown in Fig: 3.16.



(a) No-load equivalent (b) Blocked rotor equivalent

Fig: 3.16

These two observations and the reduced equivalent circuits are used as the basis for the two most commonly used tests to find out the equivalent ci~~rc~~uit parameters the blocked rotor test and no load test. They are also referred to as the short circuit test and open circuit test respectively in conceptual analogy to the transformer.

1. No-load test

The behaviour of the machine may be judged from the equivalent circuit of Fig: 3.16 (a). The current drawn by the machine causes a stator-impedance drop and the balance voltage is applied across the magnetizing branch. However, since the magnetizing branch impedance is large, the current drawn is small and hence the stator impedance drop is small compared to the applied voltage (rated value). This drop and the power dissipated in the stator resistance are therefore neglected and the total power drawn is assumed to be consumed entirely as core loss. This can also be seen from the approximate equivalent circuit, the use of which is justified by the foregoing arguments. This test therefore enables us to compute the resistance and inductance of the magnetizing branch in the following manner.

Let applied voltage $= V_s$. Then current drawn is given by

$$I_s = \frac{V_s}{R_m} + \frac{V_s}{jX_m}$$

The power drawn is given by

$$P_s = \frac{V_s^2}{R_m} \Rightarrow R_m = \frac{V_s^2}{P_s}$$

V_S, I_S and P_S are measured with appropriate meters. With R_m known by above equation, X_m also can be found. The current drawn is at low power factor and hence a suitable wattmeter should be used.

2. Blocked-rotor Test

In this test the rotor is prevented from rotation by mechanical means and hence the name. Since there is no rotation, slip of operation is unity, s = 1. The equivalent circuit valid under these conditions is shown in Fig: 3.16 (b). Since the current drawn is decided by the resistance and leakage impedances alone, the magnitude can be very high when rated voltage is applied. Therefore in this test~~,~~ only small voltages are applied just enough to cause rated current to flow. While the current magnitude depends on the resistance and the reactance, the power drawn depends on the resistances.

The parameters may then be determined as follows. The source current and power drawn may be written as -

$$\begin{aligned} I_s &= \frac{V_s}{(R_s + R_r') + j(X_s + X_r')} \\ P_s &= |I_s|^2 (R_s + R_r') \end{aligned}$$

In the test Vs, Is and Ps are measured with appropriate meters. Above equation enables us to compute (Rs + R'r). Once this is known, (Xs + X'r) may be computed from the above equation.

Note that this test only enables us to determine the series combination of the resistance and the reactance only and not the individual values. Generally, the individual values are assumed to be equal [the assumption $R_s = R'_r$ and $X_s = X'_r$ suffices for most **purposes.**

In practice, there are differences. If more accurate estimates are required IEEE guidelines may be followed which depend on the size of the machine.

These two tests determine the equivalent circuit parameters in a Stator-referred sense **i.e., the rotor resistance and leakage inductance are not the actual values but what they** 'appear' **to** be' **when looked at from the stator. This is sufficient for most purposes as interconnections to the external world are generally done at the stator terminals.**

Construction of Circle Diagram

Conduct No load test and blocked rotor test on the induction motor and find out the per phase values of no load current I_0, short circuit current I_{SC} and the corresponding phase angles $Φ_0$ and $Φ_{SC}$. Also find short circuit current I_{SN} corresponding to normal supply voltage. With this data, the circle diagram can be drawn as follows see Fig: 3.17.

1. With suitable scale, draw vector OA with length corresponding to I_0 at an angle $Φ_0$ **from the vertical axis. Draw a horizontal line AB.**

2. Draw OS equal to I_{SN} at an angle $Φ_{SC}$ **and join AS.**

3. Draw the perpendicular bisector to AS to meet the horizontal line AB at C.

4. With C as centre, draw a portion of circle passing through A and S. This forms the circle diagram which is the locus of the input current.

5. From point S, draw a vertical line SL to meet the line AB.

6. Divide SL at point K so that SK : KL = rotor resistance : stator resistance.

7. For a given operating point P, draw a vertical line PEFGD as shown. then PE = output power, EF = rotor copper loss, FG = stator copper loss, GD = constant loss (iron loss + mechanical loss)

8. 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 and maximum torque point.

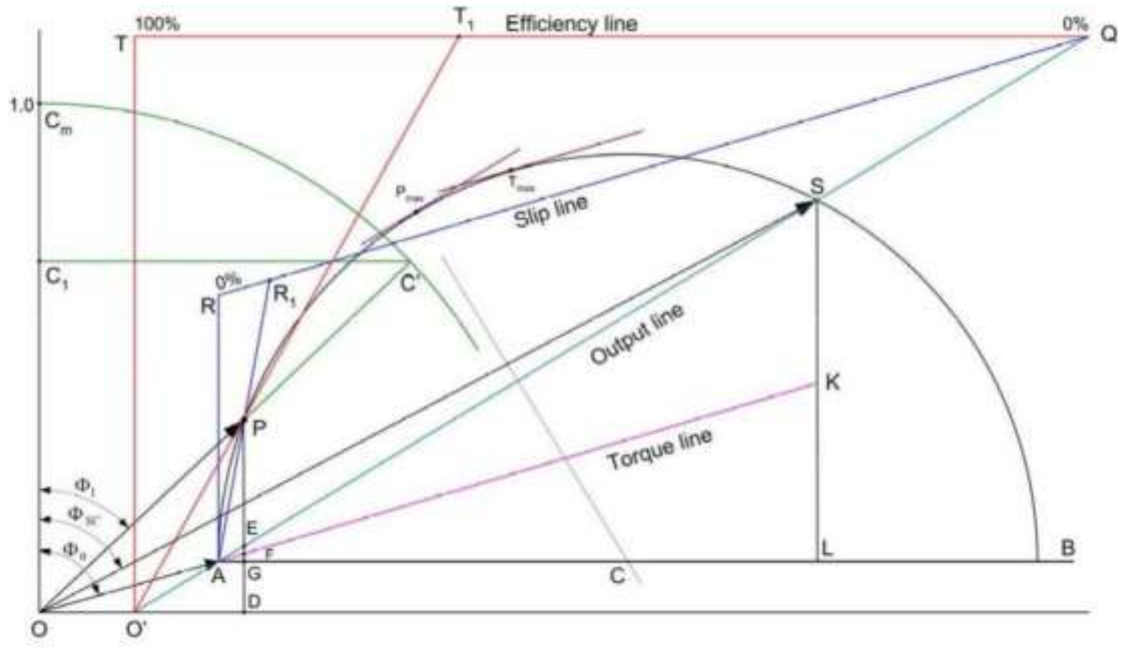


Fig: 3.17 Construction of Circle Diagram

Efficiency line

1. The output line AS is extended backwards to meet the X-axis at O'

2. From any convenient point on the extended output line, draw a horizontal line QT so as to meet the vertical from O'. Divide the line QT into 100 equal parts.

3. To find the efficiency corresponding to any operating point P, draw a line from O' to the efficiency line through P to meet the efficiency line at T1. Now QT1 is the efficiency.

Slip Line

1. Draw line QR parallel to the torque line, meeting the vertical through A at R. Divide RQ into 100 equal parts.

2. To find the slip corresponding to any operating point P, draw a line from A to the slip line through P to meet the slip line at R1. Now RR1 is the slip

Power Factor Curve

1. Draw a quadrant of a circle with O as centre and any convenient radius. Divide OCm into 100 equal parts.

2. To find power factor corresponding to P, extend the line OP to meet the power factor curve at C. Draw a horizontal line CC1 to meet the vertical axis at C1. Now OC1 represents power factor.

Performance Characteristics of Three phase Induction Motor

The equivalent circuits derived in the preceding section can be used to predict the performance characteristics of the induction machine. The important performance characteristics in the steady state are the efficiency, power factor, current, starting torque, maximum (or pull-out) torque.

The complete torque-speed characteristic

In order to estimate the speed torque characteristic let us suppose that a sinusoidal voltage is impressed on the machine. Recalling that the equivalent circuit is the per-phase representation of the machine, the current drawn by the circuit is given by

$$I_s = \frac{V_s}{(R_s + \frac{R'_r}{s}) + j(X_{ls} + X'_{lr})}$$

Where, Vs is the phase voltage phasor and Is is the current phasor. The magnetizing current is neglected Since this current is flowing through R'r/s the air**-gap power is given by**

$$\begin{aligned} P_g &= |I_s|^2 \frac{R'_r}{s} \\ &= \frac{V_s}{(R_s + \frac{R'_r}{s})^2 + (X_{ls} + X'_{lr})^2} \frac{R'_r}{s} \end{aligned}$$

The mechanical power output was shown to be $(1-s)P_g$ (Power dissipated in r/s). The torque is **obtained by dividing this by the shaft speed ω_m .Thus we have,**

$$\frac{P_g(1-s)}{\omega_m} = \frac{P_g(1-s)}{\omega_s(1-s)} = |I_s|^2 \frac{R'_r}{s\omega_s}$$

where ω_m is the synchronous speed in radians per second and s is the slip. Further,

this is the torque produced per phase. Hence the overall torque is given by

$$T_e = \frac{3}{\omega_s} \cdot \frac{V_s^2}{(R_s + \frac{R'_r}{s})^2 + (X_{ls} + X'_{lr})} \cdot \frac{R'_r}{s}$$

The torque may be plotted as a function of s and is called the torque-slip (or torque- speed, since slip indicates speed) characteristic a very important characteristic of the induction machine.

A typical torque-speed characteristic is shown in Fig: 3.18. This plot corresponds to a 3 kW, 4 pole, and 60 Hz machine. The rated operating speed is 1780 rpm.

Further, this curve is obtained by varying slip with the applied voltage being held constant. Coupled with the fact that this is an equivalent circuit valid under steady state, it implies that if this characteristic is to be measured experimentally, we need to look at the torque for a given speed after all transients have died down. One cannot, for example, try to obtain this curve by directly starting the motor with full voltage applied to the terminals and measuring the torque and speed dynamically as it runs up to steady speed.

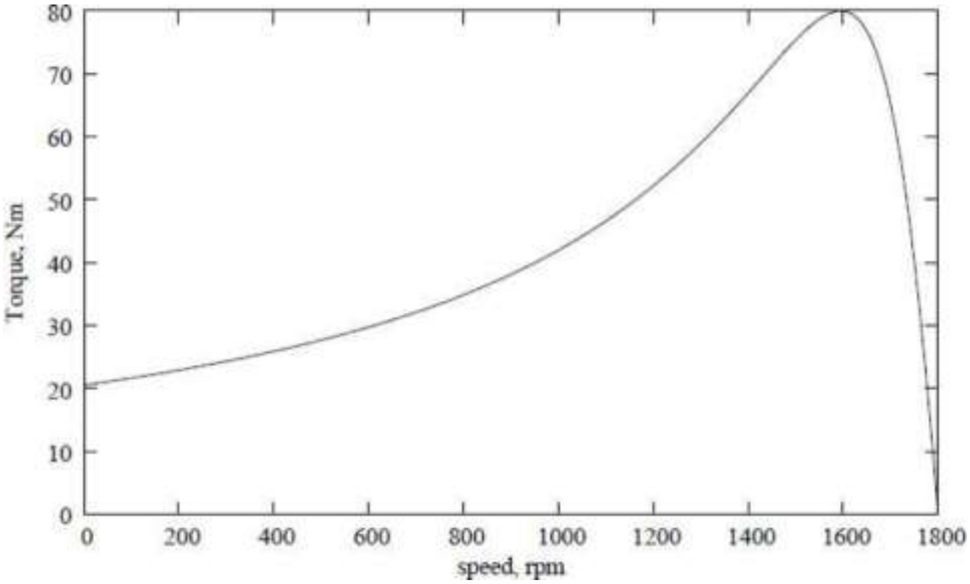


Fig: 3.18

With respect to the direction of rotation of the air-gap flux, the rotor maybe driven to higher speeds by a prime mover or may also be rotated in the reverse direction. The torque-speed relation for the machine under the entire speed range is called the complete speed-torque characteristic. A typical curve is shown in Fig: 3.19 for a four-pole machine, the synchronous speed being 1500 rpm. Note that negative speeds correspond to slip values greater than 1, and speeds greater than 1500 rpm correspond to negative slip. The plot also shows the operating modes of the induction machine in various regions. The slip axis is also shown for convenience.

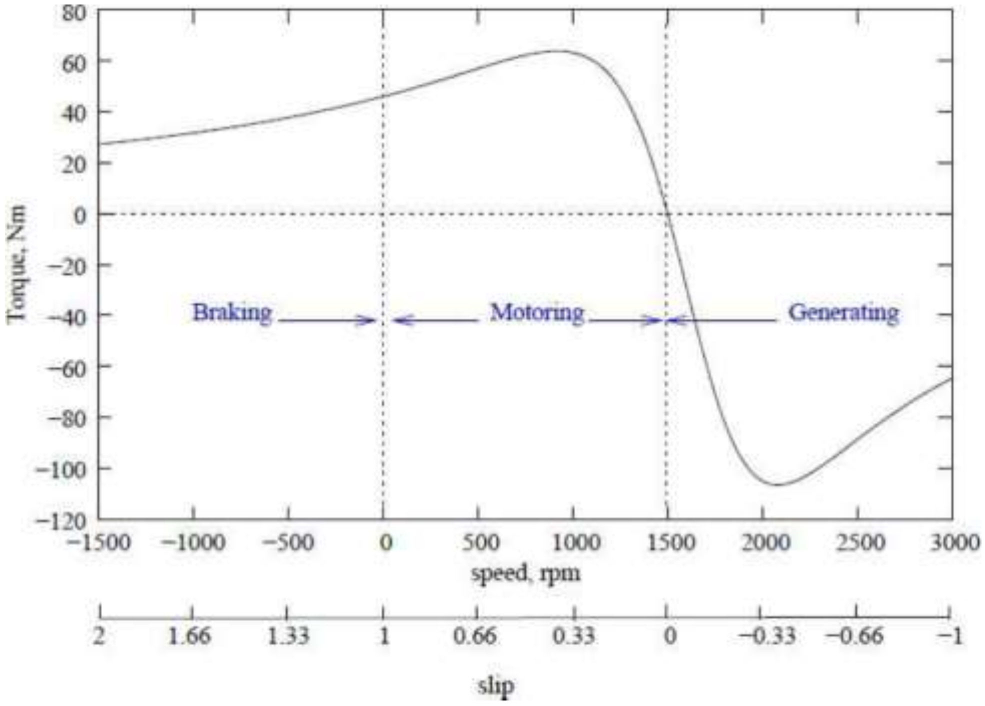


Fig: 3.19

Effect of Rotor Resistance on Speed Torque Characteristic

Restricting ourselves to positive values of slip, we see that the curve has a peak point. This is the maximum torque that the machine can produce, and is called as stalling torque. If the load torque is more than this value, the machine stops rotating or stalls. It occurs at a slip $\hat{s}$, which for the machine of Fig. 3.19 is 0.38. At values of slip lower than $\hat{s}$ the curve falls steeply down to zero at s = 0. The torque at synchronous speed is therefore zero. At values of slip higher than s = $\hat{s}$ the curve falls slowly to a minimum value at s = 1. The torque at s = 1 (speed = 0) is called the starting torque. The value of the stalling torque may be obtained by differentiating the expression for torque with respect to zero and setting it to zero to find the value of $\hat{s}$. Using this method, we can write

$$\hat{s} = \frac{\pm R_r'}{\sqrt{R_r'^2 + (X_{ls} + X_{lr}')^2}}$$

Substituting $\hat{s}$ into the expression for torque gives us the value of the stalling torque $\hat{T}_e$,

$$\hat{T}_e = \frac{3V_s^2}{2\omega_s} \cdot \frac{1}{R_s \pm \sqrt{R_s^2 + (X_{ls} + X_{lr}')^2}}$$

- **The negative sign being valid for negative slip.**

The expression shows that ˆ Te is the independent of R'r, while s is directly proportional to R'r. fact can be made use of conveniently to alter ˆs. If it is possible to change R'r, then we can get a **whole series of torque-speed characteristics, the maximum torque remaining constant all the while.**

We may note that if R'r **is chosen equal to =**

$$\sqrt{R_s^2 + (X_{ls} + X'_{lr})^2}$$

The ˆs, becomes unity, which means that the maximum torque occurs at starting. Thus changing of R'r, wherever possible can serve as a means to control the starting torque Fig: 3.20.

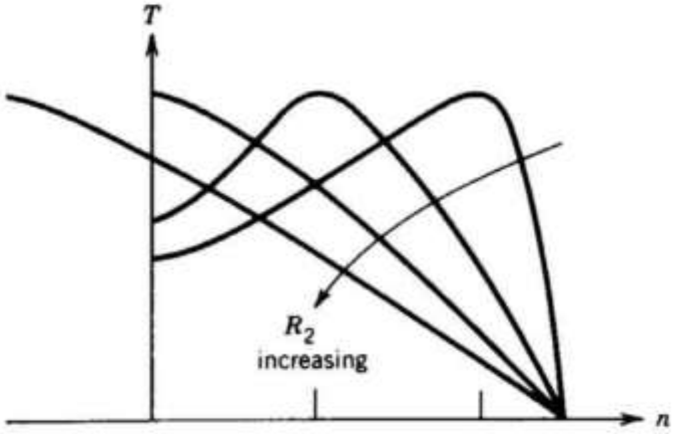


Fig: 3.20

While considering the negative slip range, (generator mode) we note that the maximum torque is higher than in the positive slip region (motoring mode).

Operating Point and Stable & Unstable region of Operation

Consider a speed torque characteristic shown in fig. 25 for an induction machine, having the load characteristic also superimposed on it. The load is a constant torque load i.e. the torque required for operation is fixed irrespective of speed.

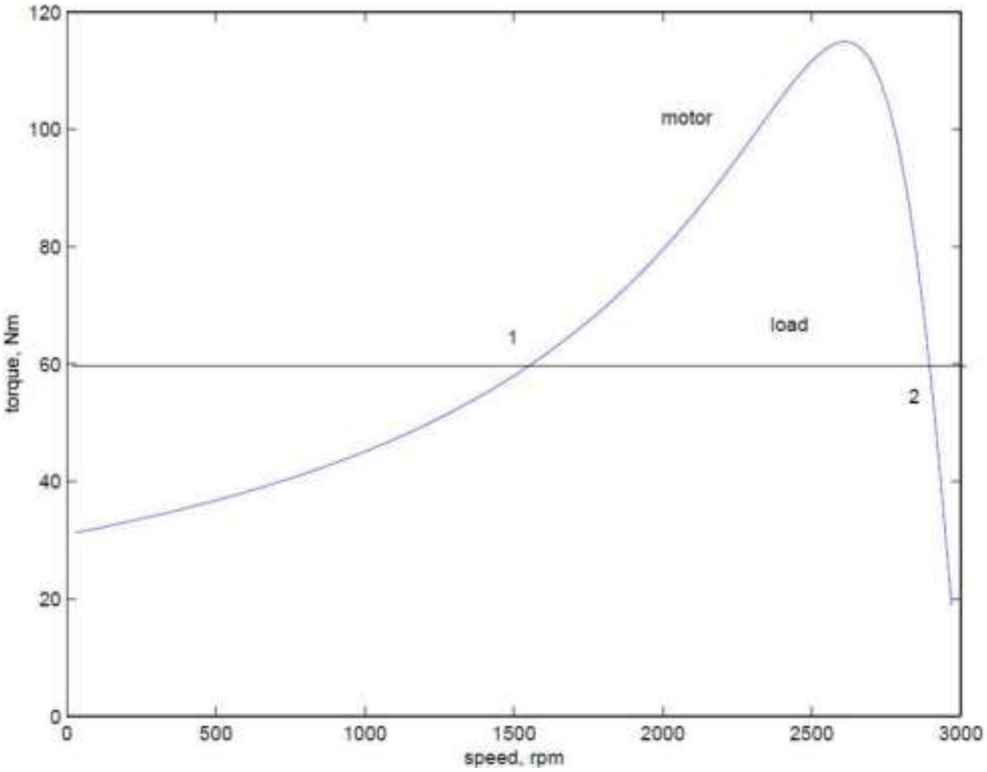


Fig: 3.21

The system consisting of the motor and load will operate at a point where the two characteristics meet. From the above plot, we note that there are two such points. We therefore need to find out which of these is the actual operating point. To answer this we must note that, in practice, the characteristics are never fixed; they change slightly with time. It would be appropriate to consider a small band around the curve drawn where the actual points of the characteristic will lie. This being the case let us considers that the system is operating at point 1, and the load torque demand increases slightly. This is shown in Fig: 3.22, where the change is exaggerated for clarity. This would shift the point of operation to a point 1, at which the slip would be less and the developed torque higher.

The difference in torque developed ΔTe, being positive will accelerate the machine. Any overshoot in speed as it approaches the point 1 will cause it to further accelerate since the developed torque is increasing. Similar arguments may be used to show that if for some reason the developed torque becomes smaller the speed would drop and the effect is cumulative. Therefore we may conclude that 1 is not a stable operating point.

Let us consider the point 2. If this point shifts to 2, the slip is now higher (speed is lower) and the positive difference in torque will accelerate the machine. This behaviour will tend to bring the operating point towards 2 once again. In other words, disturbances at point 2 will not cause a

runaway effect. Similar arguments may be given for the case where the load characteristic shifts down. Therefore we conclude that point 2 is a stable operating point.

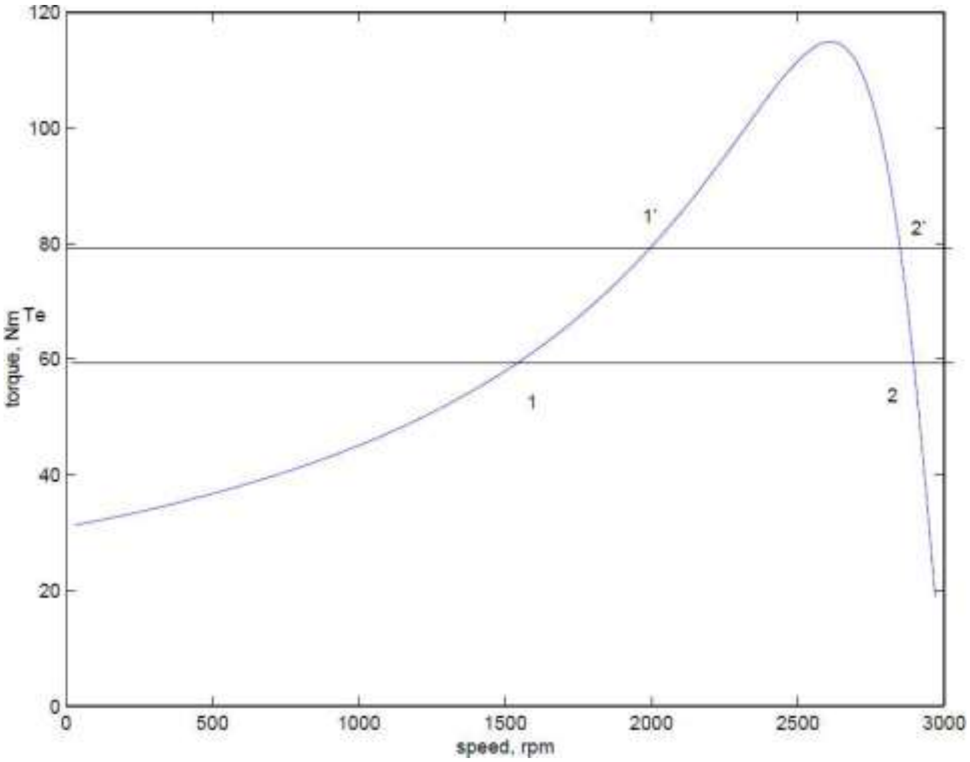


Fig: 3.22

From the above discussions, we can say that the entire region of the speed-torque characteristic from $s = 0$ to $s = \hat{s}$ is an unstable region while the region from $s = \hat{s}$ to s **= 0 is a stable region.**
Therefore the machine will always operate between $s = 0$ and $s = \hat{s}$.

Operation with Unbalanced Supply Voltage on Polyphase Induction Motors

Three phase induction motors are designed and manufactured such that all three phases of the winding are carefully balanced with respect to the number of turns, placement of the winding, and winding resistance. When line voltages applied to a polyphase induction motor are not exactly the same, unbalanced currents will flow in the stator winding, the magnitude depending upon the amount of unbalance. A small amount of voltage unbalance may increase the current an excessive amount. The effect on the motor can be severe and the motor may overheat to the point of burnout.

Unbalance Defined

The voltage unbalance (or negative sequence voltage) in percent may be defined as follows:

Percent Voltage Unbalance = 100 * (Maximum Voltage Deviation/ Average Voltage)

Example:

With voltages of 220, 215 and 210, in three phases respectively then the average is 215, the maximum deviation from the average is 5, and the percent unbalance = 100 X 5/215 = 2.3 percent.

Effect on performance-

General

The effect of unbalanced voltages on polyphase induction motors is equivalent to the introduction of a "negative sequence voltage" having a rotation opposite to that occurring with balanced voltages. This negative sequence voltage produces in the air gap a flux rotating against the rotation of the rotor, tending to produce high currents. A small negative sequence voltage may produce in the windings currents considerably in excess of those present under balanced voltage conditions.

Temperature rise and load carrying capacity

A relatively small unbalance in voltage will cause a considerable increase in temperature rise. In the phase with the highest current, the percentage increase in temperature rise will be approximately two times the square of the percentage voltage unbalance. The increase in losses and consequently, the increase in average heating of the whole winding will be slightly lower than the winding with the highest current.

To illustrate the severity of this condition, an approximate 3.5 percent voltage unbalance will cause an approximate 25 percent increase in temperature rise.

Torques

The locked-rotor torque and breakdown torque are decreased when the voltage is unbalanced. If the voltage unbalance should be extremely severe, the torque might not be adequate for the application.

Full-load speed

The full-load speed is reduced slightly when the motor operates at unbalanced voltages.

Currents

The locked-rotor current will be unbalanced to the same degree that the voltages are unbalanced but the locked-rotor KVA will increase only slightly. The currents at normal operating speed with unbalanced voltages will be greatly unbalanced in the order of approximately 6 to 10 times the voltage unbalance. This introduces a complex problem in selecting the proper overload protective devices, particularly since devices selected for one set of unbalanced conditions may be inadequate for a different set of unbalanced voltages. Increasing the size of the overload protective device is not the solution in as much as protection against heating from overload and from single phase operation is lost.

Thus the voltages should be evenly balanced as closely as can be read on the usually available commercial voltmeter.

Starting of Three Phase Induction Motor

The induction motor is fundamentally a transformer in which the stator is the primary and the rotor is short-circuited secondary. At starting, the voltage induced in the induction motor rotor is maximum ($s = 1$). Since the rotor impedance is low, the rotor current is excessively large. This large rotor current is reflected in the stator because of transformer action. This results in high starting current (4 to 10 times the full-load current) in the stator at low power factor and consequently the value of starting torque is low. Because of the short duration, this value of large current does not harm the motor if the motor accelerates normally.

However, this large starting current will produce large line-voltage drop. This will adversely affect the operation of other electrical equipment connected to the same lines. Therefore, it is desirable and necessary to reduce the magnitude of stator current at starting and several methods are available for this purpose.

Methods of Starting Three Phase Induction Motors

The method to be employed in starting a given induction motor depends upon the size of the motor and the type of the motor. The common methods used to start induction motors are:

(i) Direct-on-line starting
(ii) Stator resistance starting
(iii) Autotransformer starting
(iv) Star-delta starting
(v) Rotor resistance starting

Methods (i) to (iv) are applicable to both squirrel-cage and slip ring motors. However, method (v) is applicable only to slip ring motors. In practice, any one of the first four methods is used for starting squirrel cage motors, depending upon, the size of the motor. But slip ring motors are invariably started by rotor resistance starting.

Except direct-on-line starting, all other methods of starting squirrel-cage motors employ reduced voltage across motor terminals at starting.

(i) Direct-on-line starting

This method of starting in just what the name implies the motor is started by connecting it directly to 3-phase supply. The impedance of the motor at standstill is relatively low and when it is directly connected to the supply system, the starting current will be high (4 to 10 times the full- load current) and at a low power factor. Consequently, this method of starting is suitable for relatively small (up to 7.5 kW) machines.

Relation between starling and F.L. torques. We know that:

$$\text{Rotor input} = 2\pi N_s T = kT$$

But $\quad \text{Rotor Cu loss} = s \times \text{Rotor input}$

$$\therefore \quad 3(I'_2)^2 R_2 = s \times kT$$

or $\quad T \propto (I'_2)^2 / s$

or $\quad T \propto I_1^2 / s \qquad (\because I'_2 \propto I_1)$

If I_{st} is the starting current, then starting torque (T_{st}) is

$$T \propto I_{st}^2 \qquad (\because \text{ at starting } s = 1)$$

If I_f is the full-load current and s_f is the full-load slip, then,

$$T_f \propto I_f^2 / s_f$$

$$\therefore \quad \frac{T_{st}}{T_f} = \left(\frac{I_{st}}{I_f}\right)^2 \times s_f$$

When the motor is started direct-on-line, the starting current is the short-circuit (blocked-rotor) current I_{sc}.

$$\therefore \quad \frac{T_{st}}{T_f} = \left(\frac{I_{sc}}{I_f}\right)^2 \times s_f$$

Let us illustrate the above relation with a numerical example. Suppose $I_{sc} = 5\ I_f$ and full-load slip $s_f = 0.04$. Then,

$$\frac{T_{st}}{T_f} = \left(\frac{I_{sc}}{I_f}\right)^2 \times s_f = \left(\frac{5\ I_f}{I_f}\right)^2 \times 0.04 = (5)^2 \times 0.04 = 1$$

$$\therefore \quad T_{st} = T_f$$

Note that starting current is as large as five times the full-load current but starting torque is just equal to the full-load torque. Therefore, starting current is very high and the starting torque is comparatively low. If this large starting current flows for a long time, it may overheat the motor and damage the insulation.

(ii) Stator resistance starting

In this method, external resistances are connected in series with each phase of stator winding during starting. This causes voltage drop across the resistances so that voltage available across motor terminals is reduced and hence the starting current. The starting resistances are gradually cut out in steps (two or more steps) from the stator circuit as the motor picks up speed. When the motor attains rated speed, the resistances are completely cut out and full line voltage is applied to the rotor see Fig: 3.23.

This method suffers from two drawbacks. First, the reduced voltage applied to the motor during the starting period lowers the starting torque and hence increases the accelerating time. Secondly, a lot of power is wasted in the starting resistances.

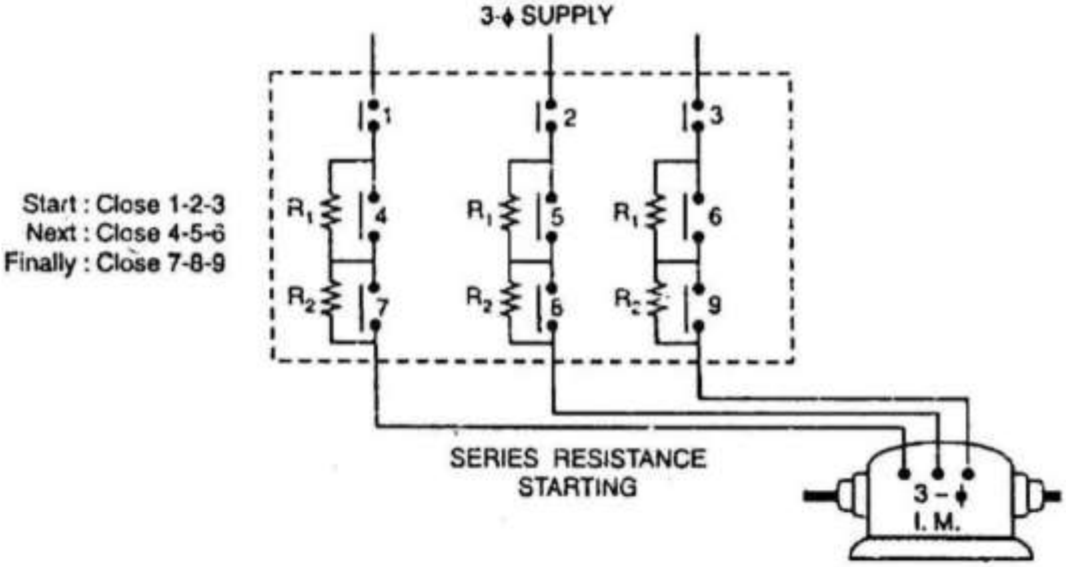


Fig: 3.23

Relation between starting and F.L. torques.

Let V be the rated voltage/phase. If the voltage is reduced by a fraction x by the insertion of resistors in the line, then voltage applied to the motor per phase will be xV.
So,

$$I_{st} = x\, I_{sc}$$

Now
$$\frac{T_{st}}{T_f} = \left(\frac{I_{st}}{I_f}\right)^2 \times s_f$$

or
$$\frac{T_{st}}{T_f} = x^2 \left(\frac{I_{sc}}{I_f}\right)^2 \times s_f$$

Thus while the starting current reduces by a fraction x of the rated-voltage starting current (Isc), the starting torque is reduced by a fraction x2 of that obtained by direct switching. The reduced voltage applied to the motor during the starting period lowers the starting current but at the same time increases the accelerating time because of the reduced value of the starting torque. Therefore, this method is used for starting small motors only.

(iii) Autotransformer starting

This method also aims at connecting the induction motor to a reduced supply at starting and then connecting it to the full voltage as the motor picks up sufficient speed. Fig: 3.24 shows the circuit arrangement for autotransformer starting. The tapping on the autotransformer is so set that when it is in the circuit, 65% to 80% of line voltage is applied to the motor.

At the instant of starting, the change-over switch is thrown to start position. This puts the **autotransformer in the circuit and thus reduced voltage is applied to the circuit. Consequently, starting current is limited to safe value. When the motor attains about 80% of normal speed, the changeover switch is thrown to** run **position. This takes out the autotransformer from the circuit and puts the motor to full line voltage. Autotransformer starting has several advantages viz low power loss, low starting current and less radiated heat. For large machines (over 25 H.P.), this method of starting is often used. This method can be used for both star and delta connected motors.**

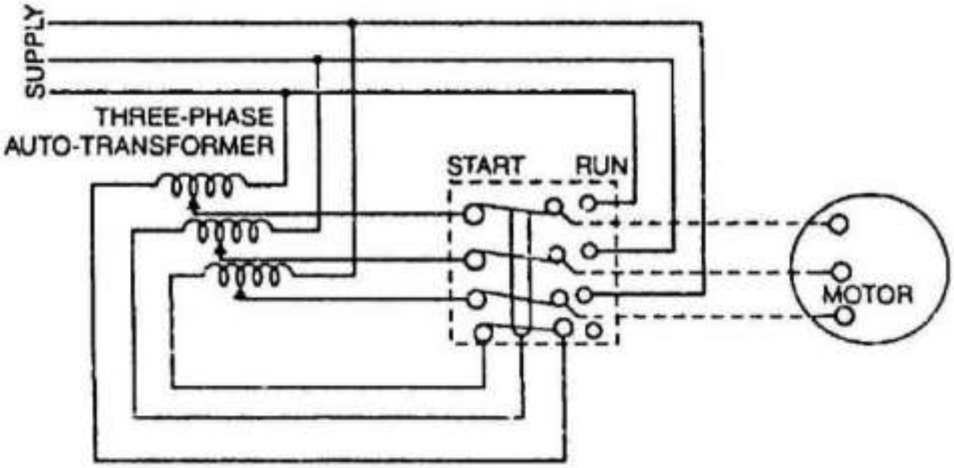


Fig: 3.24

Relation between starting And F.L. torques. Consider a star-connected squirrel-cage induction motor. If V is the line voltage, then voltage across motor phase on direct switching is $V/\sqrt{3}$ and starting current is $I_{st} = I_{sc}$. In case of autotransformer, if a tapping of transformation ratio K (a fraction) is used, then phase voltage across motor is $KV/\sqrt{3}$ and $I_{st} = K\, I_{sc}$,

Now $$\frac{T_{st}}{T_f} = \left(\frac{I_{st}}{I_f}\right)^2 \times s_f = \left(\frac{K\, I_{sc}}{I_f}\right)^2 \times s_f = K^2 \left(\frac{I_{sc}}{I_f}\right)^2 \times s_f$$

$$\therefore \quad \frac{T_{st}}{T_f} = K^2 \left(\frac{I_{sc}}{I_f}\right)^2 \times s_f$$

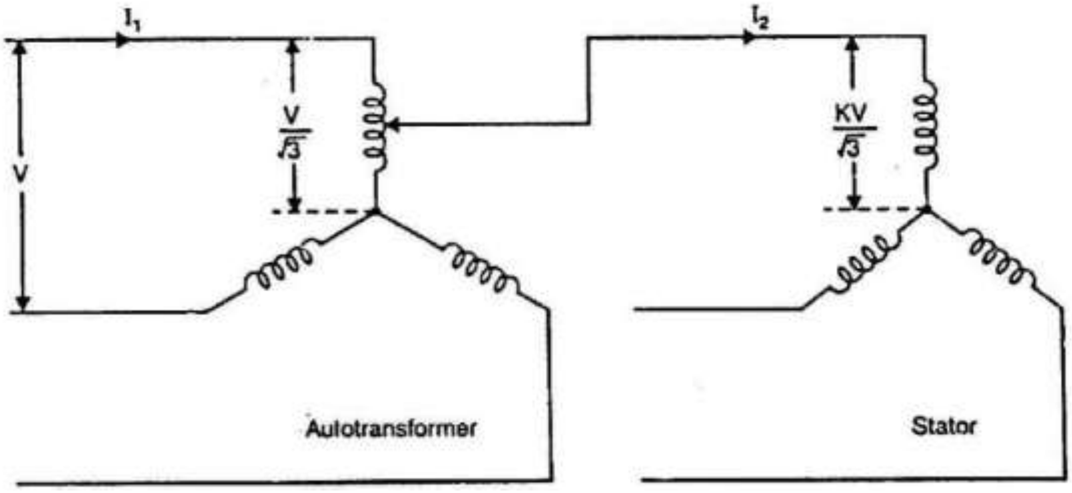


Fig: 3.25

The current taken from the supply or by autotransformer is $I_1 = KI_2 = K^2 I_{sc}$. Note that motor current is K times, the supply line current is K^2 times and the starting torque is K^2 times the value it would have been on direct-on-line starting.

(iv) Star-delta starting

The stator winding of the motor is designed for delta operation and is connected in star during the starting period. When the machine is up to speed, the connections are changed to delta. The circuit arrangement for star-delta starting is shown in Fig: 3.26.

The six leads of the stator windings are connected to the changeover switch as shown. At the instant of starting, the changeover switch is thrown to "Start" position which connects the stator **windings in star. Therefore, each stator phase gets $V/\sqrt{3}$ volts where V is the line voltage. This reduces the starting current. When the motor picks up speed, the changeover switch is thrown to** "Run" position which connects the stator windings in **delta. Now each stator phase gets full line voltage V. The disadvantages of this method are:**

(a) With star-connection during starting, stator phase voltage is $1/\sqrt{3}$ times the line voltage. Consequently, starting torque is $(1/\sqrt{3})^2$ or 1/3 times the value it would have with Δ-connection. This is rather a large reduction in starting torque.

(b) The reduction in voltage is fixed.

This method of starting is used for medium-size machines (upto about 25 H.P.).

Relation between starting and F.L. torques. In direct delta starting,

Starting current/phase, $I_{sc} = V/Z_{sc}$ where V = line voltage

Starting line current = $\sqrt{3}\, I_{sc}$

In star starting, we have,

$$\text{Starting current/phase, } I_{st} = \frac{V/\sqrt{3}}{Z_{sc}} = \frac{1}{\sqrt{3}} I_{sc}$$

Now
$$\frac{T_{st}}{T_f} = \left(\frac{I_{st}}{I_f}\right)^2 \times s_f = \left(\frac{I_{sc}}{\sqrt{3} \times I_f}\right)^2 \times s_f$$

or $$\frac{T_{st}}{T_f} = \frac{1}{3}\left(\frac{I_{sc}}{I_f}\right)^2 \times s_f$$

where I_{sc} = starting phase current (delta)
I_f = F.L. phase current (delta)

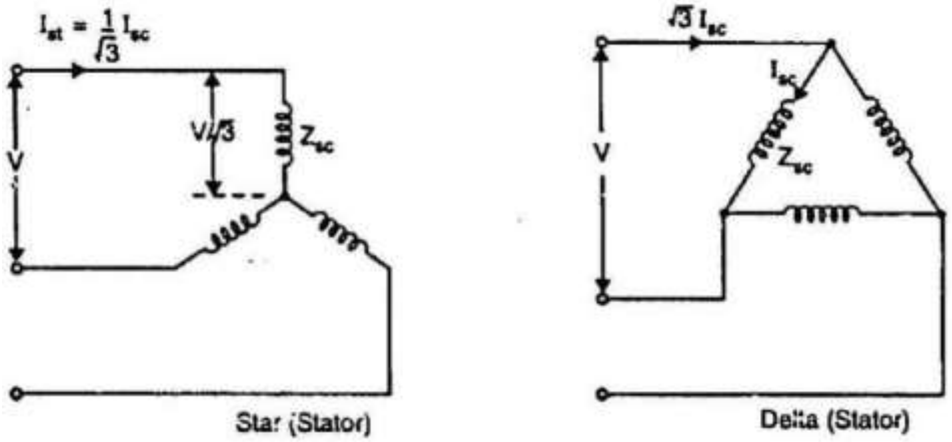


Fig: 3.26

Note that in star-delta starting, the starting line current is reduced to one-third as compared to starting with the winding delta connected. Further, starting torque is reduced to one-third of that obtainable by direct delta starting. This method is cheap but limited to applications where high starting torque is not necessary e.g., machine tools, pumps etc.

Starting of Slip-Ring Induction Motors

Slip-ring motors are invariably started by rotor resistance starting. In this method, a variable star-connected rheostat is connected in the rotor circuit through slip rings and full voltage is applied to the stator winding as shown in Fig: 3.27.

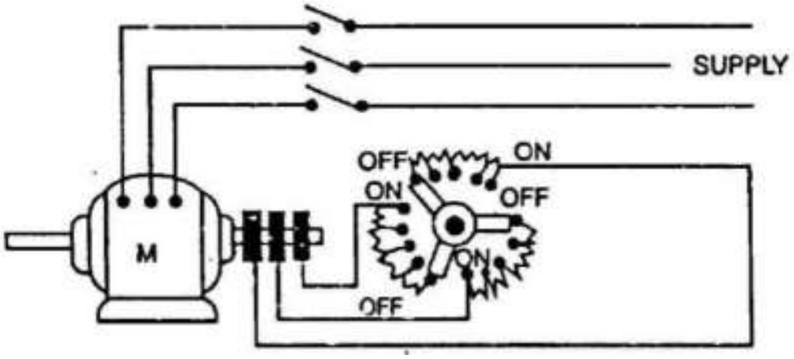


Fig: 3.27

(i) At starting, the handle of rheostat is set in the OFF position so that maximum resistance is placed in each phase of the rotor circuit. This reduces the starting current and at the same time starting torque is increased.

(ii) As the motor picks up speed, the handle of rheostat is gradually moved in clockwise direction and cuts out the external resistance in each phase of the rotor circuit. When the motor attains normal speed, the change-over switch is in the ON position and the whole external resistance is cut out from the rotor circuit.

Speed control of Three Phase Induction Motors

The induction machine, when operating from mains is essentially a constant speed machine. Many industrial drives, typically for fan or pump applications, have typically constant speed requirements and hence the induction machine is ideally suited for these. However, the induction machine, especially the squirrel cage type, is quite rugged and has a simple construction. Therefore it is good candidate for variable speed applications if it can be achieved.

Speed control by changing applied voltage

From the torque equation of the induction machine we can see that the torque depends on the square of the applied voltage. The variation of speed torque curves with respect to the applied voltage is shown in Fig: 3.28. These curves show that the slip at maximum torque ss� remains same, while the value of stall torque comes down with decrease in applied voltage. The speed range for stable operation remains the same.

Further, we also note that the starting torque is also lower at lower voltages. Thus, even if a given voltage level is sufficient for achieving the running torque, the machine may not start. This method of trying to control the speed is best suited for loads that require very little starting torque, but their torque requirement may increase with speed.

Fig: 3.28 also shows a load torque characteristic — one that is typical of a fan type of load. In a fan (blower) type of load, the variation of torque with speed is such that $TT \propto \omega\omega^{2}$.
Here one can see that it may be possible to run the motor to lower speeds within the range n_s to $(1 - s)n_s$. Further, since the load torque at zero speed is zero, the machine can start even at reduced voltages. This will not be possible with constant torque type of loads.

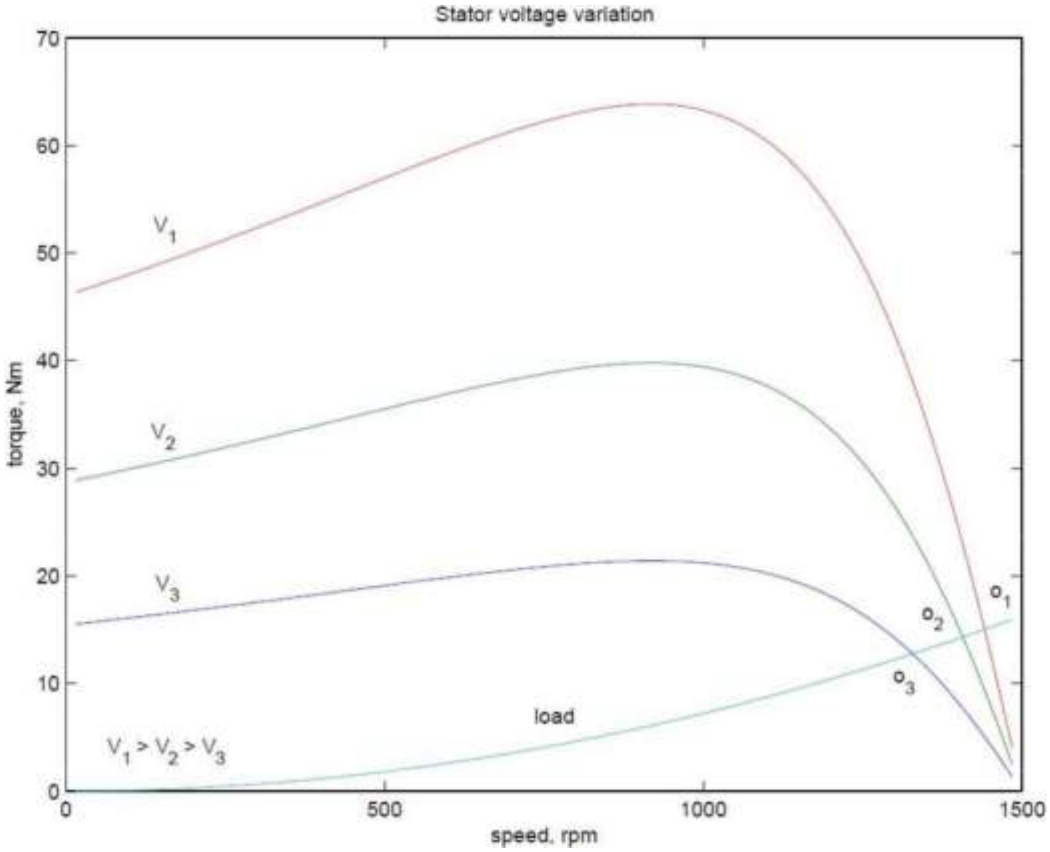


Fig: 3.28

One may note that if the applied voltage is reduced, the voltage across the magnetising branch also comes down. This in turn means that the magnetizing current and hence flux level are reduced. Reduction in the flux level in the machine impairs torque production which is primarily the explanation for Fig: 3.28. If, however, the machine is running under lightly loaded conditions, then operating under rated flux levels is not required. Under such conditions,

reduction in magnetizing current improves the power factor of operation. Some amount of energy saving may also be achieved.

Voltage control may be achieved by adding series resistors (a lossy, inefficient proposition), or a series inductor / autotransformer (a bulky solution) or a more modern solution using semiconductor devices. A typical solid state circuit used for this purpose is the AC voltage controller or AC chopper.

Rotor resistance control

The expression for the torque of the induction machine is dependent on the rotor resistance. Further the maximum value is independent of the rotor resistance. The slip at maximum torque is dependent on the rotor resistance. Therefore, we may expect that if the rotor resistance is changed, the maximum torque point shifts to higher slip values, while retaining a constant torque. Fig: 3.29 shows a family of torque-speed characteristic obtained by changing the rotor resistance.

Note that while the maximum torque and synchronous speed remain constant, the slip at which maximum torque occurs increases with increase in rotor resistance, and so does the starting torque. Whether the load is of constant torque type or fan-type, it is evident that the speed control range is more with this method. Further, rotor resistance control could also be used as a means of generating high starting torque.

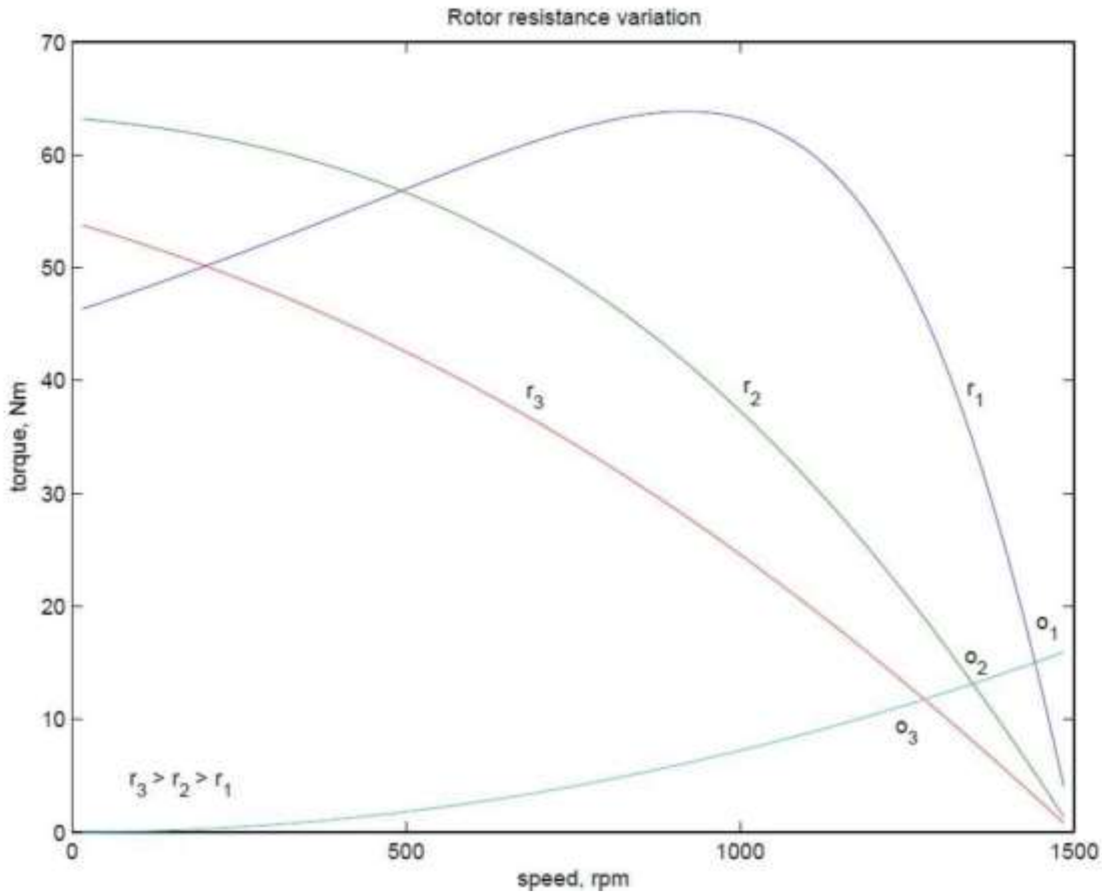


Fig: 3.29

For all its advantages, the scheme has two serious drawbacks. Firstly, in order to vary the rotor resistance, it is necessary to connect external variable resistors (winding resistance itself cannot be changed). This, therefore necessitates a slip-ring machine, since only in that case rotor terminals are available outside. For cage rotor machines, there are no rotor terminals. Secondly, the method is not very efficient since the additional resistance and operation at high slips entails dissipation.

The resistors connected to the slip-ring brushes should have good power dissipation capability. Water based rheostats may be used for this. A solid-state alternative to a rheostat is a chopper **controlled resistance where the duty ratio control of the chopper presents a variable resistance load to the rotor of the induction machine.**

Cascade control

The power drawn from the rotor terminals could be spent more usefully. Apart from using the heat generated in meaning full ways, the slip ring output could be connected to another induction machine. The stator of the second machine would carry slip frequency currents of

the first machine which would generate some useful mechanical power. A still better option would be to mechanically couple the shafts of the two machines together. This sort of a connection is called cascade connection and it gives some measure of speed control.

Let the frequency of supply given to the first machine be f_1, its number poles be p_1, and its slip of operation be S_1. Let f_2, p_2 and S_2 be the corresponding quantities for the second machine. The frequency of currents flowing in the rotor of the first machine and hence in the stator of the second machine is S_1 f_1. Therefore $f_2 = S_1$ f_1. Since the machines are coupled at the shaft, the speed of the rotor is common for both. Hence, if n is the speed of the rotor in radians,

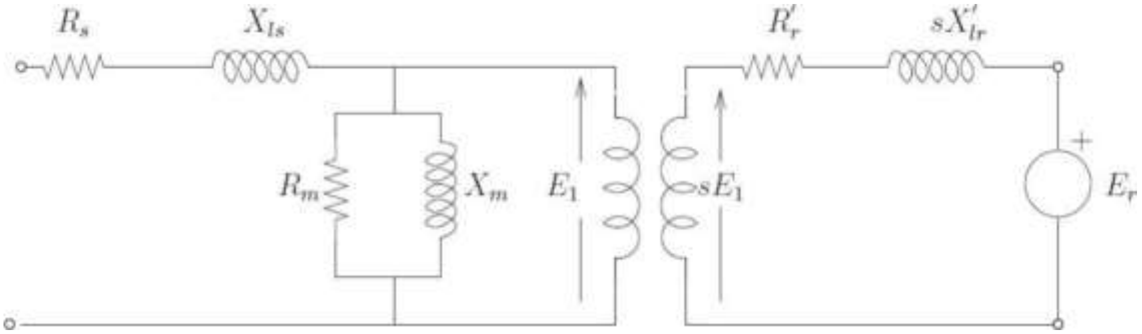
$$n = \frac{f_1}{p_1}(1 - s_1) = \pm\frac{s_1 f_1}{p_2}(1 - s_2).$$

Note that while giving the rotor output of the first machine to the stator of the second, the resultant stator mmf of the second machine may set up an air-gap flux which rotates in the same direction as that of the rotor, or opposes it. This result~~s~~ in values for speed as

$$n = \frac{f_1}{p_1 + p_2} \quad or \quad n = \frac{f_1}{p_1 - p_2} \quad (s_2\ negligible)$$

The latter expression is for the case where the second machine is connected in opposite phase sequence to the first. The cascade connected system can therefore run at two possible speeds.

Speed control through rotor terminals can be considered in a much more general way. Consider the induction machine equivalent circuit of Fig: 3.30, where the rotor circuit has been terminated with a voltage source E_r.



Fig; 3.30

If the rotor terminals are shorted, it behaves like a normal induction machine. This is equivalent to saying that across the rotor terminals a voltage source of zero magnitude is connected. Different situations could then be considered if this voltage source E_r had a non-zero magnitude. Let the power consumed by that source be P_r. Then considering the rotor side circuit power dissipation per phase

$$sE_1 I_2' \cos\phi_2 = I_2' R_2' + P_r.$$

Clearly now, the value of s can be changed by the value of P_r. for $P_r = 0$, the machine is like a normal machine with a short circuited rotor. As P_r becomes positive, for all other circuit conditions remaining constant, s increases or in the other words, speed reduces. As P_r becomes negative, the right hand side of the equation and hence the slip decreases. The physical interpretation is that we now have an active source connected on the rotor side which is able to supply part of the rotor copper losses When $P_r = -I_2^2 R_2$ the entire copper loss is supplied by the external source. The RHS and hence the slip is zero. This corresponds to operation at synchronous speed. In general the circuitry connected to the rotor may not be a simple resistor or a machine but a power electronic circuit which can process this power requirement. This circuit may drive a machine or recover power back to the mains. Such circuits are called static Kramer drives.

Pole changing method

Sometimes induction machines have a special stator winding capable of being externally connected to form two different number of pole numbers. Since the synchronous speed of the induction machine is given by $n_s = f_s/p$ (in rev. /s) where p is the number of pole pairs, this would correspond to changing the synchronous speed. With the slip now corresponding to the new synchronous speed, the operating speed is changed. This method of speed control is a stepped variation and generally restricted to two steps.

If the changes in stator winding connections are made so that the air gap flux remains constant, then at any winding connection, the same maximum torque is achievable. Such winding arrangements are therefore referred to as constant-torque connections. If however such connection changes result in air gap flux changes that are inversely proportional to the synchronous speeds, then such connections are called constant-horsepower type.

The following figure serves to illustrate the basic principle. Consider a magnetic pole structure consisting of four pole faces A, B, C, D as shown in Fig: 3.31.

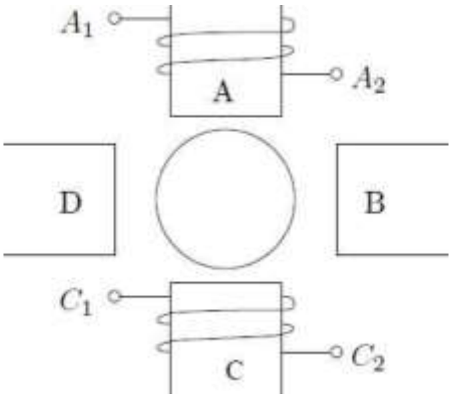


Fig: 3.31

Coils are wound on A & C in the directions shown. The two coils on A & C may be connected in series in two different ways A2 may be connected to C1 or C2. A1 with the

Other terminal at C then form the terminals of the overall combination. Thus two connections result as shown in Fig: 3.32 (a) & (b).

Now, for a given direction of current flow at terminal A1, say into terminal A1, the flux directions within the poles are shown in the figures. In case (a), the flux lines are out of the pole A (seen from the rotor) for and into pole C, thus establishing a two-pole structure. In case (b) however, the flux lines are out of the poles in A & C. The flux lines will be then have to complete the circuit by flowing into the pole structures on the sides. If, when seen from the rotor, the pole emanating flux lines is considered as North Pole and the pole into which they enter is termed as south, then the pole configurations produced by these connections is a two-pole arrangement in Fig: 3.32(a) and a four-pole arrangement in Fig: 3.32 (b).

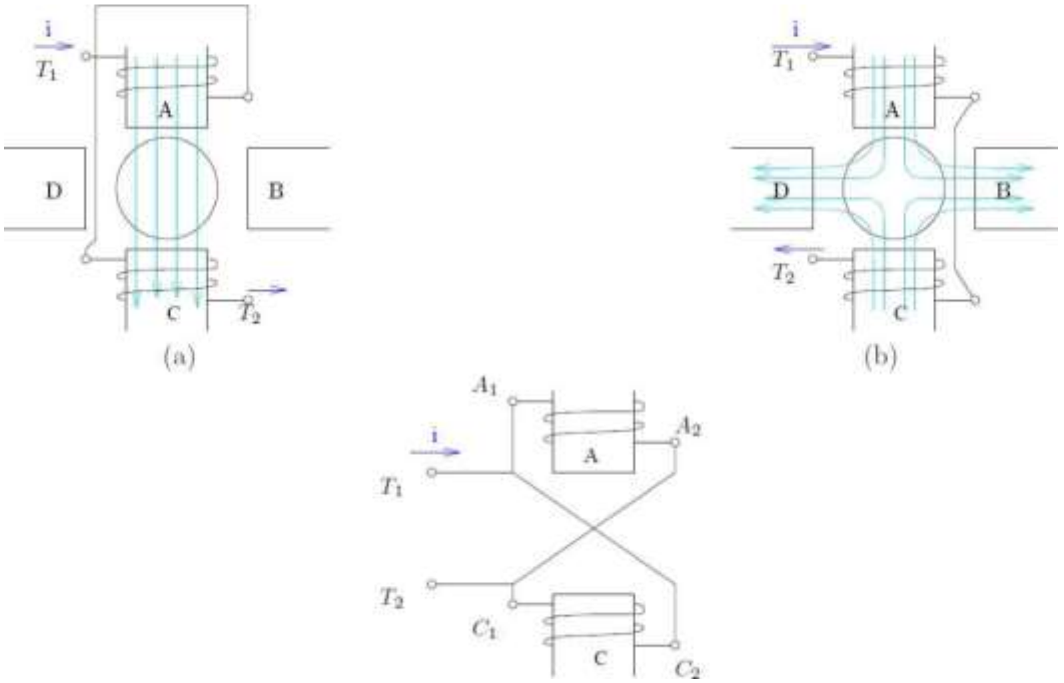


Fig: 3.32

Thus by changing the terminal connections we get either a two pole air-gap field or a four- pole field. In an induction machine this would correspond to a synchronous speed reduction in half from case (a) to case (b). Further note that irrespective of the connection, the applied voltage is balanced by the series addition of induced emf s in two coils. Therefore the air-gap flux in both cases is the same. Cases (a) and (b) therefore form a pair of constant torque connections.

Consider, on the other hand a connection as shown in the Fig: 3.32 (c). The terminals T1 and T2 are where the input excitation is given. Note that current direction in the coils now resembles that of case (b), and hence this would result in a four-pole structure. However, in Fig: 3.32 (c), there is only one coil induced emf to balance the applied voltage. Therefore flux in case (c) would therefore be halved compared to that of case (b) or case (a), for that matter). Cases (a) and (c)therefore form a pair of constant horse-power connections.

It is important to note that in generating a different pole numbers, the current through one coil (out of two, coil C in this case) is reversed. In the case of a three phase machine, the following example serves to explain this. Let the machine have coils connected as shown [C1 – C6] as shown in Fig: **3.33.**

The current directions shown in C1 & C2 correspond to the case where T1, T2, T3 are supplied with three phase excitation and Ta, Tb & Tc are shorted to each other (STAR point). The applied voltage must be balanced by induced emf in one coil only (C1 & C2 are parallel). If however the excitation is given to Ta, Tb & Tc with T1, T2, T3 open, then current through one of the coils (C1 & C2) would reverse. Thus the effective number of poles would increase, thereby bringing down the speed. The other coils also face similar conditions.

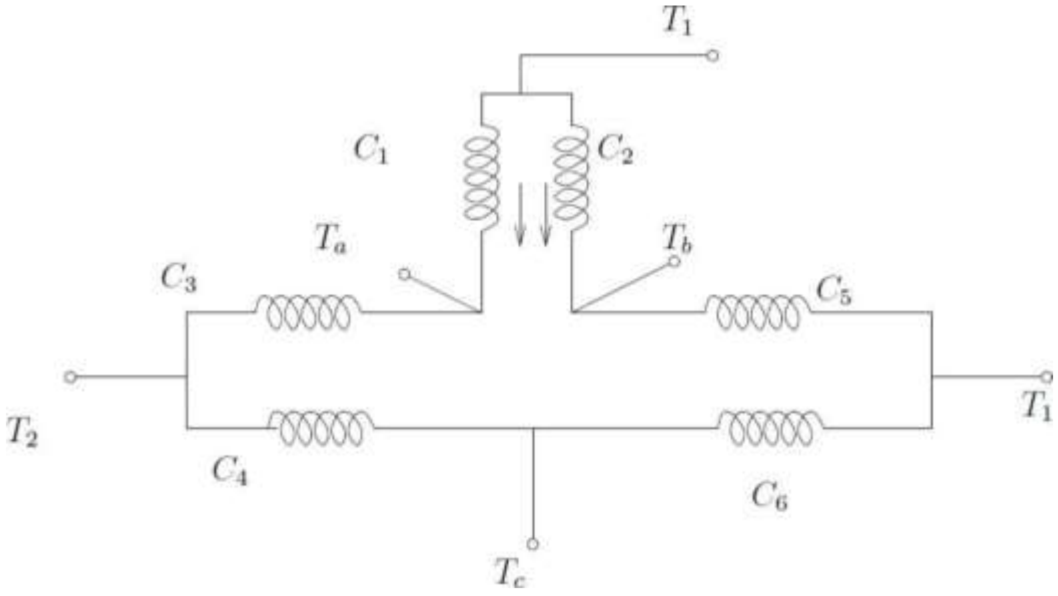


Fig: 3.33

Stator frequency control

The expression for the synchronous speed indicates that by changing the stator frequency also it can be changed. This can be achieved by using power electronic circuits called inverters which convert dc to ac of desired frequency. Depending on the type of control scheme of the inverter, the ac generated may be variable-frequency-fixed-amplitude or variable-frequency-variable- amplitude type. Power electronic control achieves smooth variation of voltage and frequency of the ac output. This when fed to the machine is capable of running at a controlled speed. However, consider the equation for the induced emf in the induction machine.

$$V = 4.44 N \phi_m f$$

Where, N is the number of the turns per phase, φ_m is the peak flux in the air gap and f is the frequency.

Note that in order to reduce the speed, frequency has to be reduced. If the frequency is reduced while the voltage is kept constant, thereby requiring the amplitude of induced emf to remain the same, flux has to increase. This is not advisable since the machine likely to enter deep saturation. If this is to be avoided, then flux level must be maintained constant which implies that voltage must be reduced along with frequency. The ratio is held constant in order to maintain the flux level for maximum torque capability.

Actually, it is the voltage across the magnetizing branch of the exact equivalent circuit that must be maintained constant, for it is that which determines the induced emf. Under conditions where the stator voltage drop is negligible compared the applied voltage. In this mode of operation, the voltage across the magnetizing inductance in the exact equivalent circuit reduces in amplitude with reduction in frequency and so does the inductive reactance. This implies that the current through the inductance and the flux in the machine remains constant. The speed torque characteristics at any frequency may be estimated as before. There is one curve for every excitation frequency considered corresponding to every

value of synchronous speed. The curves are shown below. It may be seen that the

maximum torque remains constant.

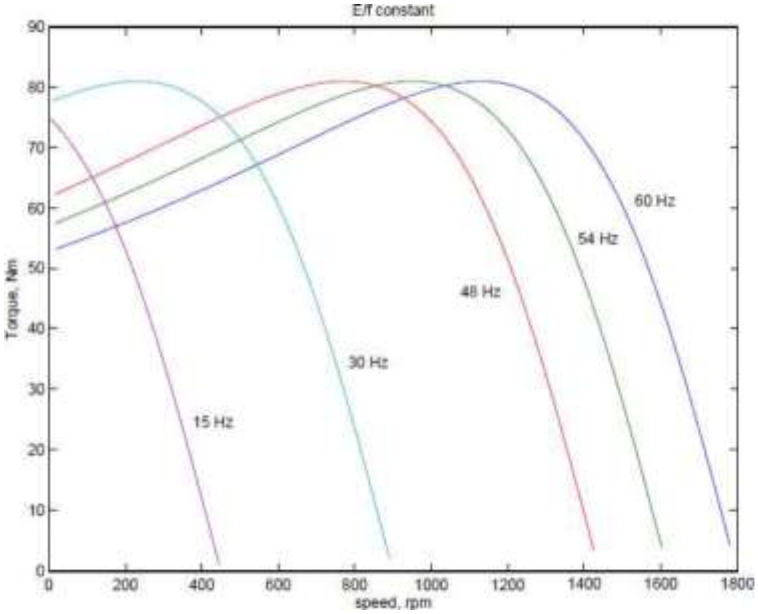


Fig: 3.34

This may be seen mathematically as follows. If E is the voltage across the magnetizing branch and f is the frequency of excitation, then E = kf, where k is the constant of proportionality. If –2π , the developed torque is given by

$$T_{E/f} = \frac{k^2 f^2}{\left(\frac{R'_r}{s}\right)^2 + (\omega L'_{lr})^2} \, \frac{R'_r}{s\omega}$$

If this equation is differentiated with respect to s and equated to zero to find the slip at maximum torque we get $s = \pm R'_r/(\omega L_{lr})$. The maximum torque is obtained by substituting this value into above equation,

$$\hat{T}_{E/f} = \frac{k^2}{8\pi^2 L'_{lr}}$$

It shows that this maximum value is independent of the frequency. Further $s\omega$ is independent of frequency. This means that the maximum torque always occurs at a speed lower than synchronous speed by a fixed difference, independent of frequency. The overall effect is an apparent shift of the torque-speed characteristic as shown in Fig: 3.34.

Though this is the aim, E is an internal voltage which is not accessible. It is only the terminal voltage V which we have access to and can control. For a fixed V, E changes with operating slip (rotor branch impedance changes) and further due to the stator impedance drop. Thus if we approximate E/f as V/f, the resulting torque-speed characteristic shown in Fig: 3.35 is far from desirable.

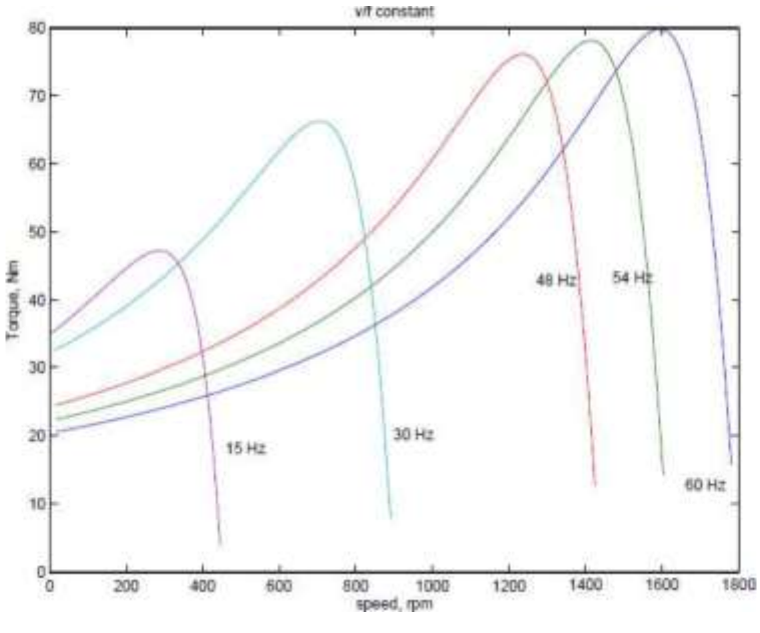


Fig: 3.35

At low frequencies and hence low voltages the curves show a considerable reduction in peak torque. At low frequencies (and hence at low voltages) the drop across the stator impedance prevents sufficient voltage availability. Therefore, in order to maintain sufficient torque at low frequencies, a voltage more than proportional needs to be given at low speeds.

Another component of compensation that needs to be given is due to operating slip. With these two components, therefore, the ratio of applied voltage to frequency is not a constant but is a curve such as that shown in Fig: 3.36

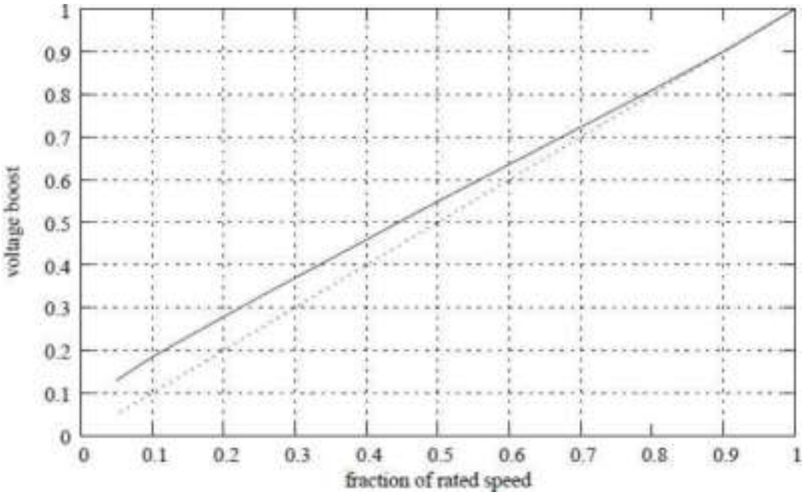


Fig: 3.36

With this kind of control, it is possible to get a good starting torque and steady state performance. However, under dynamic conditions, this control is insufficient. Advanced control techniques such as field- oriented control (vector control) or direct torque control (DTC) are necessary.

Power Stages in an Induction Motor

The input electric power fed to the stator of the motor is converted into mechanical power at the shaft of the motor. The various losses during the energy conversion are:

1. Fixed losses

(i) Stator iron loss

(ii) Friction and windage loss

The rotor iron loss is negligible because the frequency of rotor currents under normal running condition is small.

2. Variable losses

(i) Stator copper loss

(ii) Rotor copper loss

Fig: 3.37 shows how electric power fed to the stator of an induction motor suffers losses and finally converted into mechanical power.

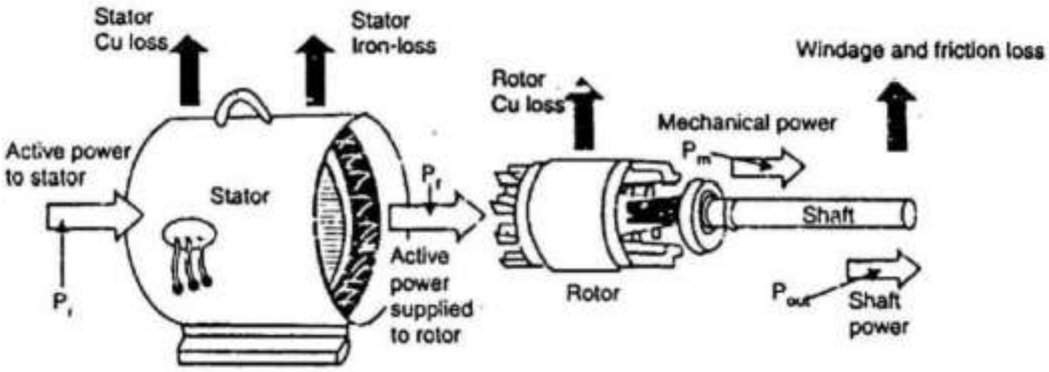


Fig: 3.37

The following points may be noted from the above diagram:

(i) Stator input, Pi = Stator output + Stator losses

= **Stator output + Stator Iron loss + Stator Cu loss**

(ii) Rotor input, Pr = Stator output

It is because stator output is entirely transferred to the rotor through air-gap by electromagnetic induction.

(iii) Mechanical power available, Pm = Pr - Rotor Cu loss

This mechanical power available is the gross rotor output and will produce a gross torque T_g.

(iv) Mechanical power at shaft, Pout = Pm - Friction and windage loss Mechanical power available at the shaft produces a shaft torque T_{sh}.

Clearly, Pm - Pout = Friction and windage loss.

Double Cage Induction Motor

One of the advantages of the slip-ring motor is that resistance may be inserted in the rotor circuit to obtain high starting torque (at low starting current) and then cut out to obtain optimum running conditions. However, such a procedure cannot be adopted for a squirrel cage motor because its cage is permanently short-circuited. In order to provide high starting torque at low starting current, double-cage construction is used.

Construction

As the name suggests, the rotor of this motor has two squirrel-cage windings located one above the other as shown in Fig: 3.38(i).

The outer winding consists of bars of smaller cross-section short-circuited by end rings. Therefore, the resistance of this winding is high. Since the outer winding has relatively open slots and a poorer flux path around its bars [See Fig: 3.38(ii)], it has a low inductance. Thus the resistance of the outer squirrel-cage winding is high and its inductance is low.

The inner winding consists of bars of greater cross-section short-circuited by end rings. Therefore, the resistance of this winding is low. Since the bars of the inner winding are thoroughly buried in iron, it has a high inductance [See Fig: 3.38(ii)].Thus the resistance of the inner squirrel cage winding is low and its inductance is high.

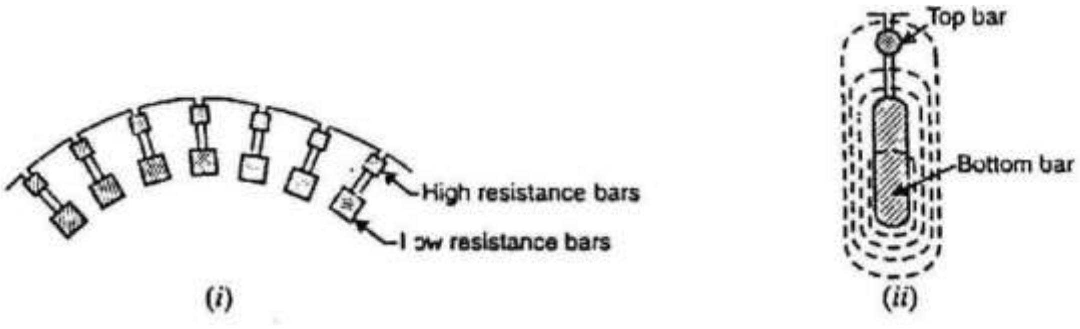


Fig: 3.38

Working

When a rotating magnetic field sweeps across the two windings, equal e.m.f.s are induced in each.

(i) At starting, the rotor frequency is the same as that of the line (i.e., 50 Hz), making the reactance of the lower winding much higher than that of the upper winding. Because of the high reactance of the lower winding, nearly all the rotor current flows in the high-resistance outer cage winding. This provides the good starting characteristics of a high-resistance cage winding. Thus the outer winding gives high starting torque at low starting current.

(ii) As the motor accelerates, the rotor frequency decreases, thereby lowering the reactance of the inner winding, allowing it to carry a larger proportion of the total rotor current At the normal operating speed of the motor, the rotor frequency is so low (2 to 3 Hz) that nearly all the rotor current flows in the low-resistance inner cage winding. This results in good operating efficiency and speed regulation.

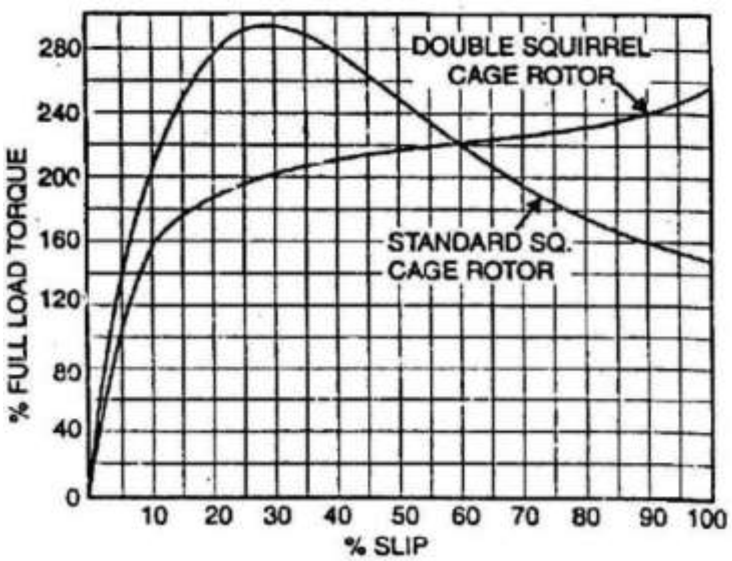


Fig: 3.39

Fig: 3.39 shows the operating characteristics of double squirrel-cage motor. The starting torque of this motor ranges from 200 to 250 percent of full-load torque with a starting current of 4 to 6 times the full-load value. It is classed as a high-torque, low starting current motor.

Cogging and Crawling of Induction Motor

Crawling of induction motor

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. Instead, 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 Ns whereas 3rd, 5th, 7th harmonics may rotate in forward or backward direction at Ns/3, Ns/5, Ns/7 speeds respectively. Hence, harmonic torques are also developed in addition with fundamental torque.

3rd harmonics are absent in a balanced 3-phase system. Hence 3rdd harmonics do not produce rotating field and torque. The total motor torque now consist three components as: (i) the fundamental torque with synchronous speed Ns, (ii) 5th harmonic torque with synchronous speed

Ns/5, (iv) 7th harmonic torque with synchronous speed Ns/7 (provided that higher harmonics are neglected).

Now, 5th harmonic currents will have phase difference of

$$5 \times 120 = 600^\circ = 2 \times 360 - 120 = -120^\circ.$$

Hence the revolving speed set up will be in reverse direction with speed Ns/5. The small amount of 5th harmonic torque produces breaking action and can be neglected.

The 7th harmonic currents will have phase difference of

$$7 \times 120 = 840^\circ = 2 \times 360 + 120 = +120^\circ.$$

Hence they will set up rotating field in forward direction with synchronous speed equal to Ns/7. If we neglect all the higher harmonics, the resultant torque will be equal to sum of fundamental torque and 7th harmonic torque. 7th harmonic torque reaches its maximum positive value just before1/7th of Ns. 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 up to its normal speed, but it will run at a speed which is nearly 1/7th of its normal speed as shown in Fig: 3.40. This phenomenon is called as crawling of induction motors.

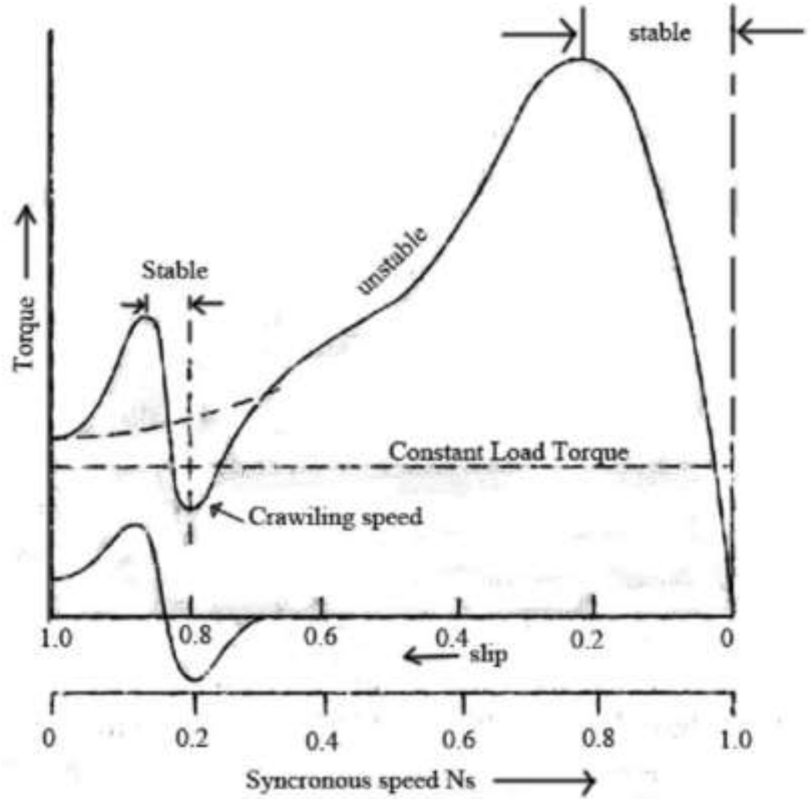


Fig: 3.40

Cogging (Magnetic Locking or Teeth Locking) of induction motor

Sometimes, the rotor of a squirrel cage induction motor refuses to start at all, particularly if the supply voltage is low. This happens especially when number of rotor teeth is equal to number of stator teeth, because of magnetic locking between the stator teeth and the rotor teeth. When the rotor teeth and stator teeth face each other, the reluctance of the magnetic path is minimum that is why the rotor tends to remain fixed. This phenomenon is called cogging or magnetic locking of induction motor.

Induction Generator

When a squirrel cage induction motor is energized from a three phase power system and is mechanically driven above its synchronous speed it will deliver power to the system. An induction generator receives its excitation (magnetizing current) from the system to which it is connected. It consumes rather than supplies reactive power (KVAR) and supplies only real power (KW) to the system. The KVAR required by the induction generator plus the KVAR requirements of all other loads on the system must be supplied from synchronous generators or static capacitors on the system.

Operating as a generator at a given percentage slip above synchronous speed, the torque, current, efficiency and power factor will not differ greatly from that when operating as a motor. The same slip below synchronous speed, the shaft torque and electric power flow is reversed. Typical speed torque characteristic of induction generator is shown in Fig: 3.41.

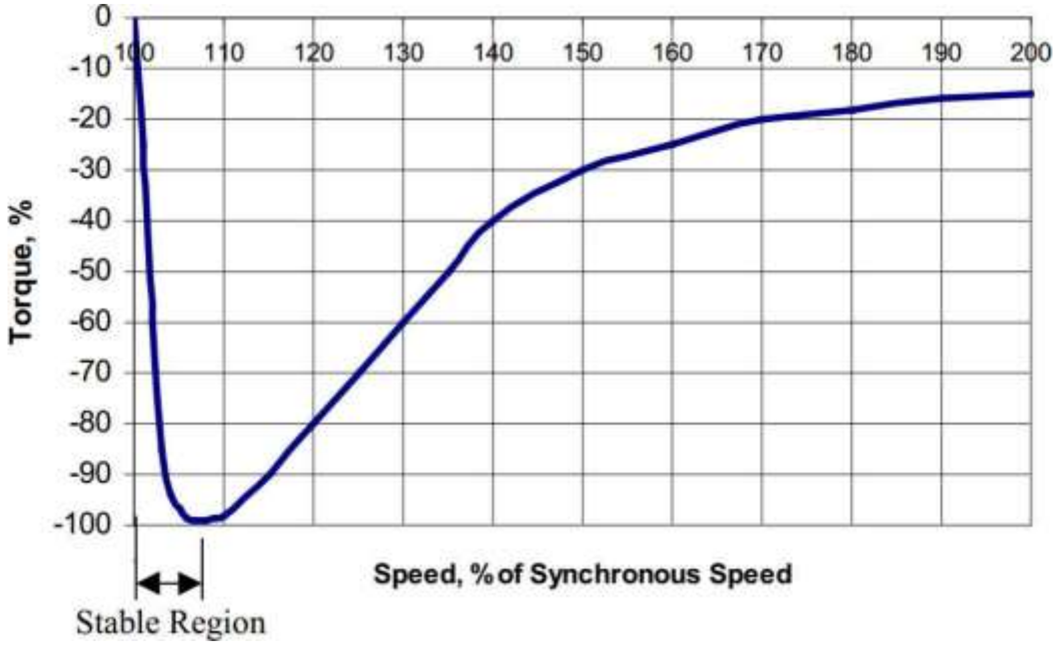


Fig: 3.41

Now for example, a 3600 RPM squirrel cage induction motor which delivers full load output at 3550 RPM as a motor will deliver full rated power as a generator at 3650 RPM. If the half-load motor speed is 3570 RPM, the output as a generator will be one-half of rated value when driven at 3630 RPM, etc. Since the induction generator is actually an induction motor being driven by a prime mover, it has several advantages.

1. **It is less expensive and more readily available than a synchronous generator.**
2. **It does not require a DC field excitation voltage.**
3. **It automatically synchronizes with the power system, so its controls are simpler and less expensive.**

The principal disadvantages of an induction generator are listed below

1. **It is not suitable for separate, isolated operation**
2. **It consumes rather than supplies magnetizing KVAR**
3. **It cannot contribute to the maintenance of system voltage levels (this is left entirely to the synchronous generators or capacitors)**
4. **In general it has a lower efficiency.**

Induction Generator Application

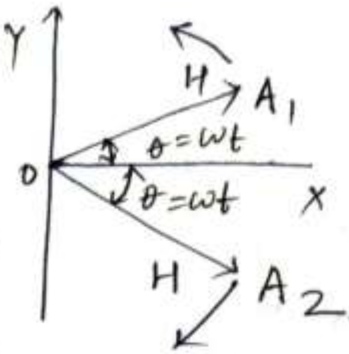
As energy costs so high, energy recovery became an important part of the economics of most industrial processes. The induction generator is ideal for such applications because it requires very little in the way of control system or maintenance.

Because of their simplicity and small size per kilowatt of output power, induction generators are also favoured very strongly for small windmills. Many commercial windmills are designed to operate in parallel with large power systems, supplying a fraction of the customer's total power needs**. In such operation, the power system**

can be relied on for voltage & frequency control, and static capacitors can be used for power-factor correction.

1φ Induction Motor

Ferrari's Principle :-



→ Ferrari's Principle states that an alternating field can be replaced exactly by two rotating fields of half amplitude travelling in opposite directions at synchronous speed.

→ Let ~~both the field~~ consider 2 rotating magnetic fields OA_1 & OA_2, each having magnitude of H units & travelling in opposite directions with angular velocity 'ω'

→ Let both the fields start travelling from axis OX at time t=0. After time = t seconds the field OA_1 & OA_2 have rotated through $\theta = \omega t$ radians.

→ X-component, $H_x = OA_1 \cos\theta + OA_2 \cos\theta$

$$= H\cos\theta + H\cos\theta = 2H\cos\theta$$

$$= 2H\cos\omega t.$$

→ Y-component, $H_y = OA_1 \sin\theta - OA_2 \sin\theta$

$$= H\sin\theta - H\sin\theta = 0$$

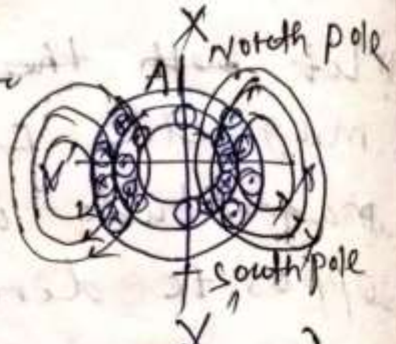
→ Hence resultant magnetic field is $2H\cos\omega t$ along X-axis. It is therefore obvious that two rotating magnetic fields, travelling in opposite directions with the same angular velocity, result in an alternating field of twice their amplitude.

Double revolving field theory :-

→ The double revolving field theory of a 1ϕ states that a pulsating magnetic field resolved into two rotating magnetic fie

• They are equal in magnitude but opp in directions. Both the revolving field rotates at the synchronous speed, $\omega_s = 2\pi f$ on the opposite direction.

I.M Action :-



→ ⊗ → Inward direction of current]
⊙ → Outward direction of current.

* mmf = N × I

→ When stator winding of 1ϕ IM is connec to a 1ϕ AC supply, a magnetic field is developed, whose axis is always along the axis of stator coils The direction of magnetic pole can be found by using right hand grip rule

→ With alternating current in the fixed stator coil the mmf wave is stationary in space but pulsates in magnitude & varies sinusoidally with time.

→ Currents are induced in the rotor conductors by transformer action, these currents being in such a direction as to oppose the sator mmf. Thus the axis of the rotor mmf wave coincides with that of the stator field, the torque angle is therefore zero. & no torque is developed at starting. However if the rotor of such a motor is given a push by hand or by another means in either direction, it will pick up the speed & continue to rotate in the same direction developing operating torque.

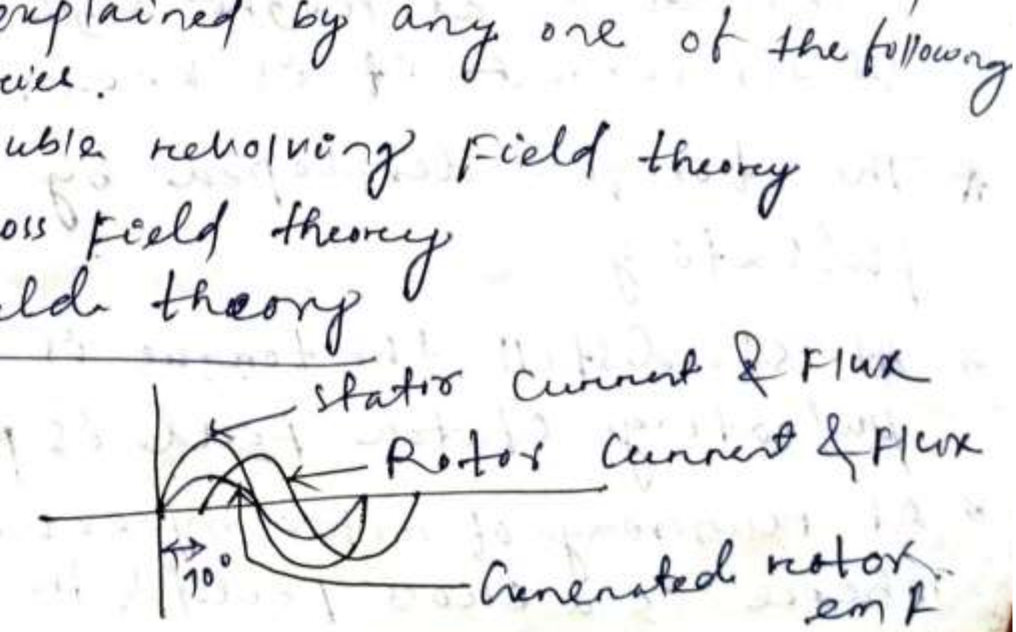
Disadvantage of 1ϕ IM :-

→ It suffer from low over-load capacity.
→ Low efficiency
→ Low power factor

* The peculiar behaviour of a 1ϕ IM may be explained by any one of the following two theories.

1. Double revolving Field theory
2. Cross Field theory

Cross - Field theory



→ If the rotor is pushed by someon means the rotor conductor cut across the stator field causing an emf kn as speed emf. to be generated in them (rotor).

→ The direction of this generated emf is determined by Flemming's right hand rul i.e. in case of 1st half cycle outward on the lower half of the rot & inward in the upper half of the rotor.

→ During the next half cycle the direc of generated emf will be reversed.

→ The generated rotor emf vary in phase with the stator current & flux.

→ The rotor current due to these emfs lags by nearly 90° owing to low resistance & high inductance of the rotor winding.

→ Since the field created by rotor currents is at right angle to the field of stator current it is known as cross field.

The torque developed by a 1ϕ IM is pulsating.

At standstill the torque is zero, only pulsating stator field is present.

- At running of rotor by external means there is a cross field & the developed torque of 1ϕ IM is pulsating i.e not of constant strength. Due to this to reduce vibrations & noise of 1ϕ IM set of rubber or spring mounts are used.

$$* \text{ Capacitor} = \frac{P(\text{watt}) \times \eta \times 1000}{V^2 \times \text{Frequency}} \qquad [\text{Put } \eta = 80]$$

Flemming's Right hand thumb rule: States that stretch your thumb, forefinger & middle finger of your left hand such that they are mutually perpendicular to each other if the 1st finger points in the direction of magnetic field & 2nd in the direc? of current then the thumb will point in the direction of motion or force acting on the conductor.

thumb = motion
Force = field
current = middle.

Methods of Starting.

(1) Split phase starting.
(2) Repulsion starting.
(3) Shaded pole starting.

→ Principle of operation of a split phase Induction motor is similar to that of a polyphase IM. The main difference is that the 1ϕ motor does not produce a rotating magnetic field

. but produces only a pulsating field
→ hence to produce the rotating magnetic field for self starting. phase splitting is to be done to make the motor to work as a 2φ motor for starting.

Working of split phase motor:

Types of split phase IM.

1. Resistance start - Induction run motor.
✓ 2. Capacitor start ①
✓ 3. capacitor start ② capacitor run
✓ 4. shaded pole ④
✓ 5. Permanent capacitor motor ③

Double revolving field theory:

Eg:- 2 motors having opposite rotating field connected to a common shaft.

→ at stand still, N = 0, So slip = $\frac{N_s - N}{N_s} = \frac{N_s - 0}{N_s} = 1$

→ 2 fields have equal strength & develop equal & opposite electro magnetic torques resulting in net torque of zero value.

→ If however the rotor is made to run at speed N by some external means in any direction say in the direction of forward field.

→ Now slips are s & 2-s. $\boxed{s = \frac{N_s - N}{N_s}}$

→ The slip of the rotor with respect to the forward rotating field F_F.

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

→ The slip of the rotor ~~with~~ w.r.t backward rotating field F_b

$$S_b = \frac{N_s - (-N)}{N_s} = \frac{N_s + N_s - N_s + (N)}{N_s}$$

$$= \frac{2N_s - (N_s - N)}{N_s} = \frac{2N_s}{N_s} - \frac{(N_s - N)}{N_s}$$

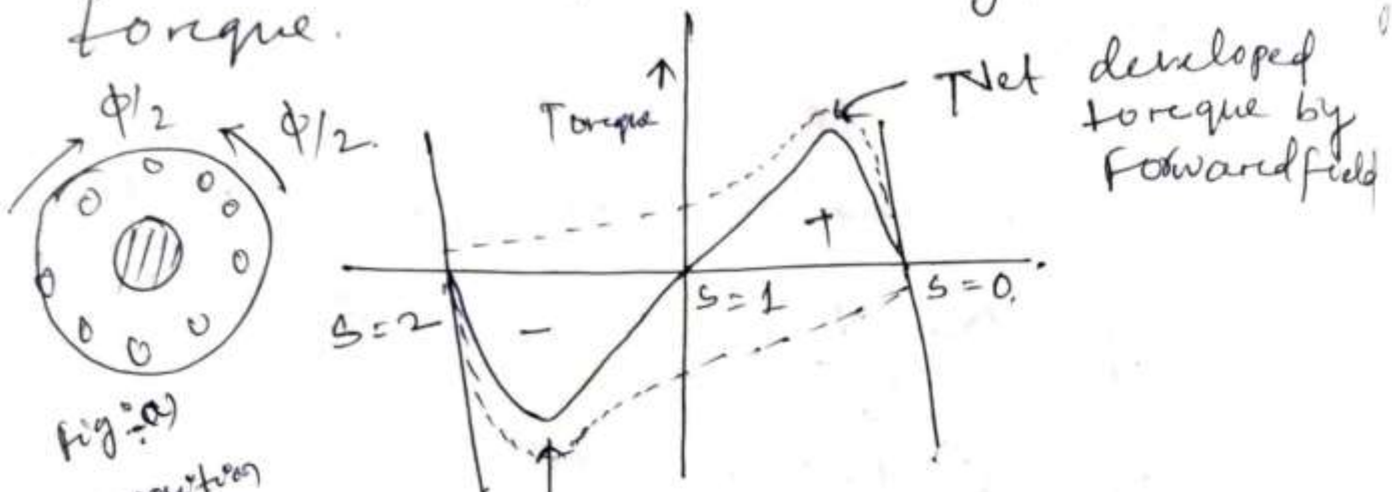
$2-s >> s$ $= 2 - s$ → backward field rotor current is more than that at standstill & have a low power factor.

For low slip i.e. s_F : Induced current is less, than at standstill. & high power factor. Weakening of backward field & strengthening of forward field depends on the slip.

→ The decrease in slip with increase in rotor speed in forward direction.

→ In fact near about N_s, the forward field may be several times the backward field.

→ let us assume that the torque developed by forward field in the direction of rotation is positive. Then the torque developed by the backward field will be negative & evidently, be a breaking torque.



Net developed torque by Forward field

fig:(a) superposition theorem Torque-slip characteristic

Net developed torque by backward field

→ It is noted that curve of the resultant torque passes through zero at a slip of unity or at stand still. Thus showing that no ~~to~~ T_{st} is developed & the motor can't start rotating independently.

* In 1φ IM the increase in rotor resistance increases the effectiveness of the backward field, which reduces the breakdown torque, lowers η & increases slip corresponding to maxm Torque.

* Frame size of 1φ IM is more due to presence of backward rotating field.

→ 1φ IM has lower breakdown torque at larger slip & increased power losses

→ It has greater power input because of their consumption in backward rotating field. Copper loss is more because all the current flows through a single winding. so temp? rise increased.

* p.f of 1φ IM tends to be lower - so it has larger frame size as compare to 3φ IM.

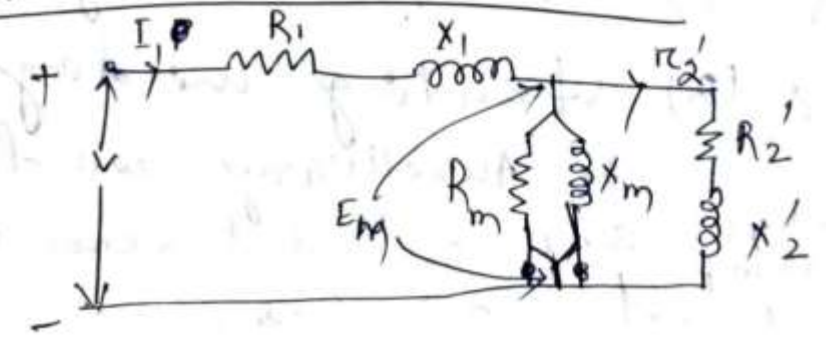
→ 1φ IM creates second harmonic pulsating torques with zero average ~~which have such~~ so it is more noisier than 3φ IM.

Cross-Field theory

→ stator mmf wave is stationary

→ stator field strength alternating in polarity & varying sinusoidally with time.

Equivalent circuit.



$S_1 = \frac{4-2}{4}$
$= \frac{2}{4}$

$S_2 = \frac{4-3}{4} = \frac{1}{4}$

$\boxed{S_1 > S_2}$

* Flemming's Left hand rule used ~~for~~ to find the direction of magnetic fo.. acting in an electric motors.

* Flemmings ~~=~~ left hand rule used to find the direction of induced current in an electric generators.

<u>1ϕ IMs</u> → Fans, refrigerators, vacuum cleaners, washing machines, Kitchen equipm.. tools, blowers, centrifugal pumps, small farming appliances etc.

→ 1ϕ IMS = Not more than 0.5 kW = 0.5 × 1000 wat.. = 500 watt

* Hence to produce the rotating magn.. field for self starting, phase splitt.. is to be done to make the motor to work as a 2 phase motor for starting.

Working of split phase motor:

→ In split phase motor 2 windings are used (1) Main winding / Running wind.. & (2) Starting winding or Auxilliary winding

→ These windings are connected across the sup.. to produce rmf.

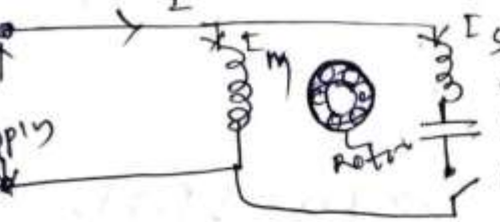
→ They are placed 90° electrical apart from each other.

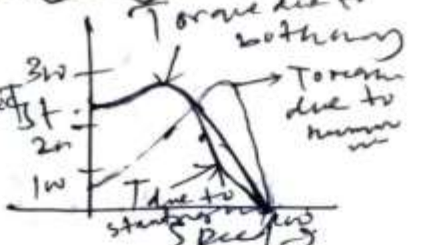
→ here rotor is squirrel cage type of rotor

→ Once the rotor starts rotating, the starting winding can be disconnected from the supply by some mechanical means as the rotor & stator fields form revolving magnetic field.

1) Capacitor start Induction run motor:-

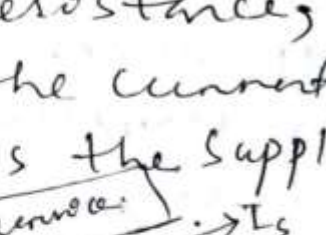
→ W_{st} has more no. of turns & heavier wire than the W_{st} of resistance start motor





The 2 windings are placed 90° electrical apart, ~~so that~~ depending upon its inductance & resistance, at the time of starting the current in the main winding lags the supply voltage by 90°.

Short duty service



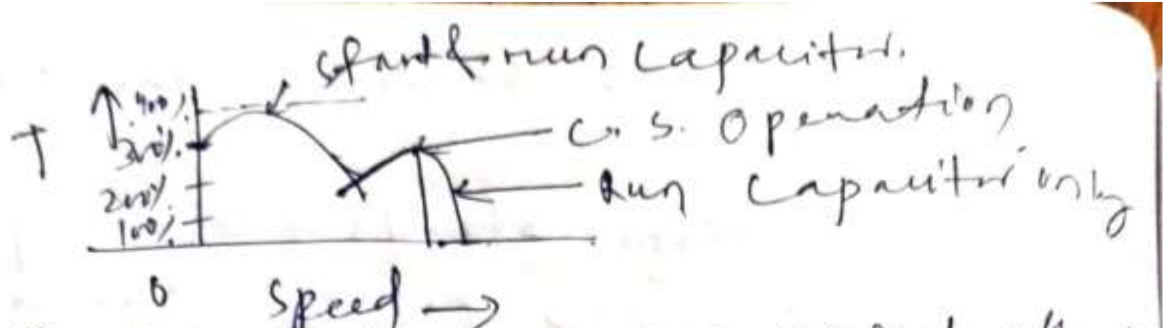
→ Application → used in belted fans.

→ $\frac{1}{10}$ kw to $\frac{3}{4}$ kw → 〃 blowers dryers. washing machines pumps & compressor.

CSIR Im :- less effi η & can't take overloads.

Larger capacitor (short duty) electrolytic

Smaller capacitor (continuous duty) oil filled



→ Here starting winding remain energized after the one capacitor or not.

* T_{st} = 300% of T_{FL}

→ I_{st} = 2 to 3 times the I_{run}

→ can be loaded up to 125% of the full load capacity.

→ Noise less operatn

Application

compressors, refrigerators, air conditioners,

Principle phase split :-

→ If however, an impedance (R, L or C) is connected in series with one of these windings, the currents may be made to differ in ~~p~~ time phase around 90°. thereby producing a rotating field. very much like the field of a two phase motor.

→ split phase motors are of following type

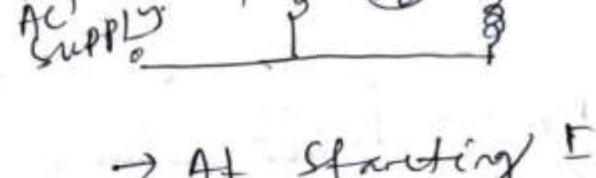
(1) Resistance start motor
(2) Capacitor - start motor.
(3) Permanent capacitor or ~~1φ~~ single value capacitor motor

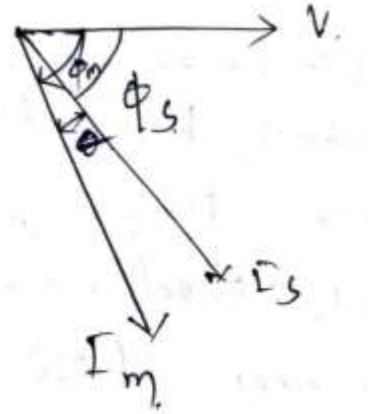
4 (4) Capacitor start capacitor run motor.

× shaded pole I.M.

Resistance start 1ϕ Induction Motor:

→ High resistance connected in series with the starting winding starting only disconnected by means of C.S as the motor picks up speed.





→ At starting I_m lags behind the applied voltage V by 65°–75°.

~~A~~ I_s lags V by 35° to 45°.

→ So the phase displacement betⁿ I_m & I_s is about 20 to 30°. This will result imperfect 2ϕ motor that produces a rotating magnetic field i.e. not uniform but sufficient for starting the motor.

→ best starting condⁿ is where I_m & I_s differ by 90° but this condⁿ is not satisfied in the motor of this type.

→ Here $T_{st} = 1.5$ to $2 \times T_{Full\,Load}$.

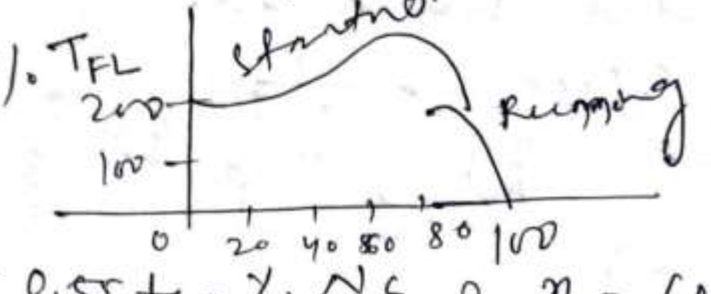
→ I_{st} = 6 to 8 times the I_{FL}

→ Speed Regulation is very good.

→ slip is about 4 to 6%.

→ $\frac{1}{20}$ to $\frac{1}{4}$ kW ~~m~~ ratings & speed ranging from 2875 to 700 rpm

0.05 kW to 0.25 kW



→ operating P.f 0.55 to 0.65 % N_s & η = 60-65%

Application $\longrightarrow$ washing machines, Fans, blowers, Centrifugal pumps, domestic refrigerators, food processing machines, wood working tools, grinders, oil burners, low inertia loads, continuous operating loads.

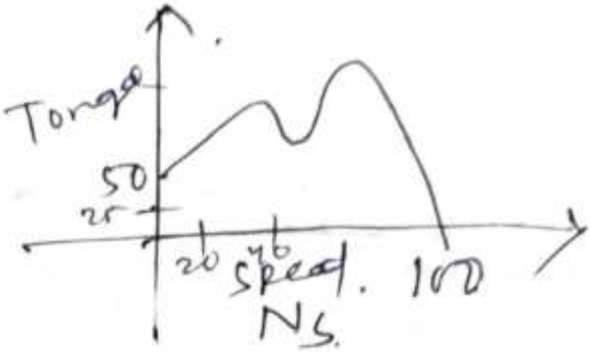
→ It has low starting torque.

Shaded pole IM :- Shading coils are used. 5W to 100-150W.

→ Poor starting torque, Low p.f & η = Poor.

→ Low power applications like toys, hair dryers, tone phonographs, Slide projectors, humidifiers, photo copying machines, advertising displays.

→ Then direc? of rotat? of such a m/c can't be reveresed.

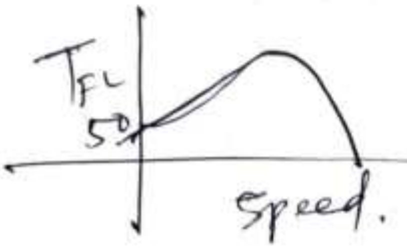


→ η is 20 to 50%.

→ P.F = 0.5 to 0.6

→ slip = 10 to 25%.

Permanent → oil type capacitor.



Application

Ceiling Fans, blowers, oil burners, room coolers, where low Tst is requird.

→ Permanent capacitor 1ϕ IM, also sometimes called the single value capacitor run motor.

→ It has two stator windings
(1) Main winding
& (2) Auxilliary winding or starting winding

* here oil capacitors are to be used.
* capacitor range 2-20μF.

* here both the windings have same no. of turns.

→ No. centrifugal switch is there. Starting winding is energized at all times when the motor is in operation so the operation of the motor when loaded resembles more closely to that of a 2phase motor. The mmf produced by 2 stator windings is more nearly uniform so it has Quieter in operation.

→ It has increased Pull out Torque.

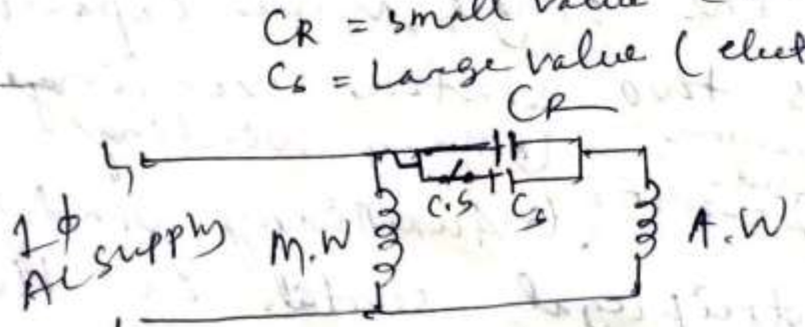
→ High P.F (0.8 to 0.95).

→ η = 55 to 65%.

Reversal of direction of split phase Induction Motor : The direction of rotation of a split phase Induction motor can be reversed simply by reversing the line connections of either the main winding or the auxilliary winding. Reversal of split phase IM takes place only when it is at rest & the starting switch is in its NC deenergized position. If reversal is attempted under normal operating cond.ⁿ nothing will happen because under normal operating condition the starting switch is ~~st~~ open position & the motor is running as a pure 1φ IM & developing torque in the direction of rotation.

C.S.C.R

C_R = small value (oil filled)
C_S = Large value (electrolytic)



here $C_R \parallel C_S$ so $C_{eq} = C_1 + C_2$

→ In practical C_S is about 10-15 times large as the running capacitor.

→ better η = 55-65%

→ P.F = 0.8 to 0.95

→ when motor attains 75% of N_S C_S is taken out by C. Switch

Methods of starting of 1ϕ IM :

(1) split phase starting
(2) Repulsion starting
& (3) shaded pole starting

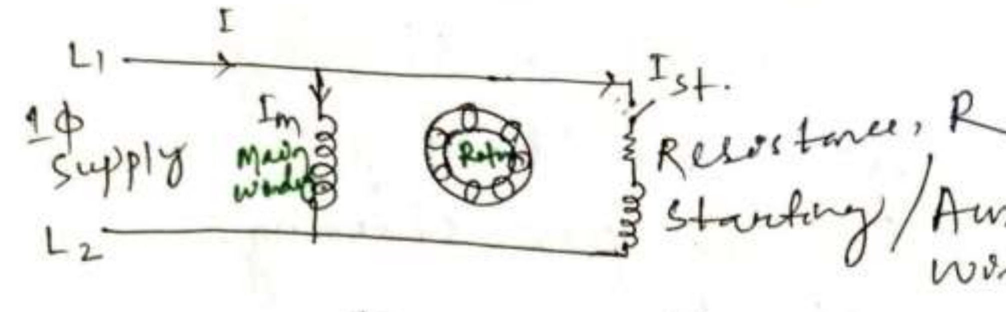
Split phase starting :

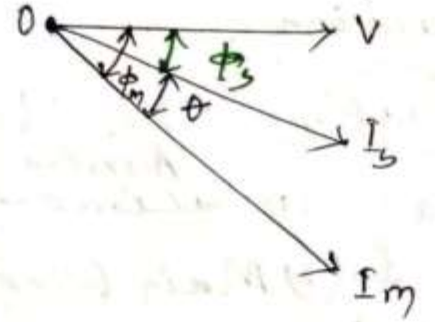
Working principle : The stator has two windings such as (1) Auxilliary / starting winding & (2) Main Winding / Running winding

→ These two windings are spaced 90° electrical degrees apart on the stator of the motor since they are excited by two alternating emfs that are 90° displaced in time phase a rotating magnetic field is produced very much like ~~the~~ field of a two phase motor. This is the principle of phase splitting & the 1ϕ IM employing this principle for starting are known as split phase motors. Split phase motors are of the following types.

(a) Resistance start motor or simply split phase motor
(b) Capacitor - start motor
(c) Permanent capacitor or single value capacitor motor
& (d) Capacitor start - capacitor run or two value capacitor motor.

Resistance start 1ϕ IM :-





→ Here two windings, Main winding & Starting are placed on the stator. A high resistance is connected in series with the starting winding.

→ Because of low resistance & high Inductive reactance of main winding and high resistance & low Inductive reactance of starting winding the starting winding current I_s does not lag so much as the main winding current (I_m)

→ At starting, Im lags behind 'V' by 65-75°, where I_s lags behind V by 35°-45°. so angle bet^n I_m & I_s is 20°-30°. as shown in Figure.

→ Here the rmf produced is not uniform in either time or space, but is sufficient for starting the motor.

→ The best starting cond^n is when θ bet^n I_m & I_s is 90°, which not possible in this type of motor

→ Here starting torque, (T_s) = 1.5 times or twice of Full load starting

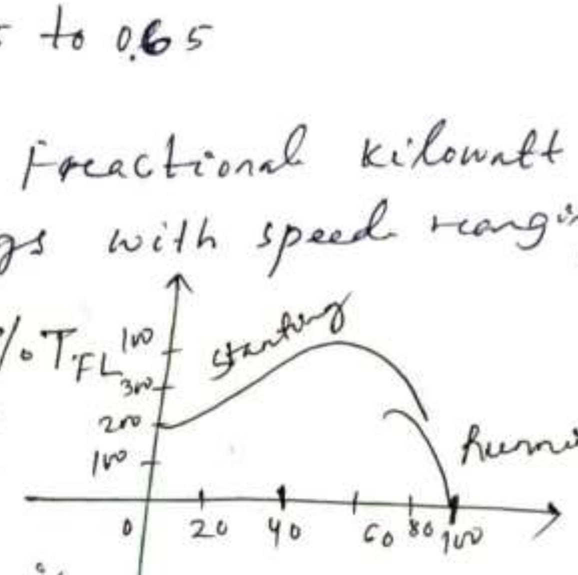
→ Speed regulation is very good.

→ slip = 4 to 6%.

→ Operating P.F = 0.55 to 0.65

→ η = 60-65%.

→ Motors are made in fractional kilowatt ($\frac{1}{20}$ to $\frac{1}{4}$ kw) ratings with speed ranging from 2875 to 700 rpm.

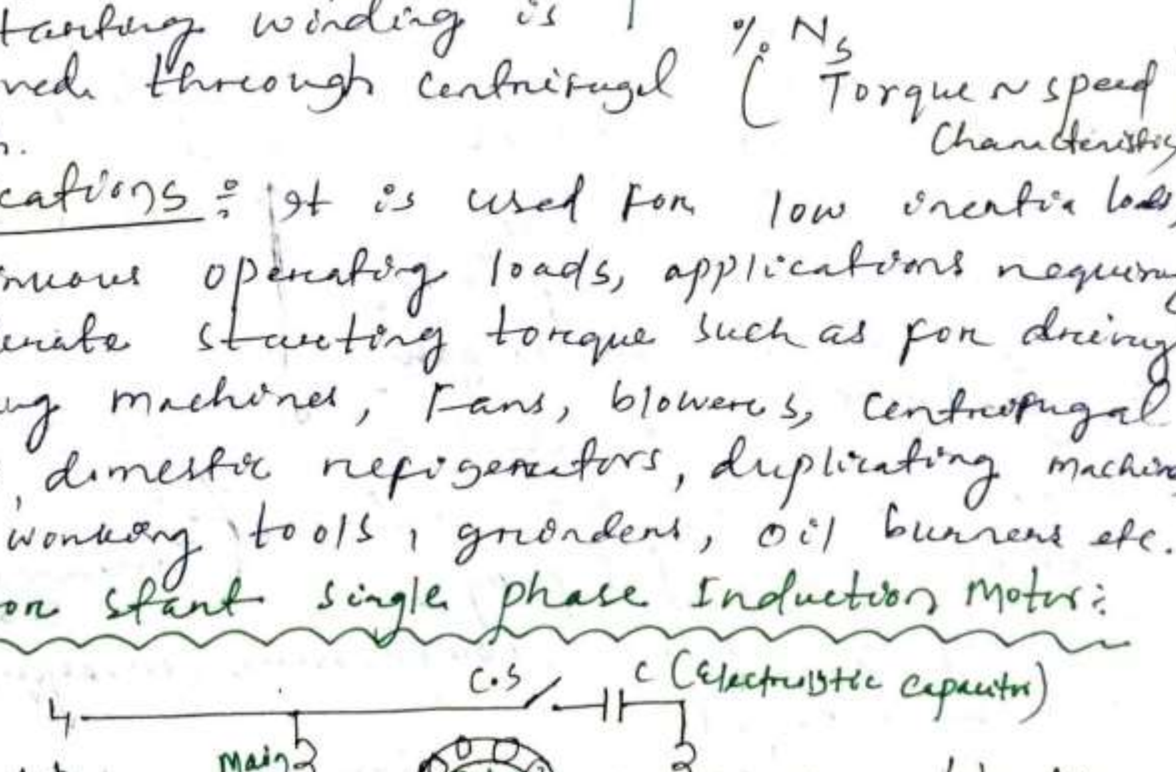


→ After the motor picks up the speed around 75% of rated speed the starting winding is removed through centrifugal switch.

(Torque ~ speed Characteristic)

Applications: It is used for low inertia loads, continuous operating loads, applications requiring moderate starting torque such as for driving washing machines, fans, blowers, centrifugal pumps, domestic refrigerators, duplicating machines, wood working tools, grinders, oil burners etc.

Capacitor start single phase Induction Motor:



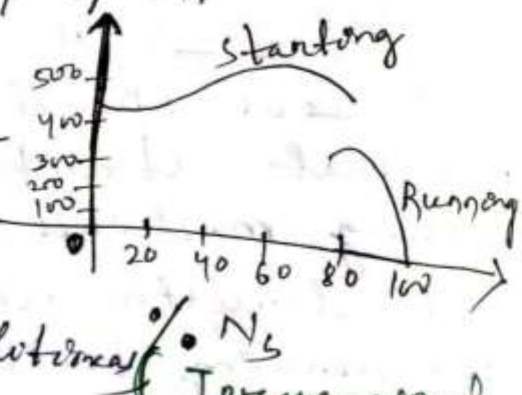
→ It is also known as Capacitor start Induction-run motor

→ Fundamentally this motor is very similar to the resistance start split phase motor except that the starting winding has a few more turns & consists of a heavier wire than the starting winding of a resis. start motor. There is a large electrolytic capacitor in place of resistor, connected in series with the starting winding.

→ The size of capacitor depends upon the rating of the motor & has a value among 50μF to a few hundred μF.

→ The capacitor-start motor, like resistance start motor has the starting winding disconnected by means of a centrifugal switch as the motor picks up speed.

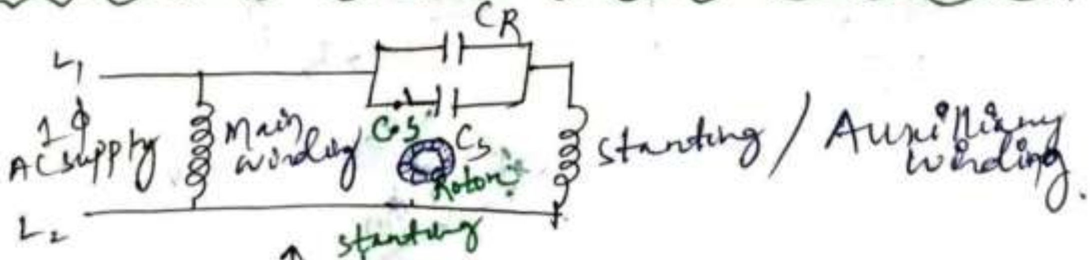
→ capacitor start motors are made in rating ranging from $\frac{1}{10}$ kw to $\frac{3}{4}$ kw

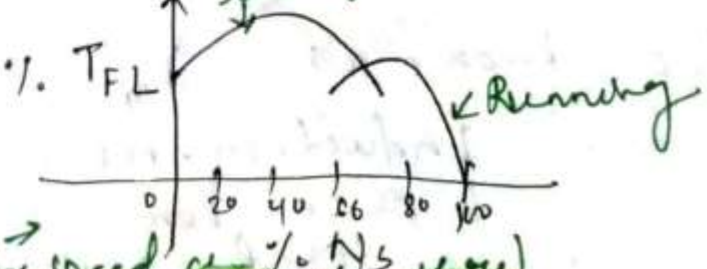


(Torque ~ speed Characteristic)

Applications :- It is used in refrigerators, air-conditioners, compressors, jet pumps, centrifugal pumps, compressors, conveyors, blowers oil burners etc.

Capacitor start-capacitor run 1ϕ IM :-





(Torque ~ speed characteristics)

→ Here except main winding and auxilliary winding 2 capacitors are present. such as

① C_R (Running capacitor):- It has continuous duty. It has small value & oil filled type.

② C_s (Starting capacitor):- It has short duty. It has much larger value & is electrolytic type of capacitor.

→ A centrifugal switch is connected in series with C_s. C_s is parallel with C_R.

→ When the motor attains the 75% of its rated speed (N_s) the capacitor C_s is ~~the~~ taken out of the circuit through the operation of centrifugal switch (CS) which is normally closed.

→ Here the starting winding has capacitance (C_{eq}) = $C_R + C_s$.

→ 'C_S' is about 10 to 15 times large as the C_R.

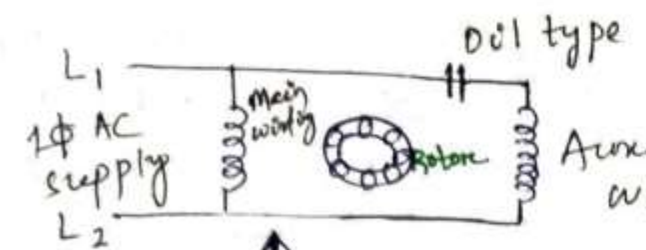
→ This motor has constant torque & not a pulsating torque, they are extremely quiet in operation, have better efficiency (55-65%) & power factor 0.8-0.95.

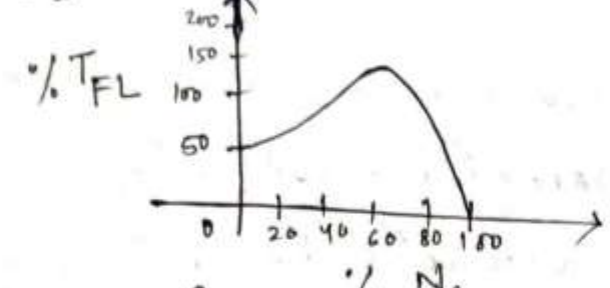
→ The direction of rotation of motor may be reversed by interchanging the connections to the supply of either the main or auxilliary winding

Applications:- Used in compressors, refrigerators, force strokers, pumps, conveyors etc.

→ The disadvantage of such machines is only high cost.

Peremanent Capacitor Single phase IM :-





(Torque ~ speed characteristics)

→ It is also known as single value capacitor-run motor has two stator windings placed mutually 90° apart

→ The main or running winding is connected direct across the supply lines. There is no centrifugal switch.

→ The auxilliary winding in such motors usually has almost the same size of wire & almost as many turns as the main winding, in fact in some motors the two windings are identical

→ Auxilliary winding is always in the motor circuit so the operation of the motor when loaded resembles more closely to that of a 2ϕ motor

→ produced mmf is nearly uniform. so the motor is quieter operation

→ Increased pull out torque.

→ Higher power factor 0.8 – 0.95

→ Higher operation η = 55 to 65%.

→ Smaller full load line current.

→ In this type of motor neither optimum starting nor run performance can be obtained.

Applications :- Ceiling fans, blowers, oil burners room coolers, portable tools other domestic & commercial electrical appliances, where low starting torque is required

Shaded pole Induction Motor:

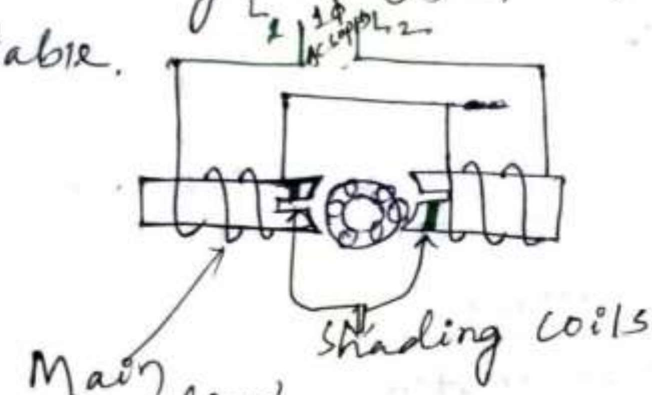
→ Shaded pole motor is a split phase type IM

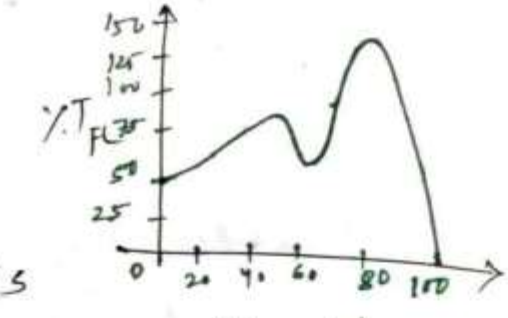
→ The stator has salient poles each provided with its own exciting coil. A part (about $\frac{1}{4}$ to $\frac{1}{3}$) of each pole is wrapped by a copper strap forming a closed loop, known as a shading coil.

→ T_{st} = 40% to 80% of T_{FL}

→ Pull out torque about 110 to 140 of T_{FL}

→ It has no commutator, brushes, collector rings, contactors, capacitors or moving switch parts, so it is relatively cheaper, simpler & extremely rugged in construction & reliable.





(Torque ~ slip)

→ T_{st} is very small about 40 to 80% of T_{FL}.

→ Poor efficiency, i.e η = 20 to 50%.

→ Poor p.f ranging from 0.5 to 0.6.

→ Speed falls with the decrease in applied voltage.

→ The direction of rotation of motor depends upon position of the shading coil i.e from unshaded region to shaded region.

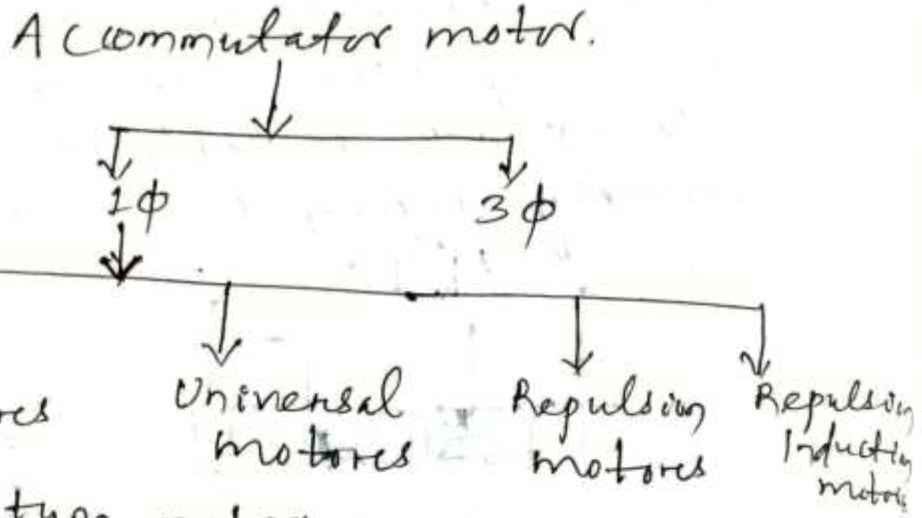
Applications: Low power applications like toys, small fans, electric clocks, hair dryers, time phonographs, slide projectors, humidifiers, advertising displays, photo copying machines,

Commutator Motores :-

→ AC commutator motors have been devely on an attempt to provide improved starting torque, good power factor & better speed control.

→ AC commutator motor is of 2 types. such as (1) 1φ & (2) 3φ machines.

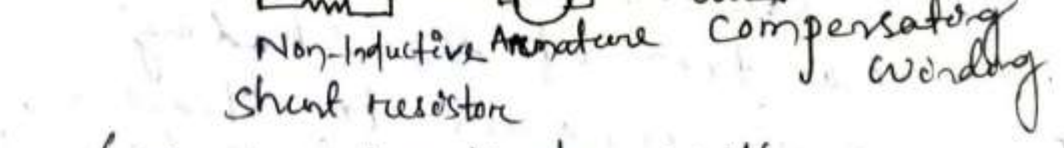
→



Repulsion type motors :-

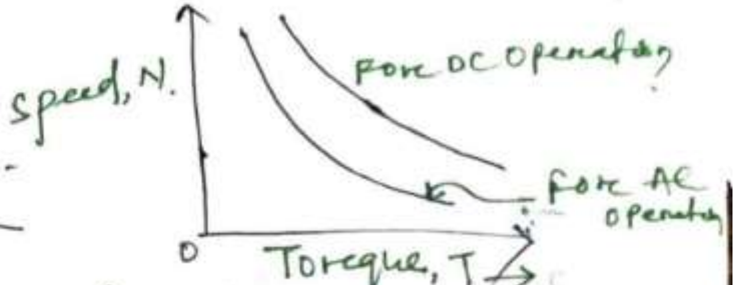
- → Repulsion motor
- → Repulsion start Induction run motor
- & → Repulsion Induction motor.

AC Series Motor :-



(AC series motor with Interpoles & compensating winding

→ AC Series motor is also known as DC series motor as their construction is very similar to that of DC series motore



(Torque speed Characteristics)

→ When AC supply is given to the dc series motor followings will happen such as

(1) An AC supply will produce an unidirectional torque because the direction of both the currents (i.e armature current & Field current) reverses at the same time.

(2) Due to presence of alternating current eddy currents are induced in the yoke & field cores which results in excessive heating of the yoke & field cores.

(3) Due to high inductance of the field and the armature circuit, the power factor would become very low.

& (4) There is sparking at the brushes of the DC series motor.

→ So considering the above points we can say that we don't have good performance of DC series motor on the application of AC supply.

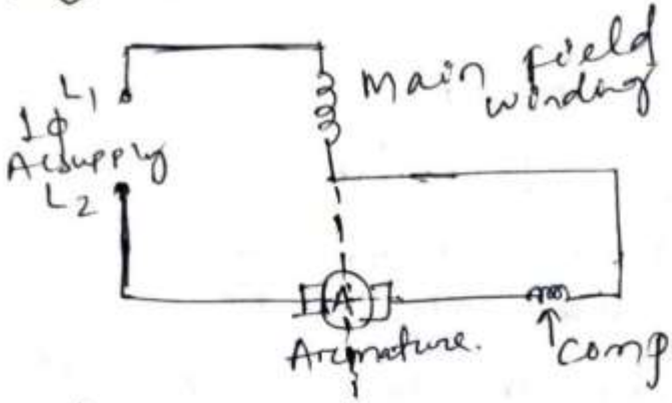
→ In order to reduce eddy currents there is need to laminate the yoke & field core.

→ Compensating winding is used to reduce Field winding reactance.

→ On the basis of usage of compensating winding we have 2 types of motor. Such as

1. conductively compensated type of Motor
2. Inductively compensated type of motors

1 Conductively compensated type of motor or series motore:



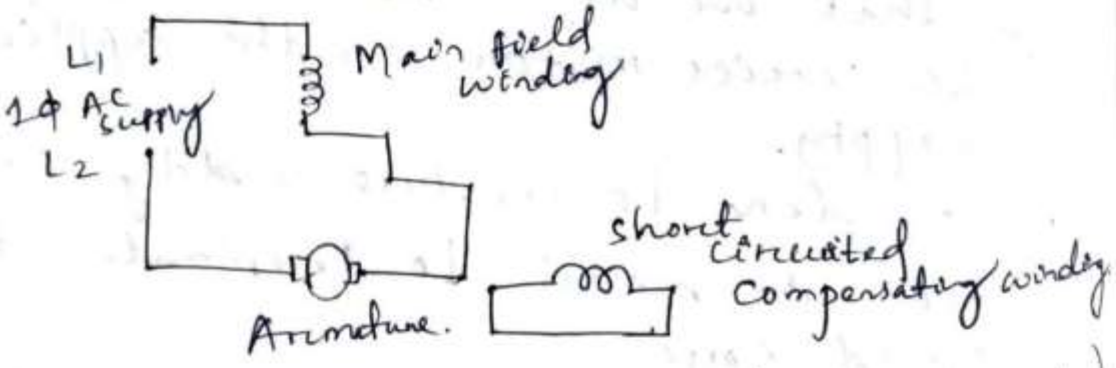
(Conductively compensated series motor)

→ In this type of motores the compensating winding is connected in series with the armature circuit.

→ The winding is put on the stator slots.

→ The axis of the compensating winding is 90° (electrical) with main field axis

2. Inductively compensated series motor.



(Inductively compensated series motor)

→ In this type of motor, the compensating winding has no interconnection with the armature circuit of the motor. In this case transformer action will take place as the armature winding will act as primary winding of T/F & the compensating winding will acts as a secondary winding.

→ The current in the compensating winding will be in phase opposition to the current in the armature winding.

→ The main function of Interpole in AC 1ϕ series motor is to improve the performance of the motor in terms of higher efficiency & a greater output from the given size of the armature core.

→ The interpole winding of ~~the~~ is connected in parallel with the non-inductive shunt resistor.

Applications: The torque speed characteristic of the 1ϕ series motor is similar to that of dc series motor i.e high starting torque & decrease in speed with increase in load, making in to have self relieving property from heavy excessive load, so ~~m~~ such a machine is particularly useful for traction services.

Repulsion type motors: In AC series motors the rotor & the stator windings are conductively coupled i.e rotor current is obtained by conduction from the stator

→ Repulsion motors are similar to series motors except that the rotor & the stator windings are inductively coupled i.e the rotor current is obtained by transformer action from the stator.

→ There are various types of repulsion motor each employing the repulsion principle for starting.

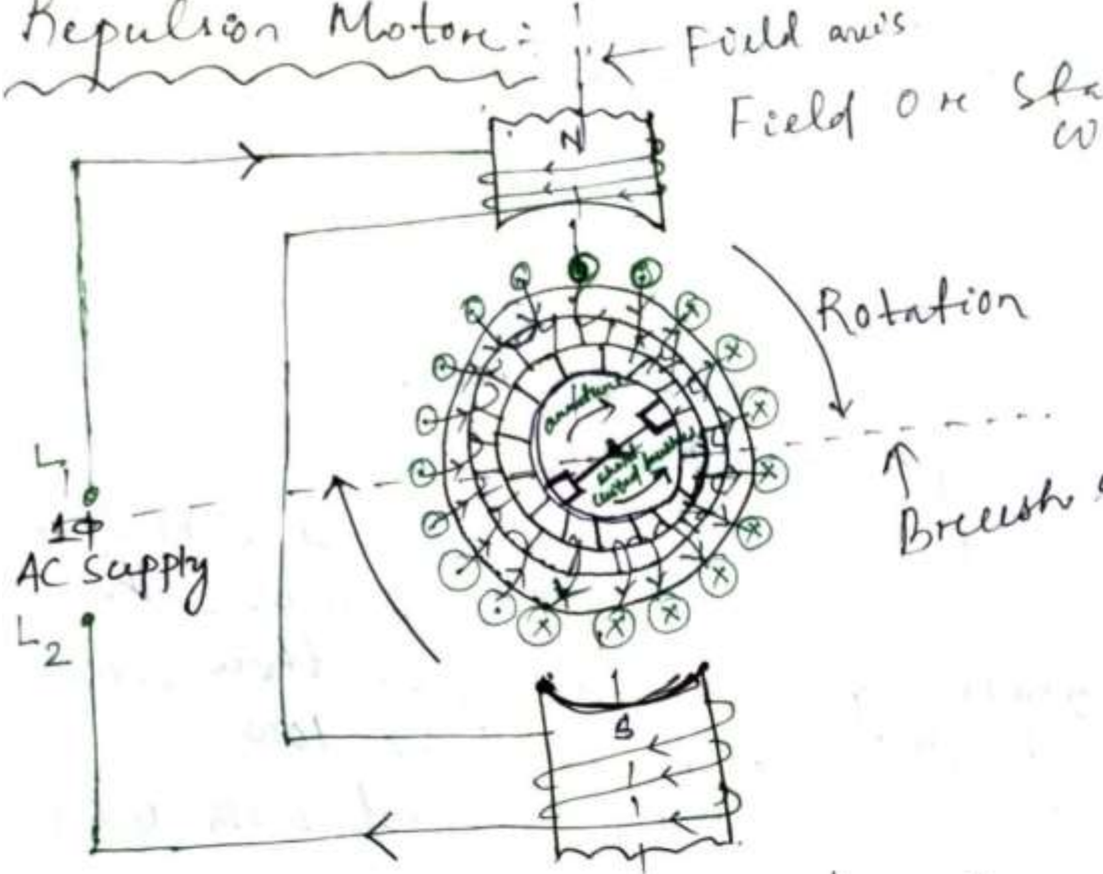
→ Repulsion motors include repulsion motor which starts & runs on the principle of magnetic repulsion

→ Repulsion - start induction - run motor which starts on the repulsion principle but at a predetermined speed operates as a 1ϕ IM.

→ Repulsion induction motor, which employs the repulsion start principle but has an additional armature winding that provides additional running torque.

→ Though the 3 types of motors, mentioned above, have similarity in names but they are different in construction, in operating characteristics, & in their application to the industrial uses.

Repulsion Motor:



(Diagram of a Repulsion motor)

* Reversal of direction of rotation of any series wound motor can be reversed by reversing the direction of the current flow in either the field or armature ckt but not through both. Universal motors are sensitive to brush position & severe arcing at the brushes occur if the direction of rotation is reversed without shifting the brushes to the neutral plane. This is the reason that the universal motors are usually wound for operation in only one direction.

Construction of Repulsion motor: Practically all repulsion motors are made with non-salient poles. The stator or field windings used are usually of the distributed type & similar to the main or running winding of a split phase, 1φ IM.

→ Non salient poles & semi closed slots & to make the air gap as small as possible, otherwise the magnetising currents for these fields will be high & p.f will be low.

→ The stator is usually wound with 4, 6 or 8 poles.

→ The stator winding is connected to the 1φ AC supply & develops the main field.

→ The rotor or armature is similar to a dc motor armature, with a drum type winding (either lap or wave type) connected to the commutator.

→ The commutator is of axial type with segments or bars parallel to the armature shaft.

→ There are 2 cast steel end shields that house the motor bearings which are secured to the motor frame.

→ Carbon brushes, in contact with commutator surface are held in place by a brush holder assembly mounted on one of the end shields.

→ The brushes are directly opposite to each other & short circuited.

→ The fact is that a repulsion motor develops a torque in the direction in which the brushes are shifted from the field axis.

→ The torque developed by a repulsion motor should be max^m, theoretically, when the space angle bet^n the pole axis & brush axis, α is 45° but in practice the angle of inclination 'α' is about 15-25 electrical degrees.

Characteristics:- The repulsion motor has high starting torque (about 3-5 times full load torque) & moderate starting current (about 3-4 times full load current) but poor speed regulation. Shifting the brushes during operation gives a wide range of speed control, as high as 6:1 ratio & yet provides a continuous variation. The upper speed is not limited by frequency. The motor is a reversing type, & the direction may be changed during rotation

Disadvantages:- The drawbacks of repulsion motor are

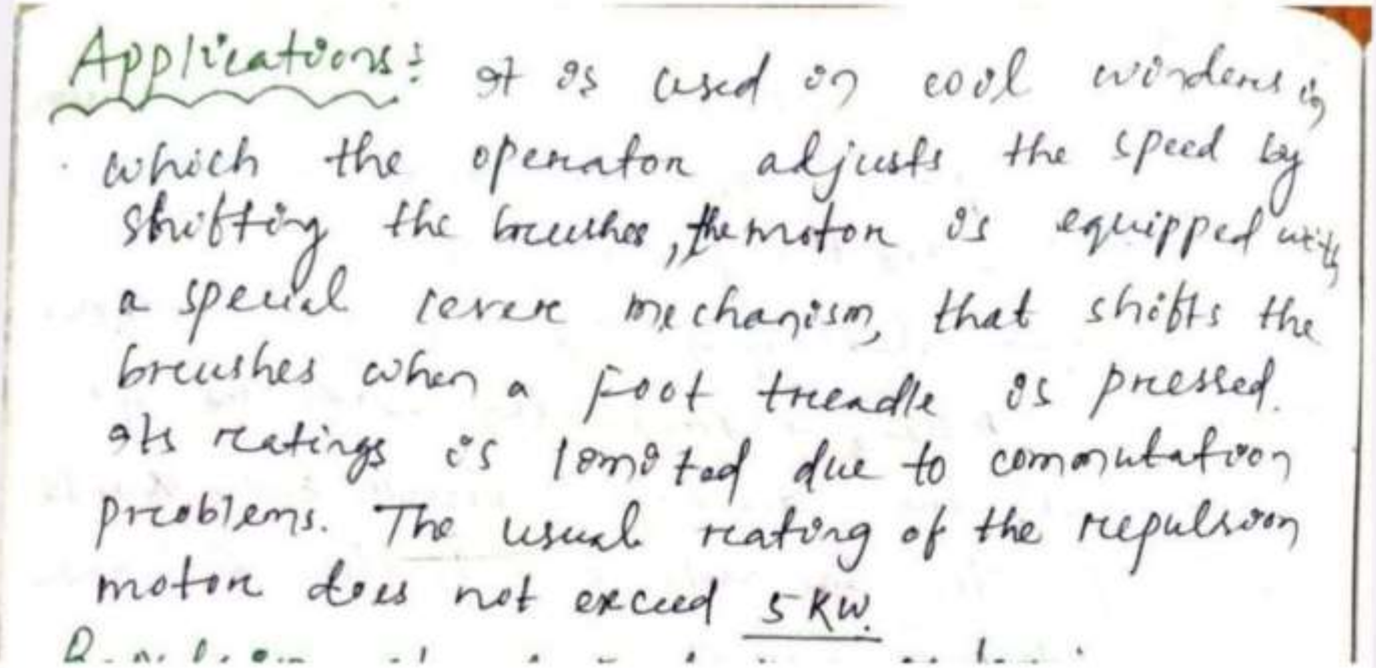
(i) Speed variations with the variations in loads dangerously high at no load.

(ii) Low power factor except at high speeds

(iii) Tendency to spark at the brushes_ sparking at the brushes is negligible at the rated speed which usually occurs near N_s.

(iv) Higher cost

(v) More attention & Maintenance is required.



Applications: It is used in coil winders in which the operator adjusts the speed by shifting the brushes, the motor is equipped with a special lever mechanism, that shifts the brushes when a foot treadle is pressed. Its ratings is limited due to commutation problems. The usual rating of the repulsion motor does not exceed 5 KW.

Special electrical machine

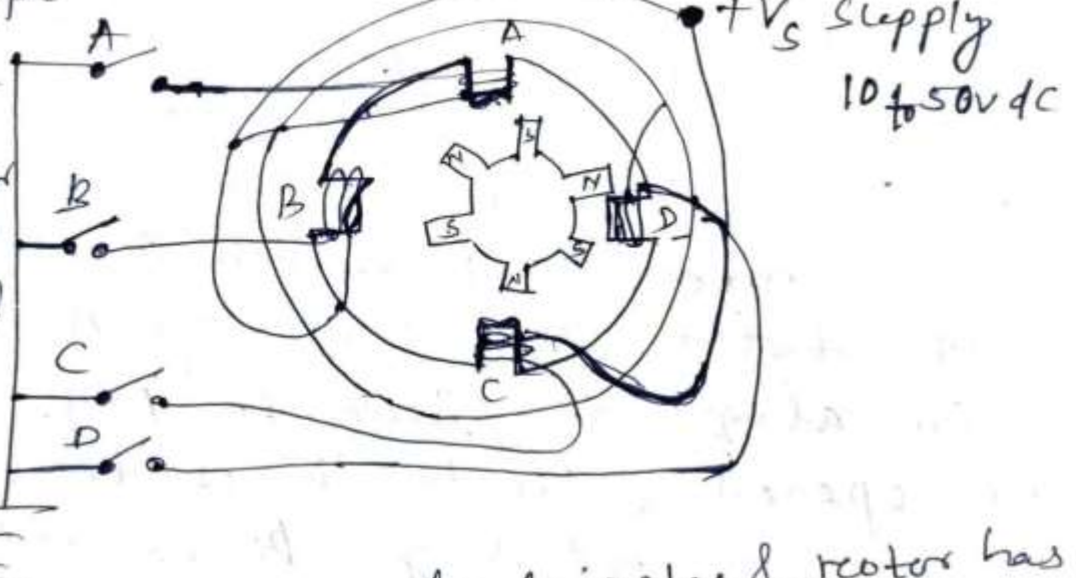
÷ Stepper Motor ÷

- Permanent Magnet stepper motor.
- Variable reluctance Stepper Motor.
- Hybrid Stepper motor.

1. Peremanent Magnet stepper Motor:

→ The representative structure of a permanent magnet type

* Permanent magnet Stepper motor is used upto $\alpha = 60°$ & max^{m} rates of 300 pulses per second.



→ Stator has 4 salient poles & rotor has 6 non-salient poles producing a full step angle of 30° as shown in fig.

→ The end terminals of all the windings are brought out to the terminal box for dc excitations.

→ The rotor of such a motor has even no. of poles made of high retentivity steel Alloy (Alnico).

→ Both rotor & stator may are salient or non-salient pole construction. Usually the stepping motors having small stepping angles are of non-salient pole construction.

→ The stator pole windings are arranged in such a way that closure of any winding control switch causes that windings pole to become magnetically north.

→ If the 6 pole rotor is paremanently magnetized as shown in figure & if only a single stator winding is energized at one time, then the rotor will always orient so that the nearest rotor south pole is aligned with the energized stator pole.

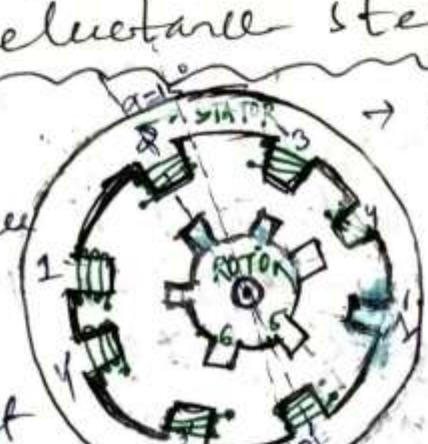
→ For instance if switch 'A' is closed, energizing stator pole winding A, the rotor will align as shown in fig. If switch 'A' is opened & switch 'B' is then closed, so that only winding 'B' is energized, the rotor will step 30° clockwise. This step will incure due to the tendency of the south pole nearest the winding B to align with the north stator pole. Similarly switch 'C' & switch 'D' are closed one at a time

→ It is seen that when the switching sequence ABCD is repeated continuously, the rotor shaft will continue to turn clockwise one 30° step per switch closure. If the switching sequence is reversed to ADCB, the rotor shaft would turn in opposite i.e. counter clockwise direction. Many stepping motor designs allow the selection of full steps or half steps. This is accomplished by altering the switching sequence to simultaneously energize two stator coils during every second timing interval. Simultaneous energization of 2 stator windings creates the effects of moving the stators magnetic north to a position betⁿ the two poles.

→ In reality, stator windings switching is accomplished by transistors rather than mechanical switching.

→ A typical stepper motor needs 1 to 10A of winding current in order to develop its rated torque. Therefore the switching transistors must be high power devices.

2. Variable - Reluctance stepper motor:



→ Here the 'α' is small

→ The Stator of variable reluctance Stepper motor is similar that of Permanent magnet Stepper motor.

→ It has no permanent magnet rotor & the rotor used is a ferro-magnetic multitoothed one.

→ The torque is developed due to large difference in magnetic reluctance that exist betⁿ the direct & quadrature axes. The stationary field developed by the direct current in some stator coil tends to develop a torque which causes the rotor to move to the position where the reluctance of the flux path is minimum.

→ A 4Φ, 8 stator pole, 6 tooth rotor,

$$\boxed{\text{Step angle}(\alpha) = \frac{360^\circ}{\underset{(n)}{\text{no. of phases}} \times \underset{(p)}{\text{no. of rotor tooth}}}}$$

$$\Rightarrow \alpha = \frac{360}{4 \times 6} = 15^\circ$$

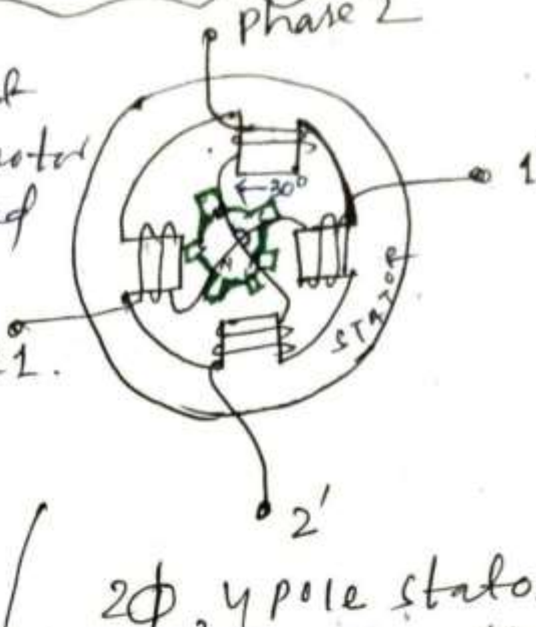
→ When the phase 1-1' is energized, keeping other coils unexcited, the rotor aligns as shown in the figure. If now the phase 1-1' is switched off & phase 2-2' is switched on to develop north pole at coil 2 & South pole at coil 2', a reluctance torque is produced to align the axes of rotor poles 2-5 with the axis of stator poles of phase 2-2'.

→ The rotor advances 15° counter-clockwise. Successive excitation of phases 3, 4, 1' yields a total advance of 60° i.e on rotor pole pitch.

→ 6 times repetation of this switching sequence completes one revolution of the shaft.

→ Rotor can be made to rotate in clock direction by reversing the switching sequ i.e in sequence 1, 4', 3', 2', 1'.

3. Hybrid stepper Motor :-



→ It is a permanent magnet stepper motor with a multi toothed rotor cased in a variable reluctance stepper motor.

→ Here according to the above figure

$\alpha = \frac{360}{2\times6} = 30^\circ$

(2Φ, 4 pole stator, 6 tooth rotor Hybrid stepper motor)

→ When phase 1-1' is switched on keeping phase 2-2' unexcited, the rotor aligns as shown in fig.

→ If now the phase 1-1' is switched off & phase 2-2' is closed such that lower pole becomes south pole & upper pole becomes North, this would cause rotor to turn in counter clockwise direction by 30° & the rotor will get locked on to the new position

→ The rotor will turn in opposite i.e clockwise direction if the phase 2-2' were oppositely excited.

→ The main advantage of the hybrid motor is that if the stator excitation is removed, the rotor continues to remain locked on to the same position, as before removal of excitation.

→ This is due to the reason that the rotor is prevented to move in either direction by the torque because of the permanent magnet excitation.

→ The hybrid type stepper motor is used in applications where stepping angle is small (e.g: 1.5°, 2.5°)

Applications of Stepper Motor:

→ The stepper motor is essentially a position control device & has following advantages.

1. The angular displacement can be precisely controlled without any feedback arrangement.
2. It can be readily interface with micro-processor/ computer based controller.

→ It is used in paper feed motors in typewriters & teleprinters, positioning of print heads, pens in X-Y graphical plotters, recording heads in computer disk drives etc.

Q.1 calculated the stepping angle for a 3 stack, 16-tooth variable reluctance motor.

Ans: No. of stacks or phases, $n = 3$

No. of teeth or poles, $p = 16$

$$\text{Stepping angle, } \alpha = \frac{360}{np} = \frac{360}{3 \times 16} = 7.5^\circ \text{ (Ans)}$$

: Synchronous Motor :

→ The essential parts of a 3ϕ synchronous motor are (i) Laminated stator core with 3ϕ armature winding
(ii) Rotating field structure complete with damper winding & slip rings
(iii) Brushes & brush holders
& (iv) Two end shields to house the bearings that support the rotor shaft.

→ The stator core & windings of synchronous motor are similar to those of 3phase Alternator.

→ The rotor of synchronous motor has salient field poles connected to give alternate polarity.

→ Hence the no. of rotor field poles must be the same as that of stator field poles.

→ The field circuit leads are brought out to 2 slip rings mounted on the shaft.

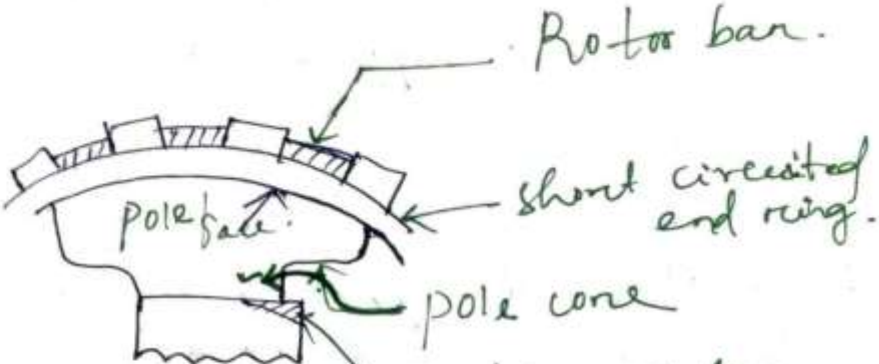
→ Carbon brushes are mounted in brush holders make contact with the two slip rings.

→ The terminals of the field circuit are brought out from the brush holders to a second terminal box mounted on the motor frame.

→ In addition to the exciting winding, a synchronous motor often is provided with a squirrel cage winding on rotor.

→ The slots of this winding are on the pole faces & are parallel to the shaft.

→ The ends of the copper or bronze bars embedded in the slots are short circuited at both ends by conducting rings. This short circuited winding on the rotor is known as the cage winding, the damper winding, the amortisseur winding or sometimes starting winding.



(Rotor pole)

Principle of Operation :-

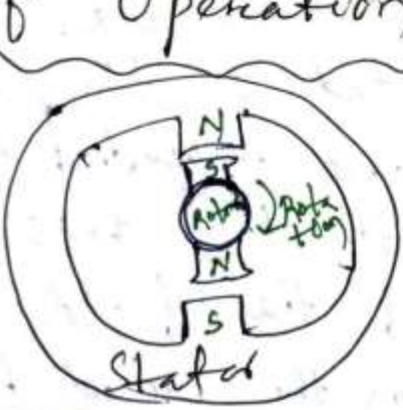


Fig. (a)

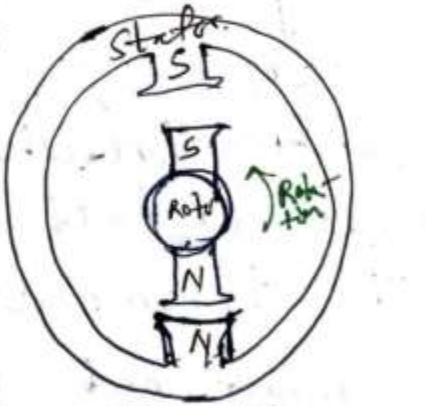
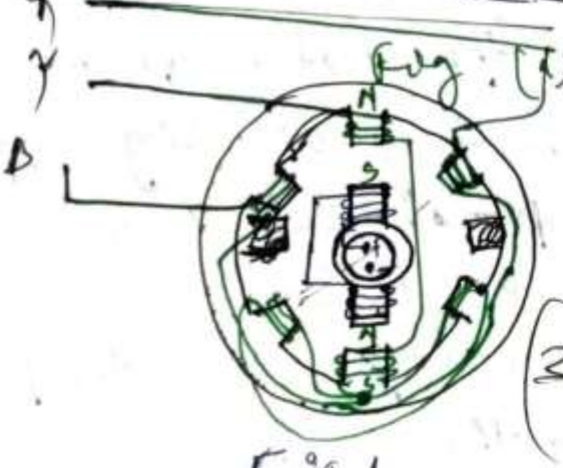


Fig. (b)



(3φ, 2 pole, synchronous motor)

Fig.1

In the above figures, the rotor has 2 poles & the stator has 2 poles per phase.

→ In practice it has salient poles on the rotor but the armature winding is housed in slots in the concave periphery of the stator.

→ As the rotor is excited from dc supply so the poles of the rotor retain the same polarity throughout but the polarity of the stator poles changes as it is connected to an ac supply.

→ First let us consider the rotor as stationary & in the position shown in fig1. At this instant the rotor S-pole is attracted to the stator N-pole & therefore, the rotor tends to rotate in clockwise direcⁿ

→ After half of a period (after $T/2$ second where $T = \frac{1}{F}$) the polarity of stator poles is reversed but the polarity of the rotor pole remains same as shown in fig b.

→ At this instant the rotor S pole is repelled by the stator S-pole, being similar in nature & therefore rotor tends to rotate in counter clockwise direction.

→ Thus the torque acting on the rotor of a synchronous motor is not unidirectional but pulsating one & due to inertia of the rotor it will not move in any direction. So the synchronous motor has <u>got no self starting torque.</u>

→ Now let's consider the rotor is rotating in clockwise direction by external means & in the position as shown in fig. a.

→ As mentioned above the rotor "S" pole is attracted to stator N-pole & so the torque acts on the rotor in clockwise direction.

→ After a half period of the one cycle, the stator polarity is reversed i.e stator S-pole becomes N-pole & N-pole becomes S-pole but if the rotor is rotated at such a speed by some external means at the starting moment the rotor S pole advances by a pole pitch so that it again under the influence of stator N-poles as shown in Fig.C, the torque acting on the rotor will be again clockwise. Hence a continuous (Unidirectional) torque will be obtained.

→ Now if the external means is removed the rotor will continue to rotate in clockwise direction (Fig.C) under the influence of clockwise continuous torque acting on the rotor.

→ Hence to obtain a continuous torque it is necessary that the rotor rotates at such a speed that it moves through the distance equal to pole pitch in half the period i.e in $T/2$ or $\frac{1}{2f}$ second where 'f' is the supply frequency.

→ If there are 'p' no. of poles then to complete one revolution it should take $\frac{P}{2f}$ second or the rotor should rotate at a speed of $\frac{2f}{p} \times 60$ revolutions per minute.

» Hence to obtain a continuous torque the rotor should rotate at synchronous speed given by the expression,

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

* 1 revolution = $\frac{P}{2F}$ second

⇛ In one second = $\frac{2F}{P}$ revolution
⇒ 60 minute = $\frac{2F}{P} \times 60$ revolutions.

Effect of load on a Synchronous Motor:

→ In the case of synchronous motor, the speed remains constant irrespective of magnitude of load, therefore, method of drawing increased current from supply means on synchronous motor can't be same as that of a dc shunt motor.

→ Since the synchronous Motor has got no Self starting torque, therefore first it is driven by some external means as an alternator & is synchronised with the supply

→ At the instant of synchronizing the induced emf across the stator circuit (also called back or counter emf or excitation voltage) is equal to the applied line voltage V but opposite in direction.

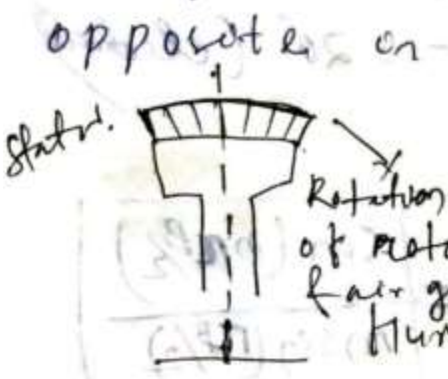


fig. a.

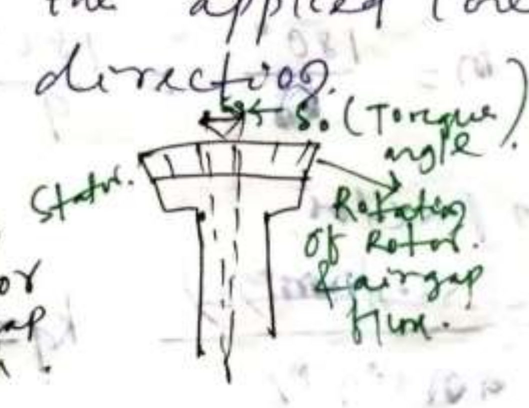


fig. b

fig. c

* $$\boxed{K_{dn} = \frac{\sin \frac{mn\beta}{2}}{m \sin \frac{n\beta}{2}}}$$

n = no. of harmonic

$m = \frac{\text{No. of slots per pole}}{\text{No. of phases}}$

β = Angular displacement betn the slots $= \frac{180°}{\text{no. of slots per pole}}$

× $$\boxed{K_C = \cos \frac{n\alpha}{2}}$$

n = no. of harmonic.

α = chording angle.

Q. The coil span for the stator winding of an alternator is 120°C Electrical. Find the chording factor of the winding for 3rd harmonic.

Ans ÷ Chording angle, α = 180° − coil span

$= 180° - 120° = 60°$

So $K_C| = \cos\left(\frac{n\alpha}{2}\right) = \cos\left(\frac{3 \times 60}{2}\right) = \cos 90° = 0$

n = 3rd harmonic

Q.2 Calculate the distribution factor for a 36-slot, 4 pole, single layer 3 φ winding for 3rd harmonic.

Ans ⇒ No. of slots per pole, $n = \frac{36}{4} = 9$

No. of slots per pole per phase

$m = \frac{180°}{n} = \frac{180°}{9} = 20°$ (electrical)

Distribution factor,

$$K_d = \boxed{\frac{\sin(mn\beta/2)}{m \sin(n\beta/2)}}$$

here n = no. of har

Armature reaction in synchronous motors.

→ In case of an alternator, the armature reaction flux induces a voltage in a given phase which always lags behind the armature current by 90° in phase.

→ In a synchronous motor, the flux created by the armature current lags the respective armature current by 90°. Since the generated or excitation voltage E is more than 90° out of phase with the armature current, armature reaction flux has a different effect on the rotor flux than it has in the case of alternator except when the armature current I & excitation voltage E are exactly 180° apart.

(1) Cross Magnetizing :- When the generated or excitation voltage of an alternator is in phase with the armature current.

(2) When the motor operates at lagging P.F such that armature flux leads the excitation voltage by less than 90°, the armature reaction has a magnetising component as well as cross-magnetising one.

(3) With a leading P.F on the motor, the armature reaction flux has a demagnetising as well as

cross magnetising component.

* In any case the motor tends to operate at a nearly constant flux or generated voltage as does the transformer.

effects of varying excitation on Armature current & Power factor :-

→ The change in field excitation neither affects the speed of the motor nore the output of the motor but does affect the p.f & consequently armature current for constant supply voltage & constant input powere.

* Lagging p.f = magnetising in nature.

(1) Over excitation → motor run with leading p.f
Synchronous capacitor.

(2) Under excitation → Motor runs with lagging p.f

(3) Normal excitation → Unity p.f

(4) 100% excitation → $E_b = V$

↳ I_a increases but its p.f decreases

→ The curve for dc field current ~ power factor looks like inverted V curve.

→ Minm. armature current corresponds to unity power factor.

Pitch factor :-

$$K_C = \frac{\text{Phasor sum of Induced emfs per coil}}{\text{Arithmatic sum of Induced emfs per coil}}$$

→ K_C must be < 1

→ Also, $K_p = \frac{\text{Resultant emf of short pitched coil}}{\text{Resultant emf of full pitched coil}}$

Distribution factor (K_p).

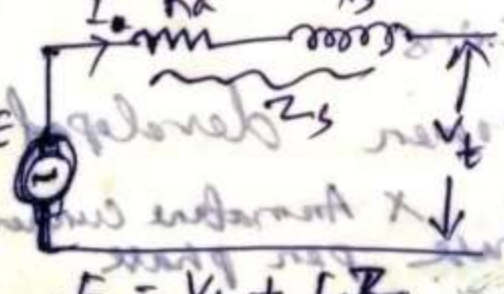
$$K_d = \frac{\text{Emf induced in distributed winding}}{\text{emf induced if the winding would have been concentrated}}$$

$$= \frac{\text{Phasor sum of component emfs}}{\text{Arithmatic sum of component emfs}}$$

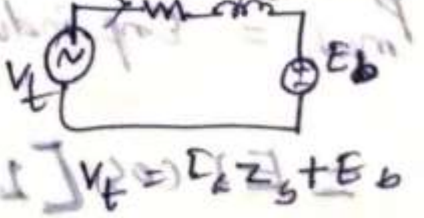
→ Also K_p must

---

equivalent ckt diagram of synchronous motor.



E_F = Field excitation.



$E = V_t + I_a Z_s$

$\Rightarrow E = V_t + I_a Z_s$

$V_t = I_a Z_s + E_b$

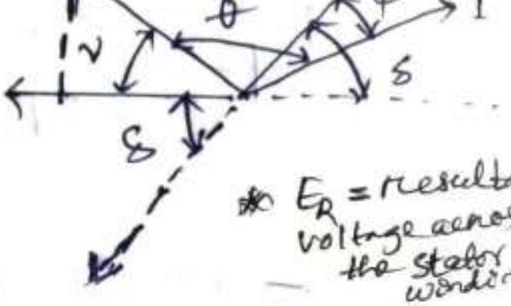
---

* Area of cube = $6a^2$ unit

* volume of cube = w. l. h = a^3 unit

Power developed in a synchronous Motor

Let's consider a 3phase synchronous motor having effective resistance R_e Ω/phase & synchronous reactance X_S Ω/phase. Let the motor be connected across 3phase ac supply having voltage per phase equal to V volts & have induced emf (or excitation voltage) per phase of E volts & Load angle δ electrical degrees.



* E_R = resultant voltage across the stator winding

→ Taking induced voltage E 'E' horizontally, resolving 'V' & E horizontally & vertically & equating the ~~angle~~ algebraic sum of ~~either~~ their horizontal & vertical components separately with the horizontal & vertical components of resultant voltage E_R respectively, we have

→ $E_R \cos\gamma = E - V\cos\delta$

& $E_R \sin\gamma = V\sin\delta$

mechanical power developed per phase

P_{mech} = Emf induced /phase × Armature current per phase × cosine of angle betn the two (angle betn I & E remains)

$= EI\cos[180° - (\theta + \gamma)]$

$= -EI\cos(\theta + \gamma)$

$= -E \times \frac{E_R}{Z_S}(\cos\theta . \cos\gamma - \sin\theta . \sin\gamma)$

$$= \frac{-E}{Z_s}\left(\cos\theta . E_R \cos\gamma - \sin\theta . E_R \sin\gamma\right)$$

Substitute $E_R \cos\gamma = E - V\cos\delta$ & $E_R \sin\gamma = V\cos\delta$

$$P_{mech} = -\frac{E}{Z_s}\left[\cos\theta\,(E - V\cos\delta) - \sin\theta\, V . \sin\delta\right]$$

$$= \frac{EV}{Z_s}\left(\cos\delta . \cos\theta + \sin\theta . \sin\delta\right) - \frac{E^2}{Z_s} . \cos\theta$$

$$= \frac{EV}{Z_s}\cos(\theta - \delta) - \frac{E^2}{Z_s} . \cos\theta$$

Since effective resistance of R_e of the synchronous motor is usually negligible as already mentioned, synchronous impedance Z_s, can be taken equal to synchronous reactance X_s & angle $\theta = 90°$, ($\because \theta = \tan^{-1}\frac{X_s}{R_e}$) & the above expression for power developed is $P_{mech} = \frac{EV}{X_s}\cos(90° - \delta) - \frac{E^2}{X_s}\cos 90°$

$$\Rightarrow \boxed{P_{mech} = \frac{EV}{X_s} . \sin\delta}$$

→ The max^m mechanical power developed or torque (since speed is constant) depends on the applied voltage 'V', induced emf 'E' (Excitation) & internal angle θ.

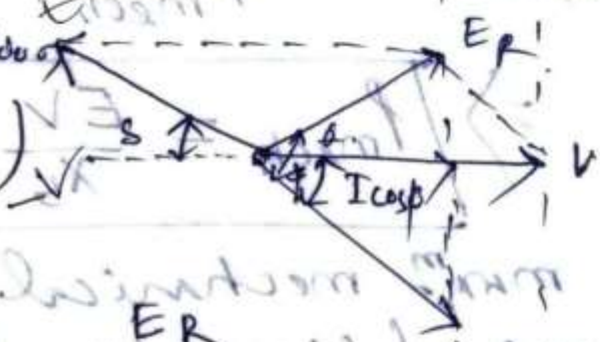
→ ~~At~~ $\boxed{P_{mech,\,max} = \frac{EV}{Z_s}}$

→ For constant applied voltage & constant input power, the active component of current drawn from the supply mains should constant & so because of large wattless (magnetising) current armature current I is much more.

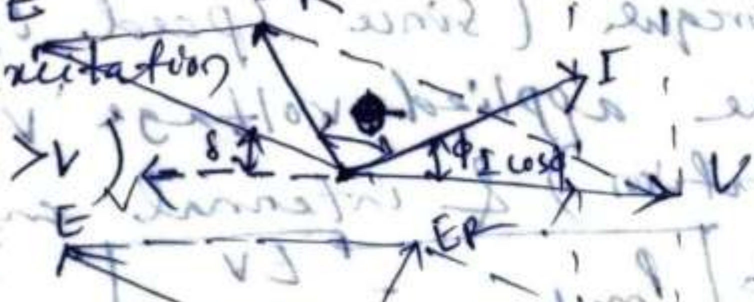
→ With the increase in excitation to 100% the magnetising current drawn from the 3φ ac supply mains is reduced i.e the magnetising component becomes a smaller part of the total input current & so the power factor improves.

(a) For 100% excitation
(i.e when E = V)

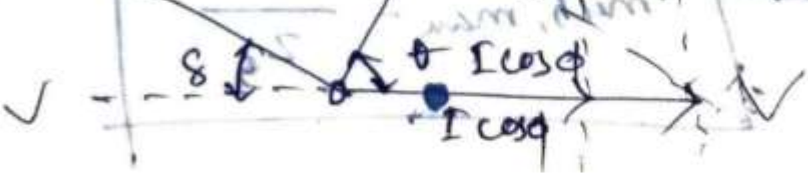
(b) For under excitation
(i.e when E < V)
Lagging P.f



(c) For over-excitation
Leading p.f (i.e when E > V)



(d) For unity p.f



→ If the excitation is further increased such that power factor becomes unity, the stator draws only energy or active current, & the dc field circuit supplies all the current necessary to magnetize the rotor field.

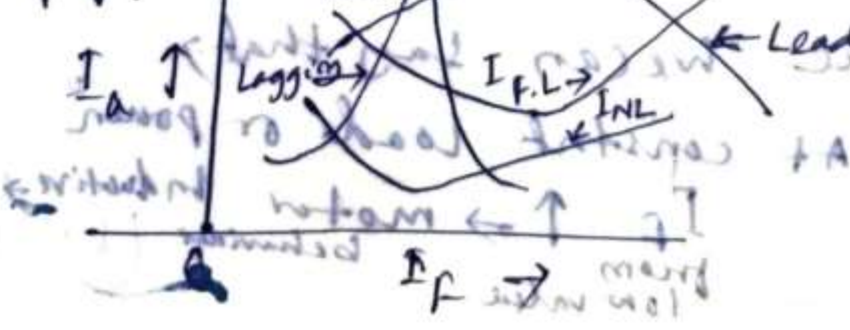
→ For unity power factor, the armature current drawn will be minimum.

→ With reduction in dc excitation synchronous motor draws more current from the supply mains at lower lagging power factor.

→ When the excitation of a synchronous ~~[illegible]~~ motor is increased above 100%, first p.f improves until it becomes unity. at this instant the current drawn from the supply mains is minm & is in phase with supply voltage.

→ With further increase in field current the power factor becomes leading one & decrease & current drawn from supply main increases

→ The variation of current & power factor of a synchronous motor with a variation of field current (excitation) & for a constant load is a V - curve



Effect of variation on excitation with constant load

→ Here I_f is variable & load is constant

→ $I_f \propto E_t$ & power $\propto$ Load.

$$\Rightarrow P = 3VI_a\cos\phi = 3V\left(\frac{E_t}{X_s}\right)\sin\delta$$

$$\Rightarrow P = 3VI_a\cos\phi = 3V\left(\frac{E_t}{X_s}\right)\sin\delta$$

For constant power or Load.

$I_a\cos\phi$ = constant.

i.e $\boxed{I_{a1}\cos\phi_1 = I_{a2}\cos\phi_2 = I_{a3}\cos\phi_3}$

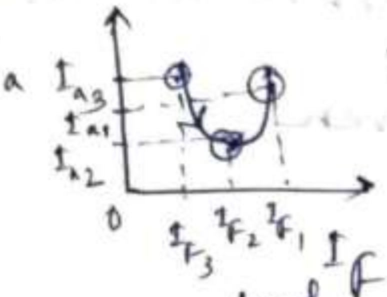
& $E_t\sin\delta$ = constant.

i.e $\boxed{E_{t1}\sin\delta_1 = E_{t2}\sin\delta_2 = E_3\sin\delta_3}$

→ here we can say that →

At constant load or power

$I_f \uparrow$ → motor behavior Inductive → Resistive → Capa
from low value ↑ (L) (R) (



V-curve of the motor.

effects of load variation ~~eq~~ at constant excitation:

→ I_f is constant i.e E_f is constant ($\because E_f \propto I_f$)

→ Motor load is variable i.e motor power is variable (Load ∝ power).

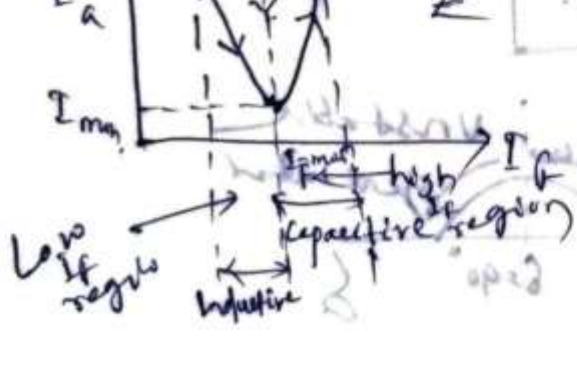
$$\boxed{P = 3\cdot V\frac{E_f}{X_s}\cdot\sin\delta}$$

where V = supply voltage per phase
E_f = Excitation emf per phase
X_s = synchronous reactance per phase
δ = Torque or power angle.

For small value of 'δ', $\Rightarrow \boxed{\sin\delta = \tan\delta = \delta}$

$\therefore P \propto \delta \Rightarrow P\uparrow \Rightarrow \delta\uparrow$
or Load $\uparrow \Rightarrow P\uparrow \Rightarrow \delta\uparrow$

→ let's consider the V-curve of the synchronous motor.



Starting methods of synchronous motor

(1) External Prime mover

(2) Pony motor

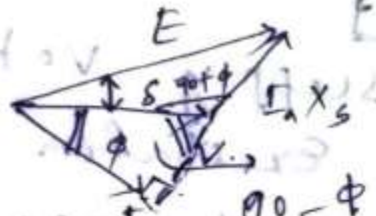
& (3) Damper winding.

Power angle characteristics of synchronous motor : (For cylindrical rotor.)

⇓

→ Air gap is more;

$R_a << X_s$ ∴ R_a is neglected.



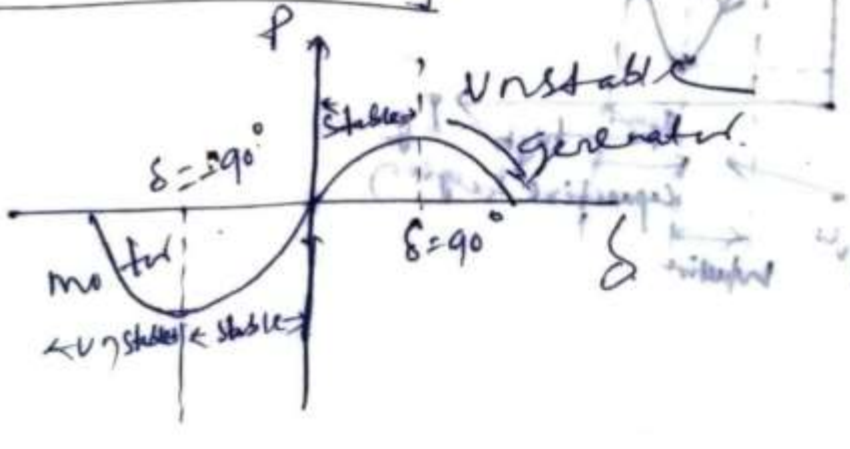
Sine rule

$$\frac{I_a X_s}{\sin\delta} = \frac{E}{\sin(90+\phi)}$$

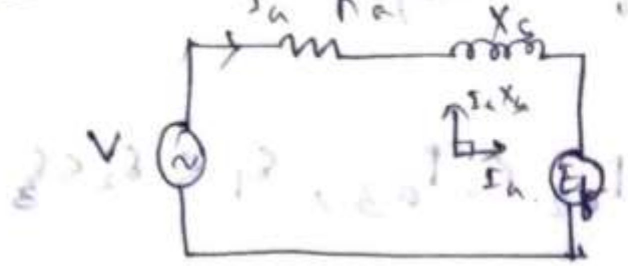
$$\Rightarrow \frac{I_a X_s}{\sin\delta} = \frac{E}{\cos\phi} \Rightarrow I_a \cos\phi = \frac{E}{X_s}\sin\delta$$

$$\Rightarrow V I_a \cos\phi = \frac{V.E}{X_s}\sin\delta \quad \left(\therefore P = \frac{EV}{X_s}\sin\delta\right)$$

$$\Rightarrow \boxed{P = V I_a \cdot \cos\phi}$$



Reef of the variation of load with constant excitation

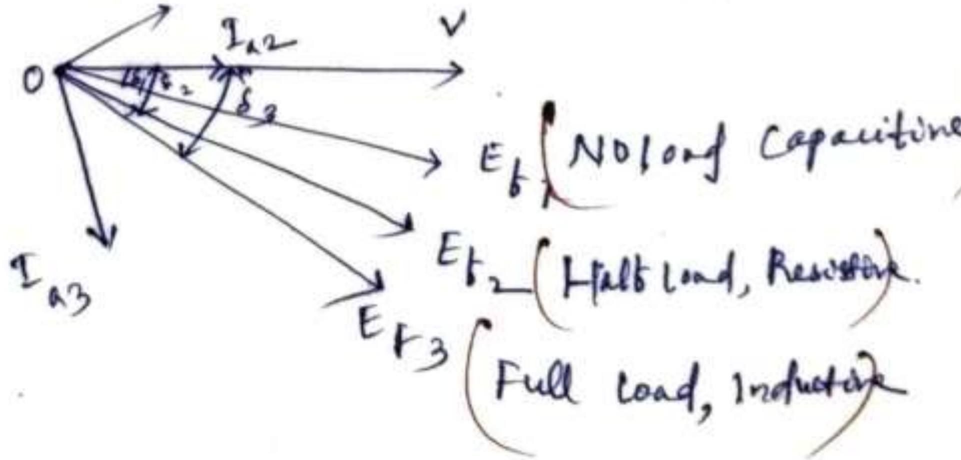


From the above phaser diagram, we have, $\boxed{\delta_1 < \delta_2 < \delta_3}$, $\boxed{I_{a1} < I_{a2} < I_{a3}}$

i.e $\boxed{\text{Load} \uparrow \Rightarrow \delta \uparrow \Rightarrow I_a \uparrow}$

& $E_{f_1} = E_{f_2} = E_{f_3}$ i.e E_f or I_f = constant.

$\Rightarrow$ $\boxed{\text{Load} \uparrow \Rightarrow \text{motor Capacitive} \rightarrow \text{Resistive} \rightarrow \text{Inductive}}$



→ Variation of load at constant excitation,

here $I_{a1} < I_{a2} < I_{a3}$, $\delta_1 < \delta_2 < \delta_3$

so $\boxed{\text{Load} \uparrow \Rightarrow I_a \uparrow \Rightarrow \delta \uparrow}$

E_f or I_f = constant.

→ Variation in excitation with constant Load → Load behaves → ① L → ② R → ③ C

→ Variation in Load with constant Excitation → Load behaves → ① C (No Load) → ② R (Half Load) → ③ L (Full Load)

Hunting: After the sudden application of load the rotor has to search or 'hunt' for its new equilibrium position that phenomenon is referred to as hunting in a synchronous motor.

→ At steady state, operation $T_{\text{electromagnetic}} = T_{\text{Load}}$
These are equal & opposite & also
Torque angle (δ) = constant.

→ Sudden change in load torque, the equillibrium is disturbed & there is resulting torque which chages the speed of the motor.

→ Unloaded Synchronous motor has zero degree load angle.

→ Shaft load ↑ ⇒ δ ↑

Causes of Hunting

(1) sudden change in load

(2) " " " I_f

(3) A load containing harmonic torque.

(4) Fault in power s/s.

Effects of Hunting in synchronous Motor:

(1) Loss of synchronism

(2) Produces mechanical stresses on the rotor shaft.

(3) m/c losses ↑ & $temp^n$ ↑

(4) Causes greater surges in current & Power flow.

(5) It increases possibility of resonance.

Reduct? of Hunting

(1) Use of Damper winding.
(2) Use of flywheels
(3) Designing synchronous m/c with Suitable synchronizing power Coefficients.

3ϕ Transformers

Grouping of winding,Advantages :

In theory of a three-phase transformer works like three equal and separated single-phase transformers (working separately with three phase system) with shared limbs. Here the magnetic circuit for the two outer limbs of the three phase transformer is lit bit longer than for the center limb of the same.

The output voltage transformation is determined by the ratio between the number of turns on the primary windings and secondary windings and assuming the even connection.

Based on this, it is theoretically possible to connect any pair of windings in a 3 phase transformer in the following pairs of combinations: Dd, Dy, Dz, Yd, Yy, Yz, Zd, Zyand Zz; of this, the first six, are the most commonly encountered ones in practice.

Here the

Y => Primary star connection

Y => Secondary star connection

D => Delta winding on Primary side

d => Secondary delta winding connection

Z => Primary Zig-Zag connection

Z => Secondary Zig-Zag connection

N => Primary connection Connected with neutral point

n => Secondary Zig-Zag connection

Numerical identity:

Here the numerical identity indicates the clock position of the phase displacement. It's may be clock wise or anti clockwise. i.e

> **Here the hour indicates phase displacement in angle. Because there are 12 hours on a clock, and a circle consists out of 360°, each hour (I mean one hour) represents 30°.Thus 1 = 30°, 2 = 60°, 3 = 90°, 6 = 180° and 12 = 0° or 360° and so on.**
>
> **The minute hand is set on 12 o'clock and replaces the line to neutral voltage (sometimes imaginary) of the HV winding. This position is always the reference point.**

Example:

> **Digit 0 =0° that the LV phasor is in phase with the HV phasor**
>
> **Digit 1 =30° lagging (LV lags HV with 30°) because the rotation is anti-clockwise.**
>
> **Digit 11 = 330° lagging or 30° leading (LV leads HV with 30°) Digit 5 = 150° lagging (LV lags HV with 150°)**

Digit 6 = 180° lagging (LV lags HV with 180°)

Definition of transformer vector group:

Actually, The transformer vector group shows the phase difference between the primary and secondary sides of the transformer.

What is the use of a transformer vector group?

Basically transformer vector group is used to find the high voltage and low voltage windings arrangement of three-phase transformers. The three-phase transformer can be connected in various ways and the transformer's connection is determined using its vector group.

The transformer's vector group is depending on the following factor:

> **Removing harmonics: The star winding of the three-phase transformer is used to reduce third harmonics.**
> **Parallel operations: To perform parallel operation All the transformer's vector group and polarity should be same.**

Let's see the most commonly used transformer's vector group is dYn11.

This is one of my power transformer's vector group, which is 110 kV/11 kV. This is can be used for both operations such as step down and step up. In this,

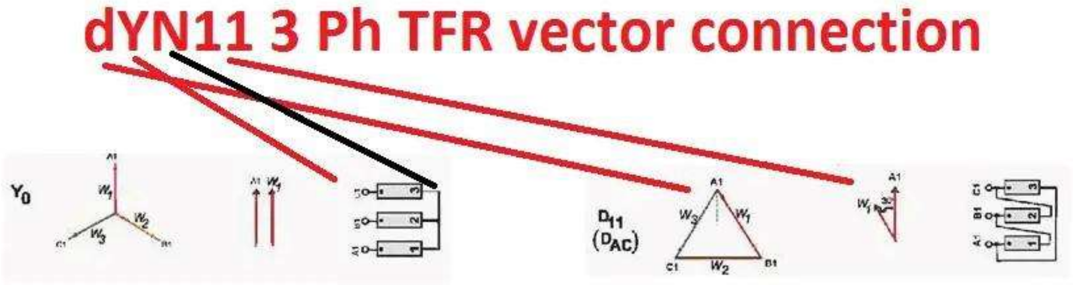
Y => indicates primary winding high voltage side is connected as star winding

d => indicates secondary winding low voltage side is connected as delta winding

N => Indicates the primary star connection is connected with the ground.

11 => indicates the clock position which means the phase difference between the primary and secondary of the transformer. The 11 indicates that the low line voltage lag, high line voltage by 11 X 30° = 330° (considered one hour for 30 deg.) measured from higher voltage phasor in a clockwise direction.

See the picture for better understanding of vector grouping:



The below-mentioned diagram can be used for a better understanding of transformer vector grouping and its usage.

The phase-bushings on a three-phase transformer are marked either ABC, UVW or 123 (HV-side capital, LV-side small letters). Two winding, three-phase transformers can be divided into four main categories

Group	O’clock	TC
Group I	0 o’clock, 0°	delta/delta, star/star
Group II	6 o’clock, 180°	delta/delta, star/star
Group III	1 o’clock, -30°	star/delta, delta/star
Group IV	11 o’clock, +30°	star/delta, delta/star

Parallel operation of the 3ϕ Transformers :

Parallel operation of three phase transformer is very common in three phase power generation, transmission and distribution. It is advantageous to use two or more Transformer units in parallel instead of using a single large unit. This offers flexibility for maintenance as well as operation.

Advantage of Parallel Operation of Three Phase Transformers

It increases the reliability of supply system. Let us try to understand how this happens. Suppose a fault occurs in any one of the Transformer unit. In such case, the faulty transformer may be taken out of service while the remaining transformers will feed the power supply. If there were only one large transformer unit is installed for supplying the load, the supply to the entire load will be interrupted during breakdown of the transformer. Thus the reliability of supply system is increased by parallel operation of transformers.

The size of transformer increases with the increase of its rating. Therefore, a larger transformer will be bigger in size. Therefore, its transportation form manufacturer to the Site will be difficult. Whereas, transportation and installation of small sized transformers are comparatively easy.

The maintenance opportunity in case of parallel operation is increases. One or more transformers may be taken under maintenance while the remaining transformers will supply the load at reduced power.

Condition for Parallel Operation of Three Phase Transformers Following are the necessary conditions for parallel operation of 3 phase transformers:

The line voltage ratio of the transformers must be same.

The transformers should have equal per unit leakage impedance. (You may read per unit system)

The ratio of equivalent leakage reactance to equivalent resistance should be same for all the transformers.

The transformers should have the same polarity.

Tap Changer :

A tap changer is a mechanism in transformers which allows for variable turn ratios to be selected in distinct steps. This is done by connecting to a number of access points known as taps along either the primary or secondary winding.

Tap changers exist in two primary types, no-load tap changers (NLTC), which must be de-energized before the turn ratio is adjusted, and on-load tap changers (OLTC), which may adjust their turn ratio during operation. The tap selection on any tap changer may be made via an automatic system, as is often the case for OLTC, or a manual tap changer, which is more common for NLTC. Automatic tap changers can be placed on a lower or higher voltage winding, but for high-power generation and transmission applications, automatic tap changers are often placed on the higher voltage (lower current) transformer winding for easy access and to minimize the current load during operation.

No-load tap changer

No-load tap changer (NLTC), also known as Off-circuit tap changer (OCTC) or De-energized tap changer (DETC), is a tap changer utilized in situations in which a transformer's turn ratio does not require frequent changing and it is permissible to de-energize the transformer system. This type of transformer is frequently employed in low power, low voltage transformers in which the tap point often may take the form of a transformer connection terminal, requiring the input line to be disconnected by hand and connected to the new terminal. Alternatively, in some systems, the process of tap changing may be assisted by means of a rotary or slider switch.

No load tap changers are also employed in high voltage distribution-type transformers in which the system includes a no load tap changer on the primary winding to accommodate transmission system variations within a narrow band around the nominal rating. In such systems, the tap changer will often be set just once, at the time of installation, although it may be changed later to accommodate a long-term change in the system voltage profile.

On-load tap changer (OLTC), also known as On-circuit tap changer (OCTC), is a tap changer in applications where a supply interruption during a tap change is unacceptable, the transformer is often fitted with a more expensive and complex on load tap changing mechanism. On load tap changers may be generally classified as either mechanical, electronically assisted, or fully electronic.

These systems usually possess 33 taps (one at centre "Rated" tap and sixteen to increase and decrease the turn ratio) and allow for ±10% variation[3] (each step providing 0.625% variation) from the nominal transformer rating which, in turn, allows for stepped voltage regulation of the output.

Tap changers typically use numerous tap selector switches which may not be switched under load, broken into even and odd banks, and switch between the banks with a heavy-duty diverter switch which can switch between them under load. The result operates like a dual-clutch transmission, with the tap selector switches taking the place of the gearbox and the diverter switch taking the place of the clutch.

Maintenance Schedule of Power Transformers :

Power transformers are stationary electrical machines used for transforming power from one circuit to another without changing frequency. This is a very basic definition of transformer. Since, there is no rotating or moving part, so a transformer is a static device. Transformer operates on an A/C supply. A transformer works on the principle of mutual induction. As the leader in distribution of power transformers in Nigeria, GZ has understood how to ensure power transformers are well maitained and serve a usefull lifespan for owners

Power transformers are electrical devices used to step up or step down the voltage level of its supply source. The process of stepping up or down depends upon the number of turns of primary and secondary winding. Transformers have primary winding and the secondary winding. The primary winding is the coil that draws power from the source. The secondary winding is the coil that delivers the energy at the transformed or changed voltage to the load.

Generally, a power transformer is used in stepping up the voltage of the supply to decrease the transmission losses, and then stepping down is done for the distribution purpose at the load centers. Power transformers are larger size devices that transfer the energy to substations or public electricity supply.

MAINTENANCE OF POWER TRANSFORMER

GZ Industrial Supplies, in adherence to IS 10028-3: Code of practice for selection, installation and maintenance of transformers advocates proper transformer maintenance. The efficiency of transformers is dependent on proper installation, loading, and maintenance, as well as on proper design and manufacture. Neglecting certain fundamental requirements may lead to serious troubles, if not to the loss of the equipment. The types of transformer maintenance can be described as follows:

Unscheduled Maintenance:

This type of maintenance is based on reactionary mode of operation. That is to say, maintain the equipment when it breaks down, otherwise leave it alone.

Ordinary Maintenance:

This type of maintenance takes irregular visual inspection and making repairs, adjustments, and replacements as necessary.

Routine Basis (Preventative Maintenance): This maintenance consists of performing preventive maintenance, predictive maintenance, and corrective maintenance. The preventive maintenance involves schedule maintenance and testing on a regular basis. Predictive maintenance involves additional monitoring and testing, whereas corrective maintenance involves repairing and restoring transformer integrity to its original condition when exacerbate conditions are discovered.

This maintenance can be summarized by the following:

Maintain transformer protective coating
Test and maintain transformer insulation
systems Inspect and maintain transformer
auxiliary devices Control transformer heat
Maintain transformer bushing insulation

There are different preventative maintenance actions we perform on a power transformer, they can be on a daily, monthly, quarterly, half-yearly, or yearly interval.

Daily Interval Transformer Maintenance:

Testing and Checking

Always maintain to keep oil filled up to the desired level in Magnetic Oil Gauge (MOG)
Change the silica gel if its color changes to pink. Seal any leakage detected.

Monthly Interval Transformer Maintenance

The oil level in the oil cap must be checked on a monthly interval.
Breathing holes in silica gel breather should also be checked and properly cleaned for proper breathing action.
If your electrical transformer has oil filling bushing, make sure that the oil is filled up to the correct level.

Maintenance of Transformer on Half Yearly Interval

The transformer oil must be checked on a half yearly interval, for dielectric strength, water content, acidity, sludge content, flash point, and resistivity for transformer oil.

Yearly Transformer Maintenance

Oil pumps, air fans, along with other items that are used to cool down a transformer and control circuit must be inspected annually.
Ensure to clean all the bushings of your electrical transformer with only soft cotton.
Oil conditions should be carefully examined on a yearly basis.
Ensure to clean out the inside of all of the marshalling boxes yearly.
Check proper functioning of the space and illumination heaters.
Terminal connections of control and relay wiring should be tightened at least once a year.
Control Panel has to be cleaned with a proper cleaning agent.
Ensure to measure the resistive value of the earth connection
Mechanical inspection of Buchholz relays should be carried out on a yearly basis.

FAULTS AND ITS CAUSES IN POWER TRANSFORMERS

The causes of faults and failures in power transformers can be classified into: electrical, mechanical, and thermal. The failures can be further classified into external or internal components.

Winding Failure: There are different causes of breakdown of winding which are listed below.

Dielectric faults: This happens in the winding because of the turn-to-turn insulation breakdown. These are the insulation between the turns of the winding. Insulation breakdown occurs because of the high current and voltage which are high above the rated values. The breakdown of the insulation upshots in the spark of the winding turns and causes a short circuit.

Windings are made of copper: Because of the copper line resistance, thermal losses do occur. This makes hot areas in the winding due to poor or lack of maintenance. This with time causes wear and tear and reduction of the physical strength up to the point of breaking of the winding.

Mechanical faults: This includes deformation, loosening or supplanting of the windings. The outcome is the deformation in the efficiency of the transformer and the tearing of the turn-to-turn ratio. The major causes of this fault include poor maintenance, improper repair, corrosion, manufacturing deficiencies, and vibrations in the transformer.

Deterioration of oil: This occurs due to the effect of lengthened overloading of the transformer. High oil temperature produces the formation of sludge, water, and acids. Water entering the oil as a result of the breathing action reduces its dielectric strength.

Bushing: Bushing are insulating devices that allow a high voltage electrical conductor to pass through an earth conductor. In the transformer, it provides a current path through the tank wall. In the transformer paper, insulators are used which are surrounded by oil that provides further insulation. Bushings may fail due to incomplete discharge. This is sometimes due to the slow and progressive degradation of the insulation over many years of service. Seal breaking of bushes happens due to entrance of water, aging or excessive dielectric losses. Because of this fault, core failure of the transformer may happen.

BENEFITS OF POWER TRANSFORMER MAINTENANCE

Increased safety

Problems are detected before they are a

hazard Increased equipment efficiency,

Reduced expenses

Repair work can be properly scheduled.

MAINTENANCE PROCESS

This encompasses maintenance activities such as: overhauls, breakdowns prevention and removing, changeover management and production of tools and special equipment. The structure also includes maintenance resources: tools and equipment, spare parts, procedures and documentation, maintenance works, etc.

The Maintenance Process can be summarized in four stages: Planning, Organization, Execution and Recording with a feedback stage providing for Optimization.

RECORDING OF DISTURBANCES

Power transformer maintenance must include historical test data. A properly documented and readily accessible testing data is required to assure an effective analysis during the power transformer maintenance.

- **Date and time of the occurrence.**
- **Data for installed over-voltage protection.**
  - **Network data, were connections or other relevant things made when the disturbance took place.**
  - **Weather data**
  - **Is the gas relay filled with gas?**
  - **Is oil sooty?**
  - **Thermometer readings.**
  - **Were coolers or tanks damaged?**
  - **Are there visible marks of arcing on the bushings, cover or conservator?**

WHY TRANSFORMER MAINTENANCE IS IMPORTANT

The main purpose of maintenance of the transformer is to ensure the internal and external parts of the transformer and accessories are in good condition, efficient and able to operate safely. Another essential purpose is to maintain a historical record of the condition of the transformer.