5th Semester	REL5C003	Electrical Machines - II	L-T-P 3-0-0	3 Credits

Electrical Machines - II

Module I: **(8 Hours)**
Physical arrangement of windings in stator and cylindrical rotor; slots for windings; singleturn coil - active portion and overhang; full-pitch coils, concentrated winding, distributed winding, winding axis, Air-gap MMF distribution with fixed current through winding - concentrated and distributed, Sinusoidally distributed winding, winding distribution factor

Module II: **(4 Hours)**
Constant magnetic field, pulsating magnetic field - alternating current in windings with spatial displacement, Magnetic field produced by a single winding - fixed current and alternating current Pulsating fields produced by spatially displaced windings, Windings spatially shifted by 90 degrees, Addition of pulsating magnetic fields, Three windings spatially shifted by 120 degrees (carrying three-phase balanced currents), revolving magnetic field.

Module III: **(12 Hours)**
Three Phase Induction Motor
Construction, Types (squirrel cage and slip-ring), Torque Slip Characteristics, Starting and Maximum Torque. Equivalent circuit. Phasor Diagram, Losses and Efficiency. Effect of parameter variation on torque speed characteristics (variation of rotor and stator resistances, stator voltage, frequency). Methods of starting, braking and speed control for induction motors. Generator operation. Self-excitation. Doubly-Fed Induction Machines.

Module IV: **(6 Hours)**
Single Phase Induction Motor
Constructional features, double revolving field theory, equivalent circuit, determination ofparameters. Split-phase starting methods and applications

Module V: **(10 Hours)**
Constructional features, cylindrical rotor synchronous machine - generated EMF, equivalent circuit and phasor diagram, armature reaction, synchronous impedance, voltage regulation. Operating characteristics of synchronous machines, V-curves. Salient pole machine – two reaction theory, analysis of phasor diagram, power angle characteristics. Parallel operation of alternators - synchronization and load division.

Books:

[1] Stephen J. Chapman-‘Electric Machinery and Fundamentals’- Mc Graw Hill International Edition, (Fourth Edition), 2015.
[2] M. G. Say, “Performance and design of AC machines”, CBS Publishers, 2002.

[3] A. E. Fitzgerald and C. Kingsley, "Electric Machinery”, McGraw Hill Education, 2013.
[4] P. S. Bimbhra, “Electrical Machinery”, Khanna Publishers, 2011.
[5] I. J. Nagrath and D. P. Kothari, “Electric Machines”, McGraw Hill Education, 2010.

[6] A. S. Langsdorf, “Alternating current machines”, McGraw Hill Education, 1984.

[7] P. C. Sen, “Principles of Electric Machines and Power Electronics”, John Wiley & Sons, 2007

Digital Learning Resources:

Course Name:	Electrical Machine-II
Course Link:	https://nptel.ac.in/courses/108/105/108105131/
Course Instructor:	Prof. T K Bhattacharya, IIT Kharagpur

AC MACHINES

UNIT-I

Fundamentals of AC Machine Windings

UNIT – I

Armature Windings in Alternator & Types of Armature Windings

What are Armature Windings?

The winding through which a current is passed to produce the main flux is called the field winding. The winding in which voltage is induced is called the armature winding.

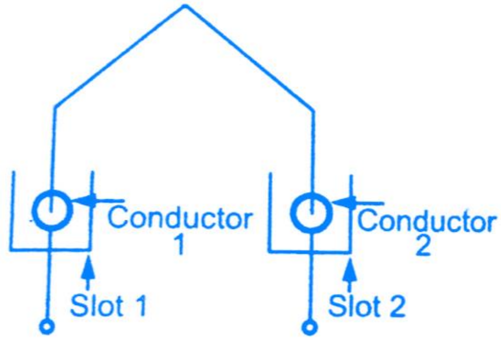
For an alternator, the armature is kept stationary on the stator. The stationary armature has its several advantages over rotating armature. The armature winding is placed on the slots of the stator.

The armature winding of dc motor is of closed circuit type but in case of alternator, it is either closed giving delta connection or open giving star connection. But however, the general principles governing armature winding of dc machine and alternator are the same.

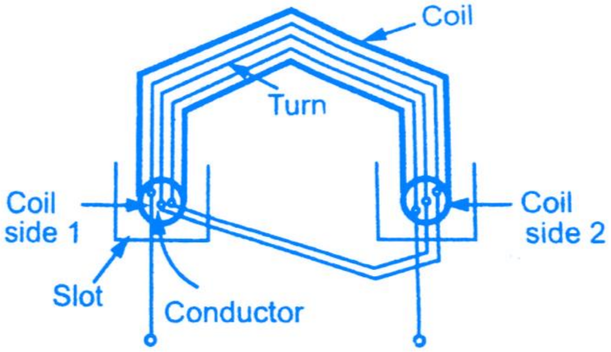
Some Basic terms related to the armature winding are defined as follows

1) Conductor: The part of the wire, which is under the influence of the magnetic field and responsible for the induced emf is called active length of the conductor. The conductors are placed in the armature slots.

2) Turn: A conductor in one slot, when connected to a conductor in another slot forms a turn. So two conductors constitute a turn.This is shown in the below figure (a).

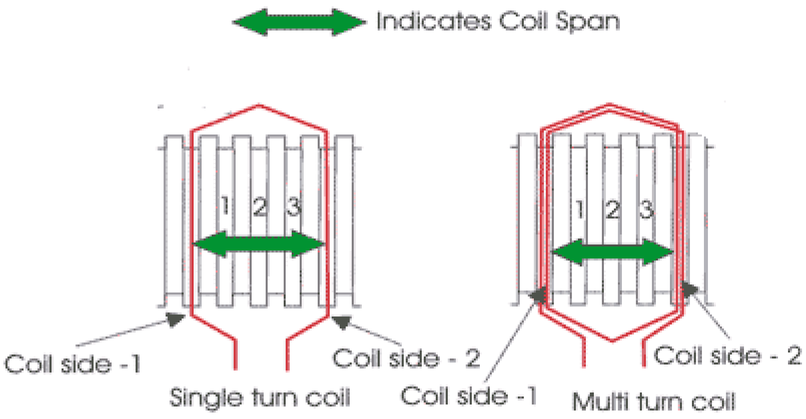


(a)Turn



(b)Multiturn coil

3) Coil: As there are a number of turns, for simplicity the number of turns are grouped together to form a coil. Such a coil is called a multi-turn coil. A coil may consist of single turn called single turn coil. Figure(b) shows a multi-turn coil.



4) Coil Side: Coil consists of many turns. Part of the coil in each slot is called coil side of acoil as shown in the above figure(b).

5) Pole Pitch: It is centre to centre distance between the two adjacent poles. We have seen that for one rotation of the conductors, 2 poles are responsible for 360° electrical ofemf, 4 poles are responsible for 720° electrical of emf and so on. So 1 pole is responsible for 180° electrical of induced emf.

Key Point: **So 180° electrical is also called one pole pitch.** Practically how many slots are under one pole which is responsible for 180°electrical, are measured to specify the pole pitch.For example let us consider 2 poles, 18 slots armature of an alternator. Then under slots are responsible for producing a phase difference of 180° between the emfs induced in different conductors.

This number of slots/pole is denoted as 'n'.

Pole pitch = 180° electrical
= slots per. Pole (no. of slots/P)
= n

COIL PITCH : The distance between the two sides of a coil is called the coil span or coil pitch.

A pole pitch always 180 electrical degrees regardless of the number of poles on the machine.

6) Slot angle (β): The phase difference contributed by one slot in degrees electrical iscalled slot angle As slots per pole contributes 180° electrical which is denoted as 'n', wecan write,

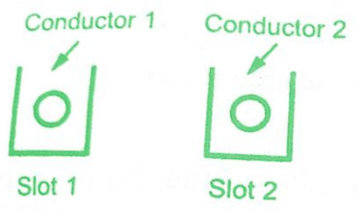
1 slot angle = $180^\circ/n$

$\beta = 180^\circ/n$

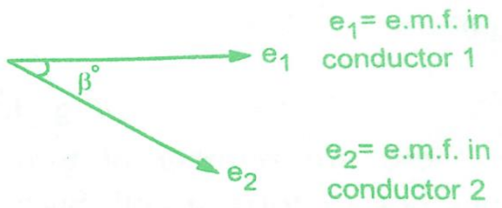
In the above example,

$n = 18/2 = 9$, while $\beta = 180^\circ/n = 20^\circ$

Note: This means that if we consider an induced e.m.f. in the conductors which areplaced in the slots which are adjacent to each other, there will exist a phase difference ofin between them.While if emf induced in the conductors which are placed in slots whichare 'n' slots distance away, there will exist a phase difference of 180° in between them.



(a) Adjacent slots



(b) Indication of phase differe

Types of Armature Windings in Alternator:

The different types of armature windings in alternators are,

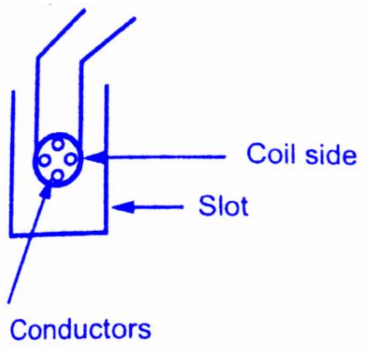
1) Single layer and double layer winding

2) Full pitch and short pitch winding

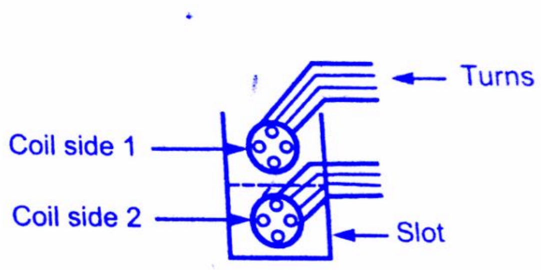
3) Concentrated and distributed winding

1)Single Layer and Double Layer Winding:

If a slot consists of only one coil side, winding is said to be a single layer. This is shown in figure(a). While there are two coil sides per slot, one, at the bottom and one at the top the winding is called double layer as shown in figure(b).A lot of space gets wasted in single layer hence in practice generally double layer winding is preferred.



(a) Single layer



(b) Double layer

2)Full Pitch and Short Pitch Winding:

As seen earlier, one pole pitch is 180° electrical. The value of 'n', slots per pole indicates how many slots are contributing 180° electrical phase difference. So if coil side in one slot is connected to a coil side in another slot which is one pole pitch distance away from the first slot, the winding is said to be full pitch winding and coil is called full pitch coil.

i.e

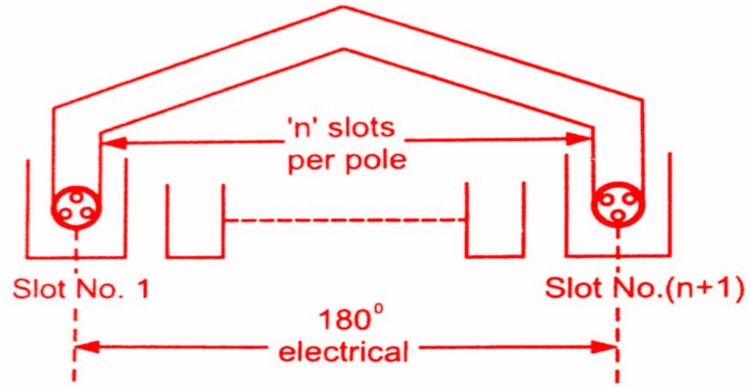
Coil Span = Pole pitch = 180^0 electrical = Slots / Poles = Full pitch coil

For example, in 2 poles, 18 slots *alternator,* the pole pitch is n = 18/2 = 9 slots.

So (1+9 = 10 Slot) if coil side in slot No. 1 is connected to coil side in slot No. 10 such that two slots No. 1 and No. 10 are one pole pitch or n slots or 180° electrical apart, the coil is called full pitch coil.

Here we can define one more term related to a coil called coil span.

Coil Span:



It is the distance on the periphery of the armature, between two coil sides of a coil. It is usually expressed in terms of number of slots or degrees electrical. So if coil span is 'n' slots or 180° electrical the coil is called 180° full pitch coil. This is shown in the figure to left. As against this if coils are used in such a way that coil span is slightly less than a pole pitch i.e. less than 180° electrical, the coils are called, short pitched coils or fractional pitched coils.Generally, coils are shorted by one or two slots.

Coil span = 180^0-α(**α is called short pitch angle or chording angle)**

So in 18 slots, 2 pole alternatorinstead of connecting a coil side in slot No 1 to slot No.10, it is connected to a coil side in slot No.9 or slot No. 8, the coil is said to be short pitched coil and winding are called short pitch winding.This is shown in the below figure.

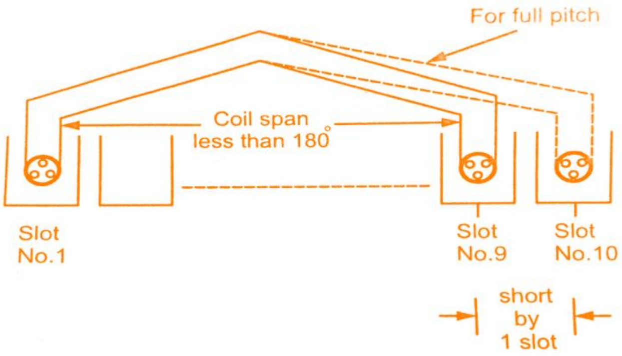


Fig: Short pitch coils

Advantages of Short Pitch Coils:

In actual practice, short pitch coils are used as it has following advantages,

1) The length required for the end connections of coils is less i.e. the inactive length of winding is less. So less copper is required. Hence economical.

2) Short pitching eliminates high frequency harmonics which distort the sinusoidal nature of e.m.f. Hence waveform of an induced e.m.f. is more sinusoidal due to short pitching.

3) As high frequency harmonics get eliminated, eddy current and hysteresis losses which depend on frequency also get minimised. This increases the efficiency.

3) Concentrated and Distributed winding:

In three phase alternators, we have seen that there are three different sets of windings, each for a phase. So depending upon the total number of slots and number of poles, we have certain slots per phase available under each pole. This is denoted as 'm'.

m = Slots per pole per phase = n/number of phases

= n/3 (generally no. of phases is 3)

For example in 18 slots, 2 pole alternator

we have, n = 18/2 = 9 andm = 9/3

So we have 3 slots per pole per phase available. Now let 'x' number of conductors per phase are to be placed under one pole. And we have 3 slots per pole per phase available. But if all 'x' conductors per phase are placed in one slot keeping remaining 2 slots per pole per phase empty then the winding is called concentrated winding.

Key Point: So in a concentrated winding, all conductors or coils belonging to a phase are placed in one slot under every pole.

But in practice, an attempt is always made to use all the 'm' slots per pole per phase available for distribution of the winding. So if 'x' conductors per phase are distributed amongst the 3 slots per phase available under every pole, the winding is called distributed winding. So in distributed type of winding all the coils belonging to a phase are well distributed over the 'm' slots per phase, under every pole.Distributed winding makes the waveform of the induced e.m.f. more sinusoidal in nature.Also in concentrated winding due to a large number of conductors per slot, heat dissipation is poor.

Key Point: So in practice, double layer, short pitched and distributed type of armature winding is preferred for the alternators.

Full pitch coils are to be used so if phase 1 says R is started in slot 1, it is to be connected to a coil in slot 7. So that coil span will be 6 slots i.e. 'n' slots i.e. 1 pole pitch.As distributed winding is to be used, both the slots per pole per phase (m = 2) available are to be used to place the coils. And all coils for one phase are to be connected in series.

So from slot No.7 we have to connect it to coil slot No.2 and slot No.2 second end to slot No.8 and so on.After finishing all slots per phase available under the first pair of pole, we will connect the coil to slot No.13 under next pole and winding will be repeated in a similar fashion. The starting end Rs and final end Rf winding for R-phase are taken out finally. Connections for R-phase only are shown in the below figure.

Now, we want to have a phase difference of 120° between 'R' and 'Y'. Each slot contributes 30° as $\beta = 30°$.So start of 'Y' phase should be 120° apart from the start of 'R' i.e. 4 slots away from the start of R. So start of 'Y' will be in slot 5 and will get connected to slot No.11 to have full pitch coil. Similarly, the start of 'B' will be further 120° apart from 'Y' i.e. 4 slots apart start of 'Y' i.e. will be in slot No.9 and will continue similar to 'R'.

Finally, all six terminals of three sets will be brought out which are connected either in star or delta to get three ends R, Y and B outside to get three phase supply. The entire winding diagram with star connected windings is shown in the below figure.

Integral Slot Winding:

The value of slots per pole per phase decides the class of the winding.

m = slots / pole / phase

Key Point: When the value of m is an integer, then the winding is called Integral slot winding.

Consider 2 pole, 12 slots alternator

hence, n = slots / pole = 12/2 = 6

Pole pitch = 180° = 6 slots

m = n/3 = 6/3 =2

As m is an integer, the type of winding is integral slot winding. This winding can be **full pitch winding** or **short pitch winding**.

Let, the winding is full pitch winding. For integral slot winding, coils of one coil group lying under one pole pair are connected in series. Thus the end of the first coil is connected to start of the next coil lying to the right of the first coil.The alternate coil groups must be reversely connected such that EMF is induced in them is additive in nature.Any slot contains the coil sides which belong to the same phase.Such a winding is shown in the below figure.

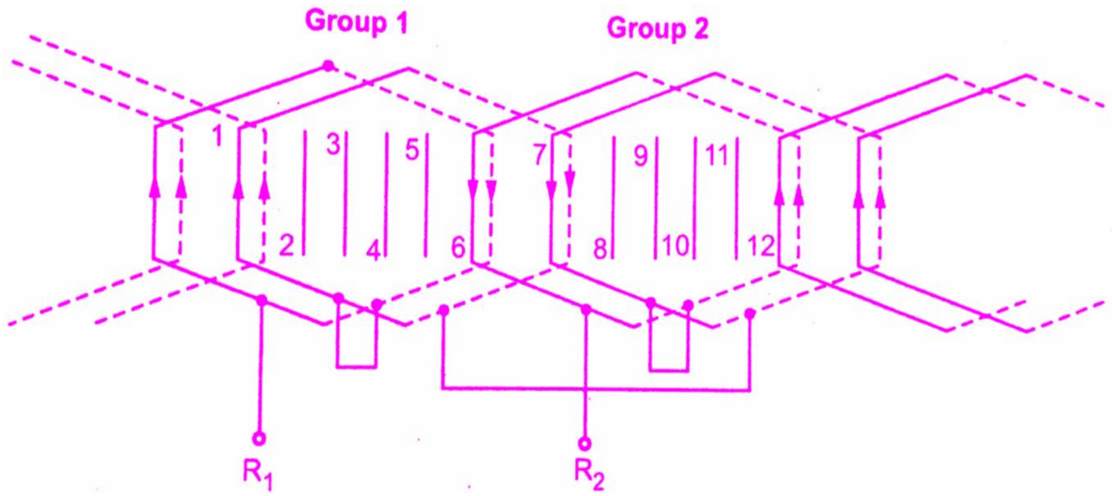


Fig: Double layer integral slot winding

If the short pitch coils are used for **integral slot winding** then in each group of the slots per pole phase, the coil sides of different phases exist.

Fractional Slot Winding:

This is another **type of winding** which depends on the value of m.

Key Point: The winding in which slots per pole per phase (m) is a fractional number is called fractional slot winding.

In such a winding, the number of slots (S) must be divisible by 3. Thus slots per phase is an integer which is necessary to obtain symmetrical three phase winding.But slots per pole (n) and slots per pole per phase (m) both are fractional. As n is a fraction, the coils cannot be full pitch. Thus if there are 54 slots and 8 poles then the slots per pole n = 54/8 = 6.75 hence coil span can be 7 or 6. Generally, short pitch coils are used.Such a fractional slot winding can be easily achieved with double layer winding.

In a balanced three phase winding, a basic unit under a pole pair (N and S) is repeated for remaining pole pairs where m is an integer. In fractional slot winding, the m is reduced to an irreducible fraction by taking out highest common factor in number of slots and poles.

Let

S = Number of slots
P = Number of poles
then for a 3 phase winding,

$$m = \frac{S}{3P} = \frac{k\left(\frac{S}{3k}\right)}{k\left(\frac{P}{k}\right)} = \frac{k\,S_k}{k\,P_k} = \frac{S_k}{P_k}$$

where

k = Highest common factor in S and P

Sk/Pk = Characteristic ratio

The number k indicates the number of repeatable units and number of possible parallel paths. The characteristic ratio indicates that there are Sk coils per phase distributed among Pk poles.Thus the winding is to be considered only of Pk poles out of P poles and for other poles it is repeated.

Similarly, the winding arrangement is to be considered for Sk slots out of total S slots and for other slots it is repeated.In a double layer winding, only the arrangement of the top layer is to be considered. This gets repeated in the bottom layer in which the corresponding coil sides are located one coil span away.

Advantages of Fractional slot Windings:

The various advantages of fractional slot winding are,

1. Though appearing to be complicated, easy to manufacture.
2. The number of armature slots (S) need not be an integral multiple of number of poles (P).
3. The number of slots can be selected for which notching gear is available, which is economical.
4. There is saving in machine tools.
5. High frequency harmonics are considerably reduced
6. The voltage waveform available is sinusoidal in nature.

Pitch Factor or Coil Span Factor

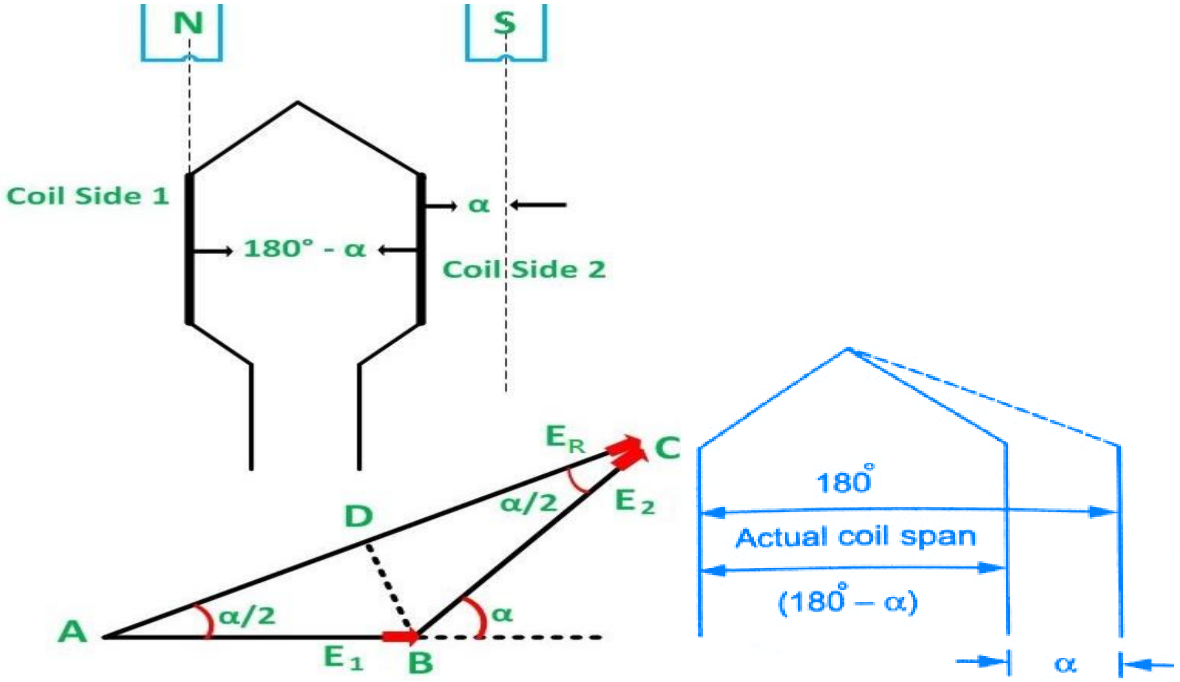
Pitch Factor or Coil SpanFactor is definite as the ratio of emf generated in short pitch coil to the emf generated in full pitch coil. It is denoted by K_p and its value is always less than unity. This factor basically represents the effect of short pitch winding on generated emf across the winding terminals of electrical machine.

As per the definition, the formula for pitch factor is given as below.

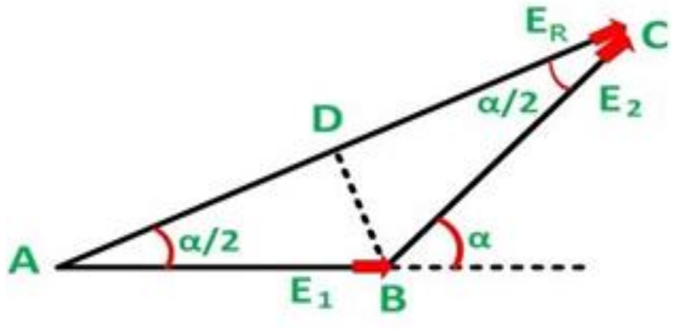
$$K_p = \frac{\text{emf generated in short pitch coil}}{\text{emf generated in full pitch coil}} \text{.............(1)}$$

Calculation of Pitch Factor or Coil Span Factor

To calculate the value of pitch factor, first of all we need to calculate the value of emf generated in short pitch coil and that in full pitch coil.Let us now calculate the emf generated in a short pitch coil. Figure below shows a short pitch coil.



Let E_1, E_2 and E_R be the emf induced in coil side lying under North Pole, South Pole and resultant of emf generated in both the active lengths of coil. As the two coil sides are separated in space by an angle of (180-α) i.e. the coil span is (180-α), therefore the emf induced in these coil sides will also be separated by this angle. This means, the angle between E_1 and E_2 phasor will be equal to α as shown in figure below.



Since the magnitude of emf generated in both the coil sides are equal, therefore $E_1 = E_2 = E$ (say). As the resultant emf E_R is the phasor sum of E_1 and E_2, therefore

$$ER = \sqrt{(E1)^2 + (E2)^2 + 2E1E2cos\varepsilon}$$

$$= \sqrt{(E)^2 + (E)^2 + 2(E)^2cos\varepsilon}$$

$$= E\sqrt{2(1 + cos\varepsilon)}$$

$$= E\sqrt{2x2cos^2(\frac{\varepsilon}{2})}$$

$$= 2Ecos(\varepsilon/2) \quad \text{..................(2)}$$

Above expression gives the emf induced in a single turn short pitch coil with chording angle α. Since the chording angle for full pitch coil is 0 degree, therefore from the above expression (2),emf generated in a full pitch coil = 2E

Thus from (1),

$$\text{Pitch Factor, Kp} = \frac{2Ecos(\alpha/2)}{2E}$$

$$= cos(\alpha/2)$$

Hence, pitch factor or coil span factor $K_p = Cos(\alpha/2)$.

For a **full pitch coil**, the value of pitch factor is **unity** whereas for its value is also **unity** for **concentrated coils**.

The pitch factor or coil span factor rth harmonics is given as

$K_p = \cos(r\,\alpha/2)$

The nth harmonic becomes zero, if,

$K_p = \cos(r\,\alpha/2)$

$\cos(r\,\alpha/2) = 0$ ***or*** $r\,\alpha/2 = 90^0$

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***

DISTRIBUTION FACTOR OR BREADTH FACTOR

The **Distribution Factor** or the **Breadth Factor** is defined as the ratio of the actual voltage obtained to the possible voltage if all the coils of a polar group were concentrated in a single slot. It is denoted by K_d and is given by the equation shown below.

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.

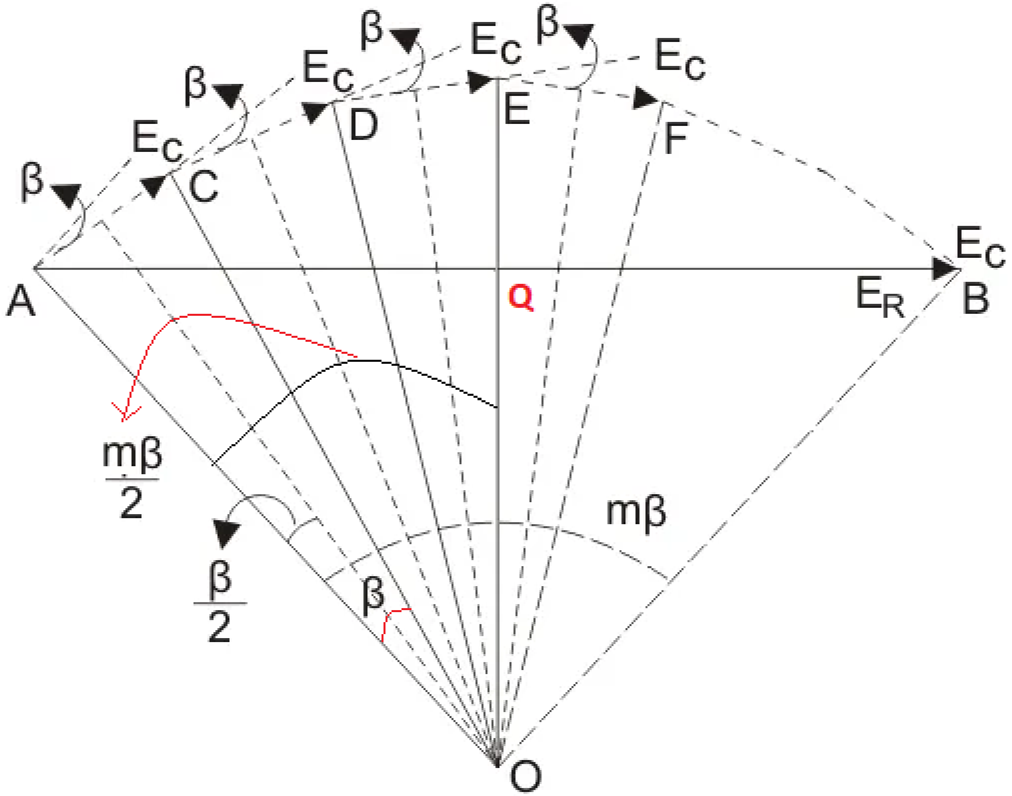
So, the resultant emf of the winding is the phasor sum of the induced emf per coil side. As it is phasor sum, must be less than the arithmetic sum of these induced emfs.Resultant emf would be an arithmetic sum if the winding would have been a concentrated one.

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 E_c.

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, EF ———. They would meet at common point O. Emf induced in each coil side,

From ΔAOP

Sin (β/2) = AP/OA

Sin (β/2) = (AC/2)/OA

AC/2 = OA Sin (β/2)

AC = 2 OA Sin (β/2)

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

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

Sin (mβ/2) = AQ/OA

Sin (mβ/2) = (AB/2)/OA

AB/2 = OA Sin (mβ/2)

AB = 2 OA Sin (mβ/2)

E_R = 2 OA Sin (mβ/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. If the flux 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.

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

$$Therefore,\ Winding\ Factor$$

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

Module-III

3.1 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.

3.2 Types and Construction of Three Phase Induction Motor

Three phase induction motors are constructed into two major types:

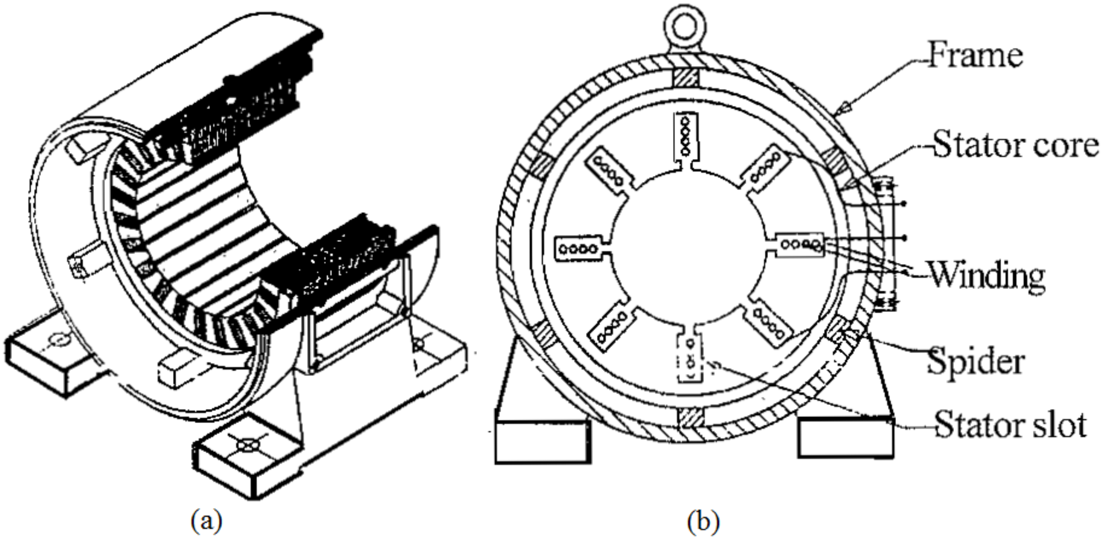
1. Squirrel cage Induction Motors
2. Slip ring Induction Motors

3.2.1 *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.



(a) (b)

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.

3.2.2 *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.

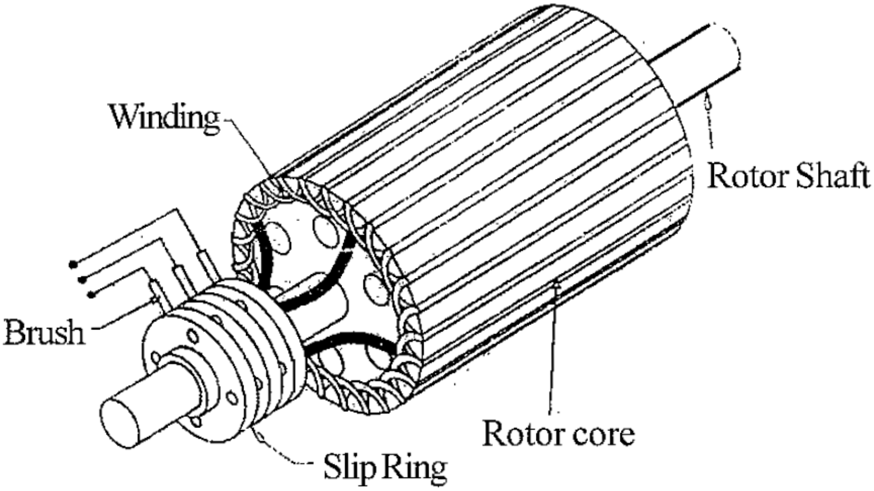


Fig: 3.2

<u>THE ADVANTAGES OF THE SLIPRING MOTOR ARE</u>

- 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.

3.2.3 Comparison of Squirrel Cage and Slip Ring Motor

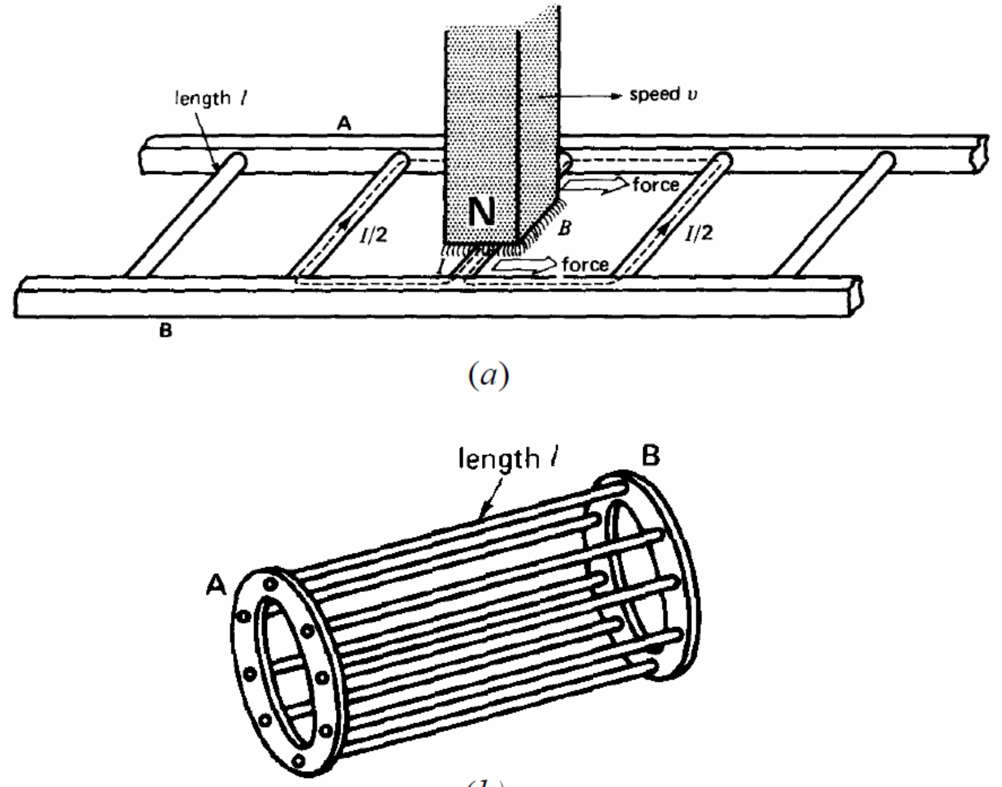
Sl.No.	Property	*Squirrel cage motor*	*Slip ring motor*
1.	**Rotor Construction**	*Bars are used in rotor. Squirrel cage motor is very simple, rugged and long lasting. No slip rings and brushes*	*Winding wire is to be used.* *Wound rotor required attention.* *Slip ring and brushes are needed also need 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*

3.3 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.

3.4 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.

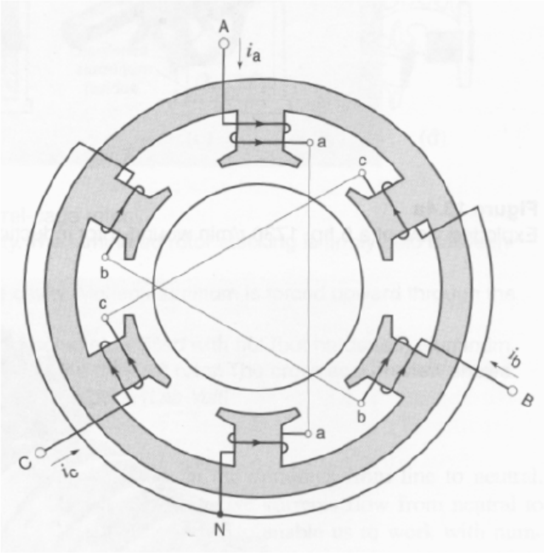


Fig: 3.4 Elementary stator having terminals A, B, C connected to a 3-phase source (not shown). Currents flowing from line to neutral are considered to be positive.

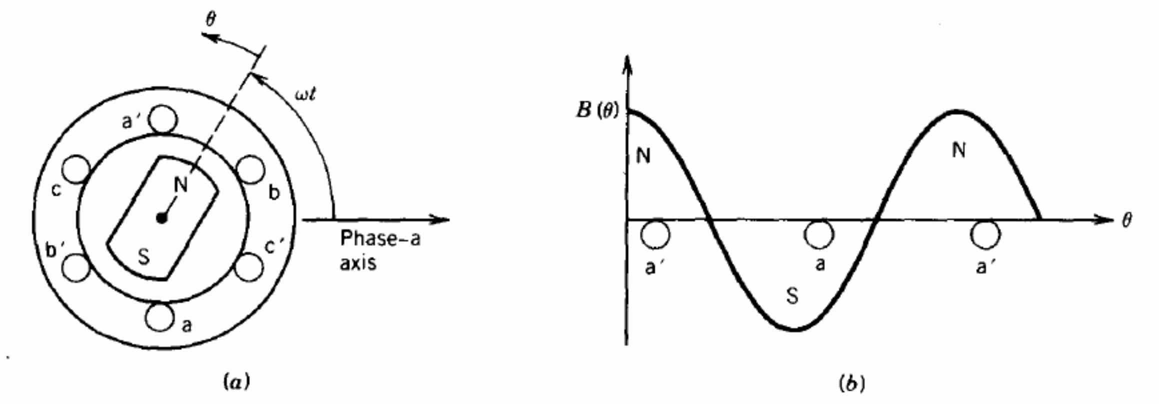


Fig: 3.5 Air gap flux density distribution.

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

$$Erms = 4.44fN_{ph}\varphi_p K_W$$

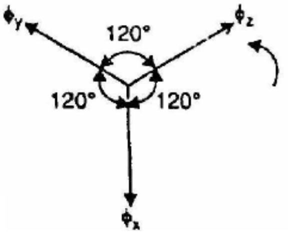
Where N_{ph} is the number of turns in series per phase.

3.5 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 ϕm as proved under:

At instant 1, $\omega t = 0°$. 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, $\omega t = 30°$. 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.

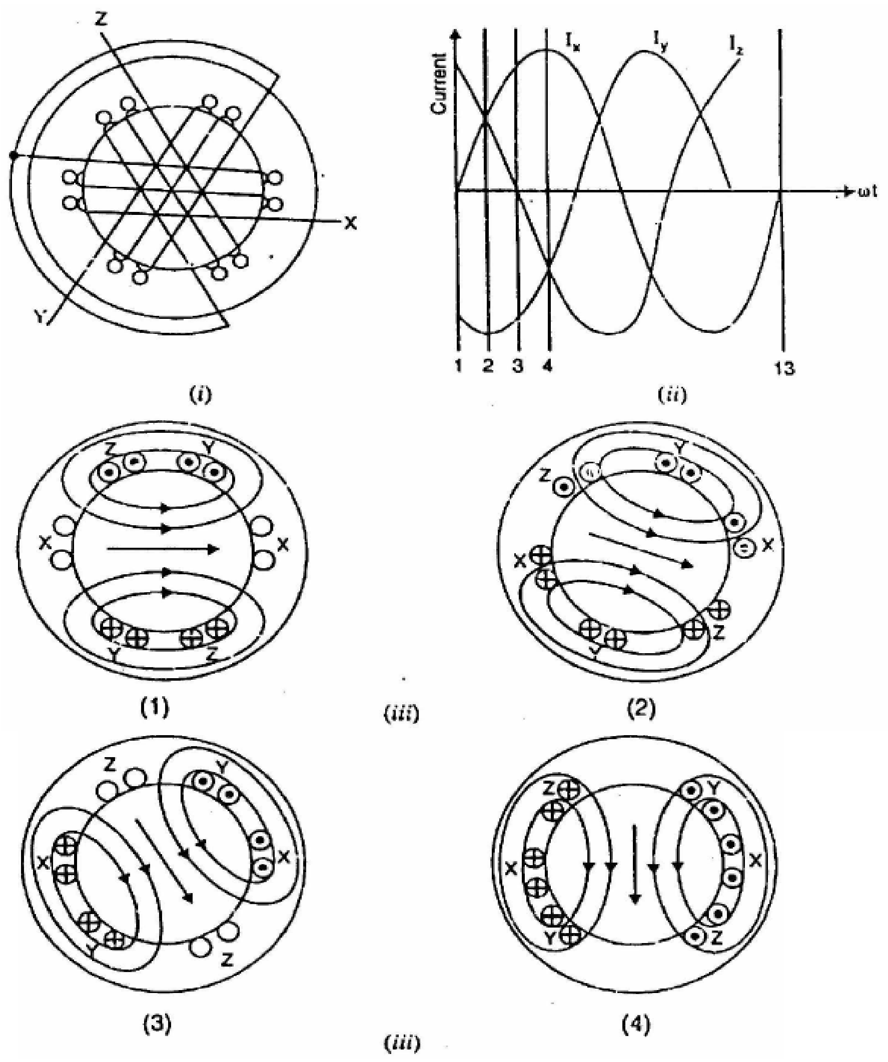
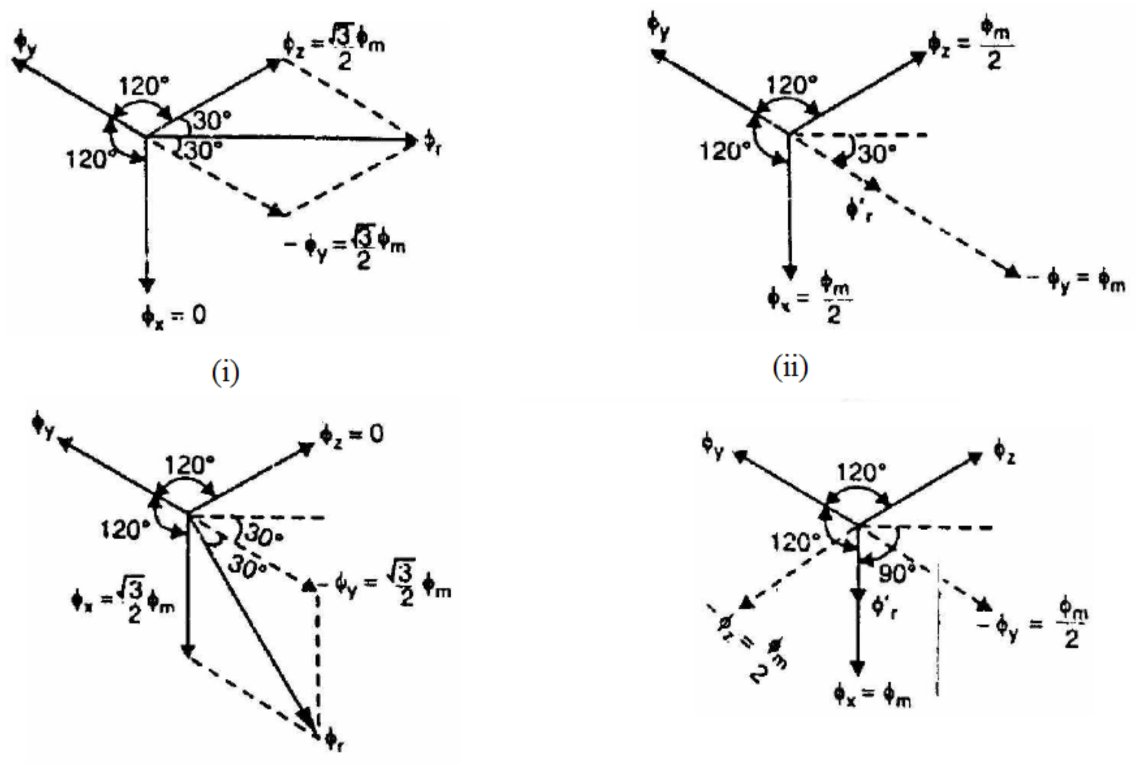


Fig: 3.6

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 ϕ_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, $\omega t = 90°$. 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).

3.5.1 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.

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

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

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,

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

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

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.

3.5.2 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.

3.5.3 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.

3.5.4 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.

3.6 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.

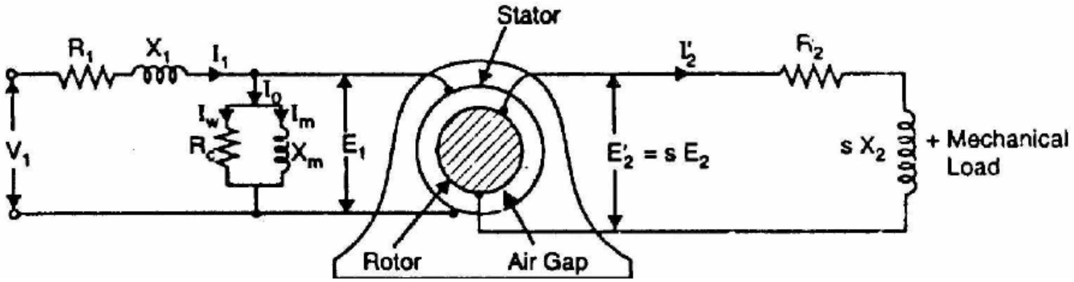


Fig: 3.8

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.

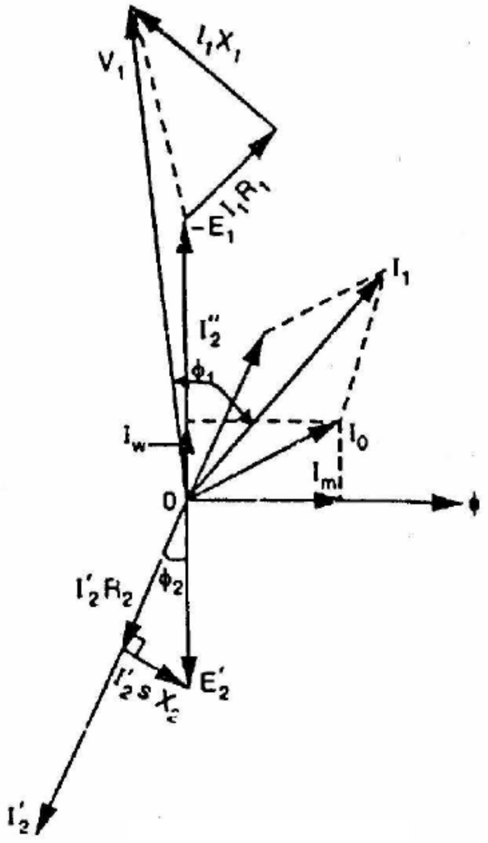


Fig: 3.9

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.

3.7 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.

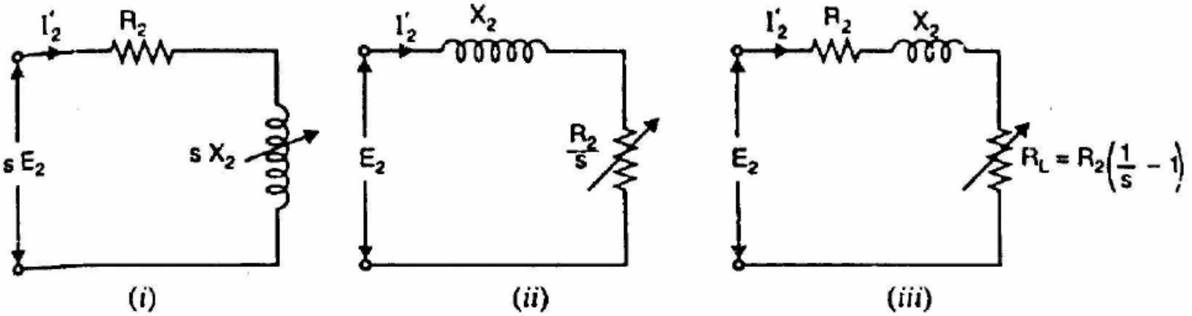


Fig: 3.10

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).

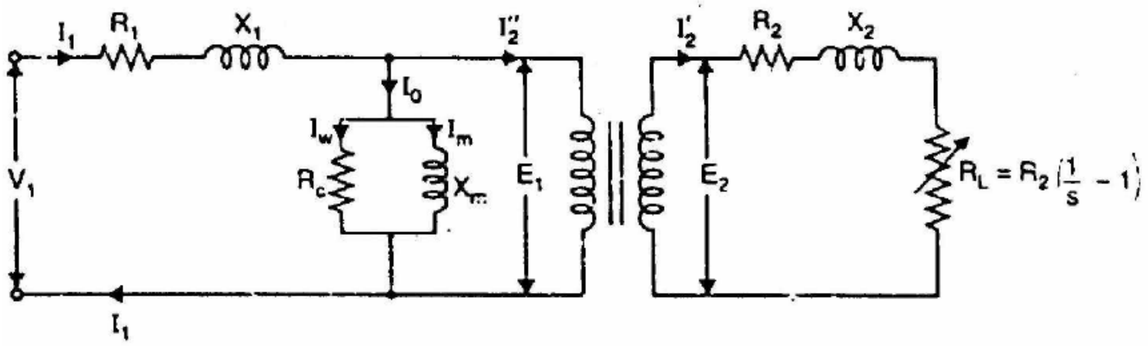


Fig: 3.11

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.

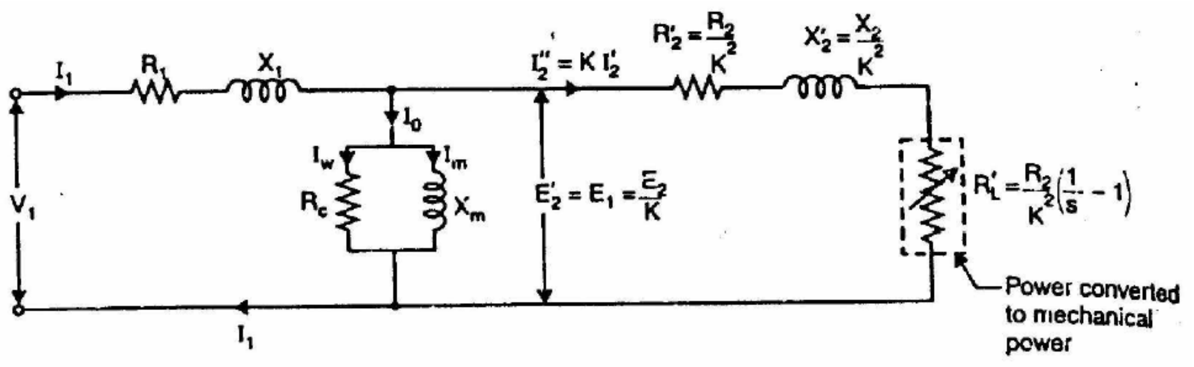


Fig: 3.12

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.

3.8 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).

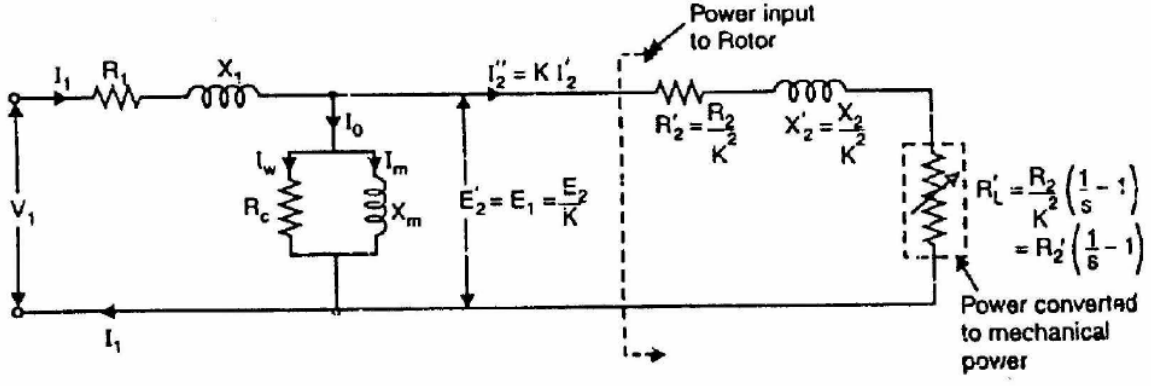


Fig: 3.13

(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,

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

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

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

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

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

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

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

3.9 Induction Motor Torque

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

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

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

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

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:

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

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

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

3.10 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.

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

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

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

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

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

(ii) Gross rotor output, P_m = Rotor input − Rotor Cu loss

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

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

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

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

It is clear that if the input power to rotor is “Pr” then “s.Pr” 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 arc neglected, then,

Gross rotor output = Useful output

Rotor input = 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%.

3.11.1 Torque Equations

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

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

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

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

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))

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

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

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

3.11.2 Rotor Torque

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

1. (i) rotor current
2. (ii) rotor e.m.f.
3. (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.

3.11.3 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.

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

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 $K = 3/2 \pi N_s$.

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

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

3.11.4 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,

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

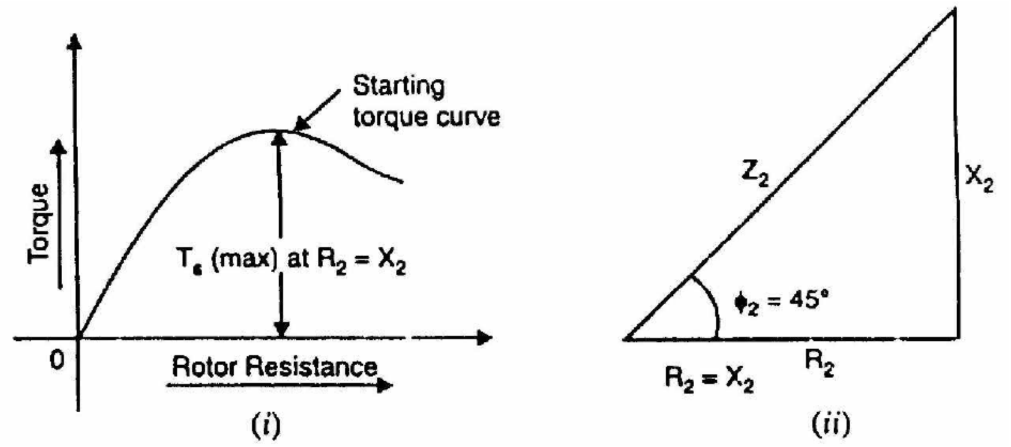
or $$R_2^2 + X_2^2 = 2R_2^2$$

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, $\phi_2 = 45°$ and rotor power factor is 0.707 lagging.



(i) (ii)

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.

3.11.5 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.

3.12 Circle Diagram

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

3.12.1 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).

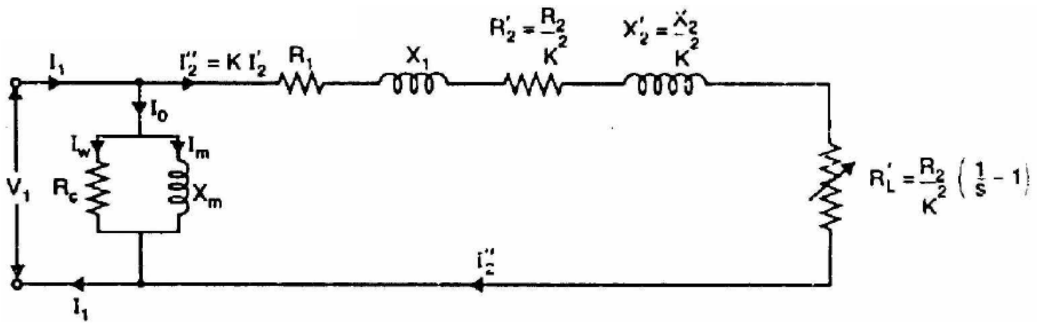


Fig: 3.15

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.

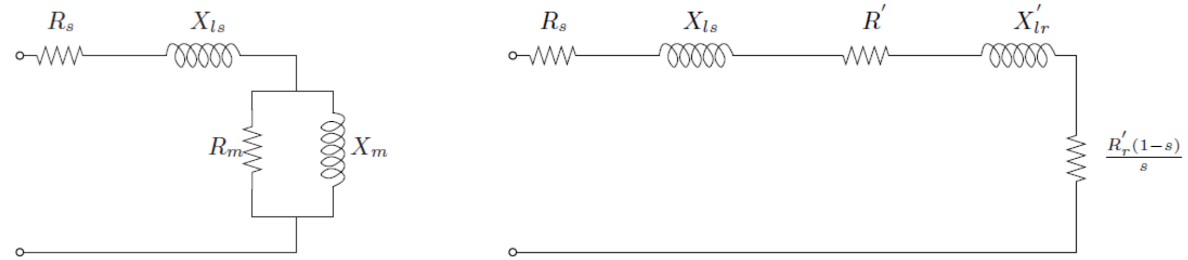
3.12.2 Tests to Determine the Equivalent Circuit Parameters

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 circuit 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 Rs = R′r, and Xs = 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.

3.12.3 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.

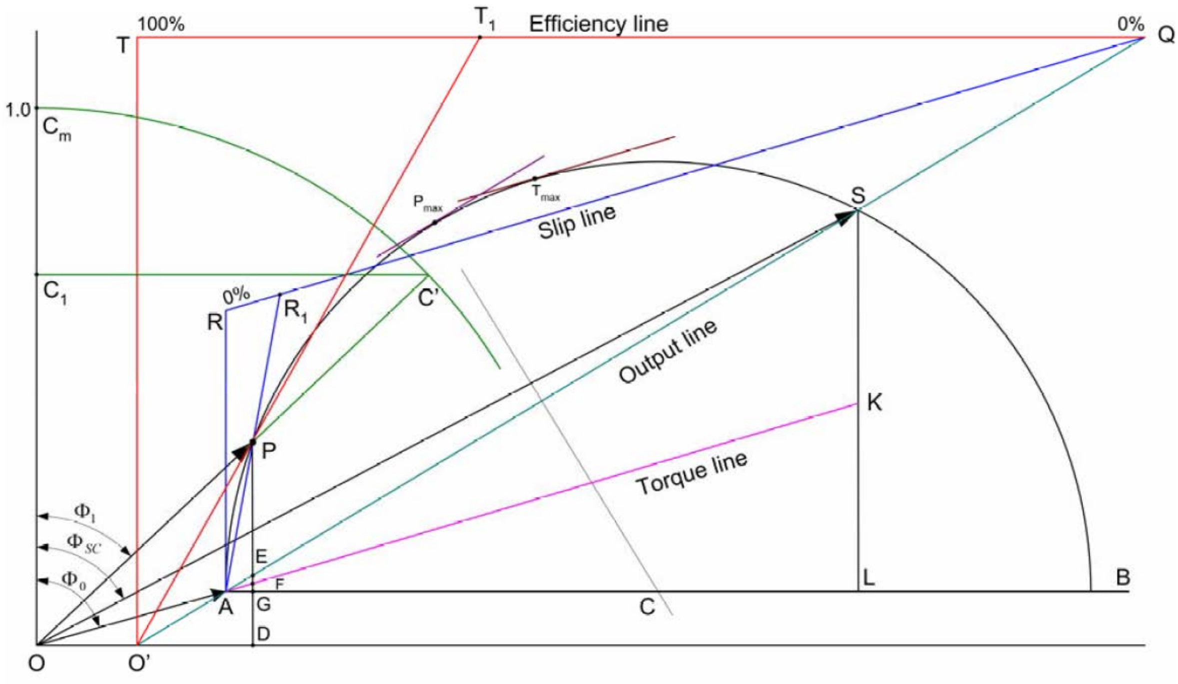


Fig: 3.17 Construction of Circle Diagram

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 C′C1 to meet the vertical axis at C1. Now OC1 represents power factor.

3.13 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.

3.13.1 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 I_s 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′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

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

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.

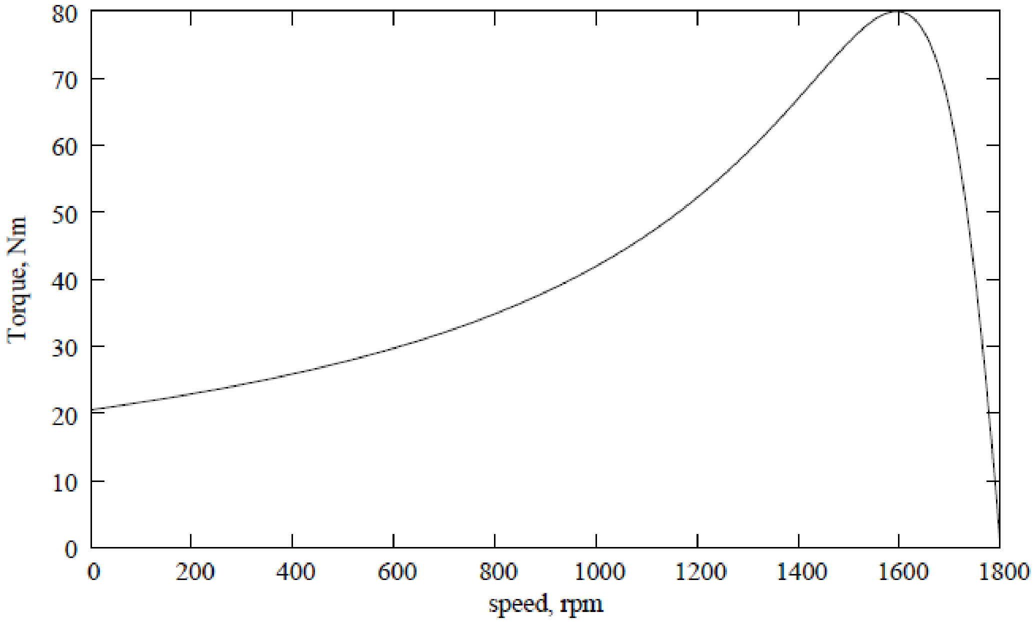


Fig: 3.18

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.

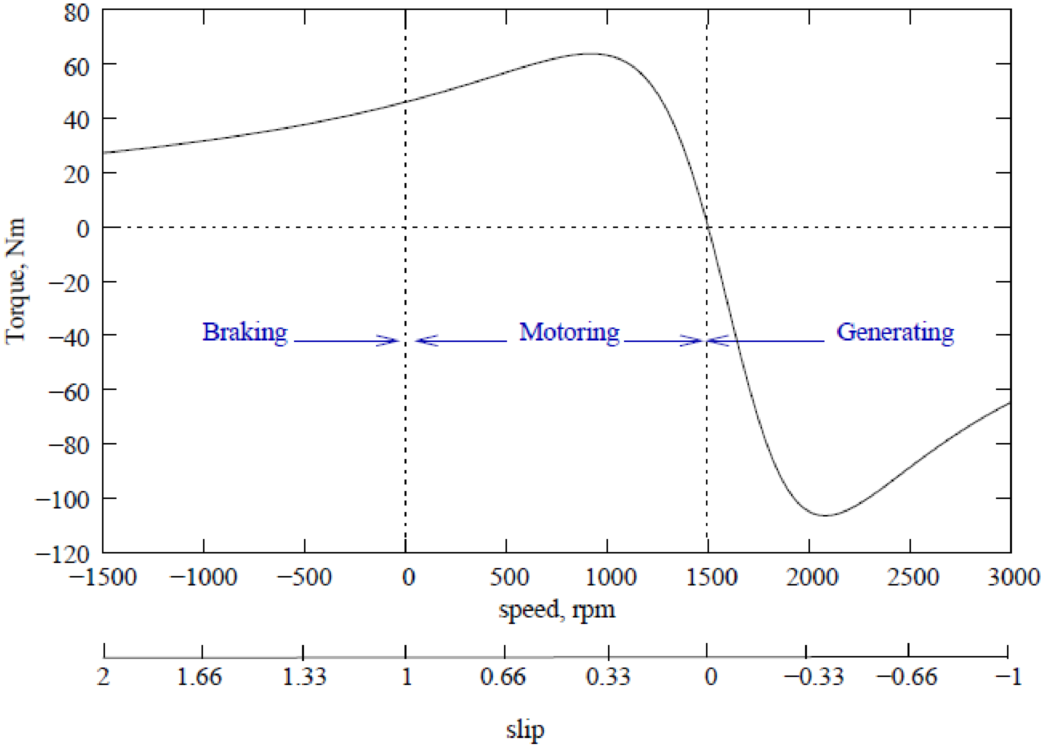


Fig: 3.19

3.13.2 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 ˆs, which for the machine of Fig: 3.19 is 0.38. At values of slip lower than ˆs, 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 = ˆs, 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 ˆs. Using this method, we can write –

$$\hat{s} = \frac{\pm R'_r}{\sqrt{R'^2_r + (X_{ls} + X'_{lr})^2}}$$

Substituting ˆs into the expression for torque gives us the value of the stalling torque ˆ Te,

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

- The negative sign being valid for negative slip.

The expression shows that ˆ Te is the independent of R′r, while ˆs is directly proportional to R′r. This 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.

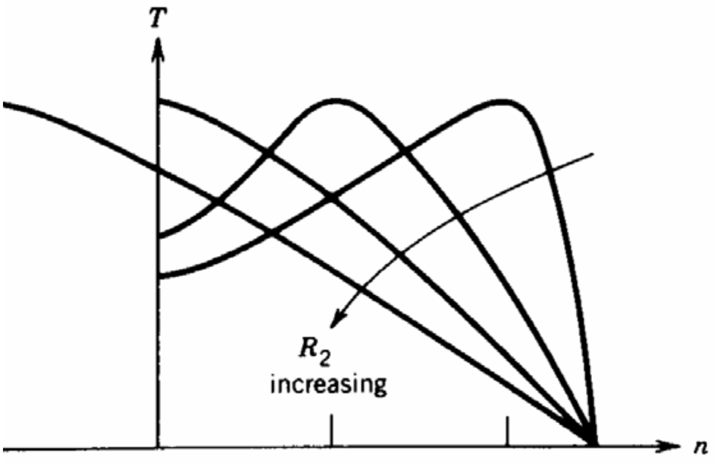


Fig: 3.20

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

3.13.3 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.

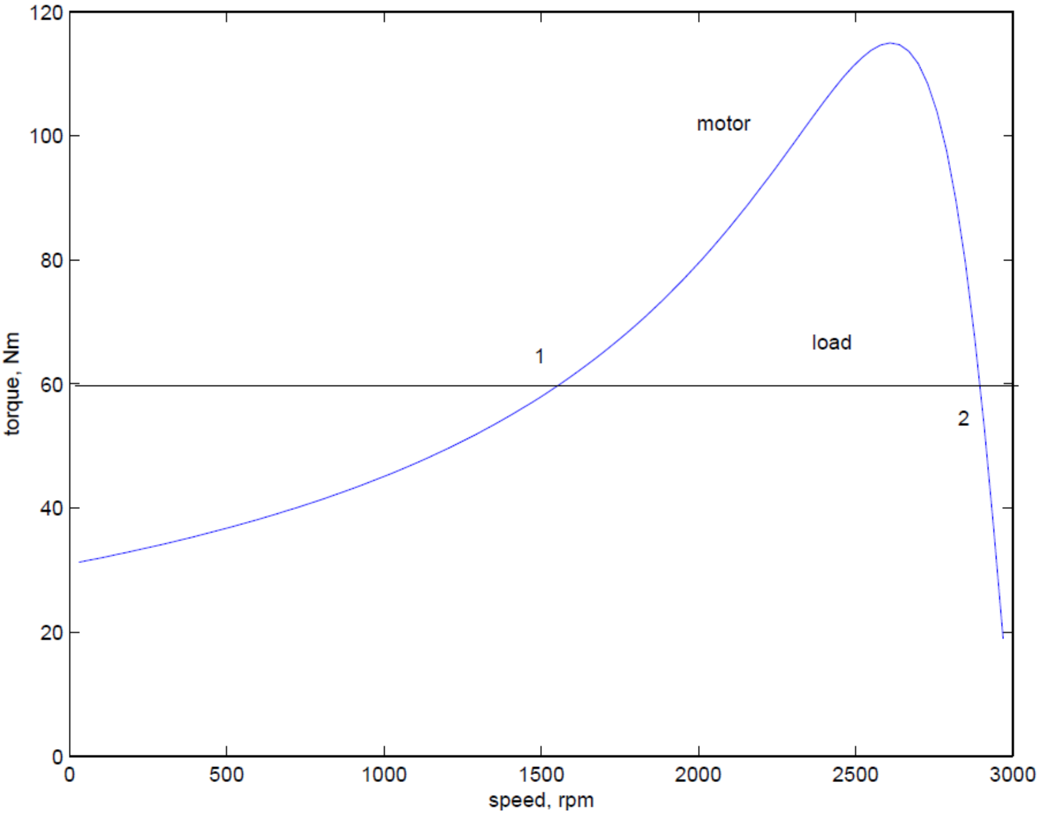


Fig: 3.21

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 △Te, 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.

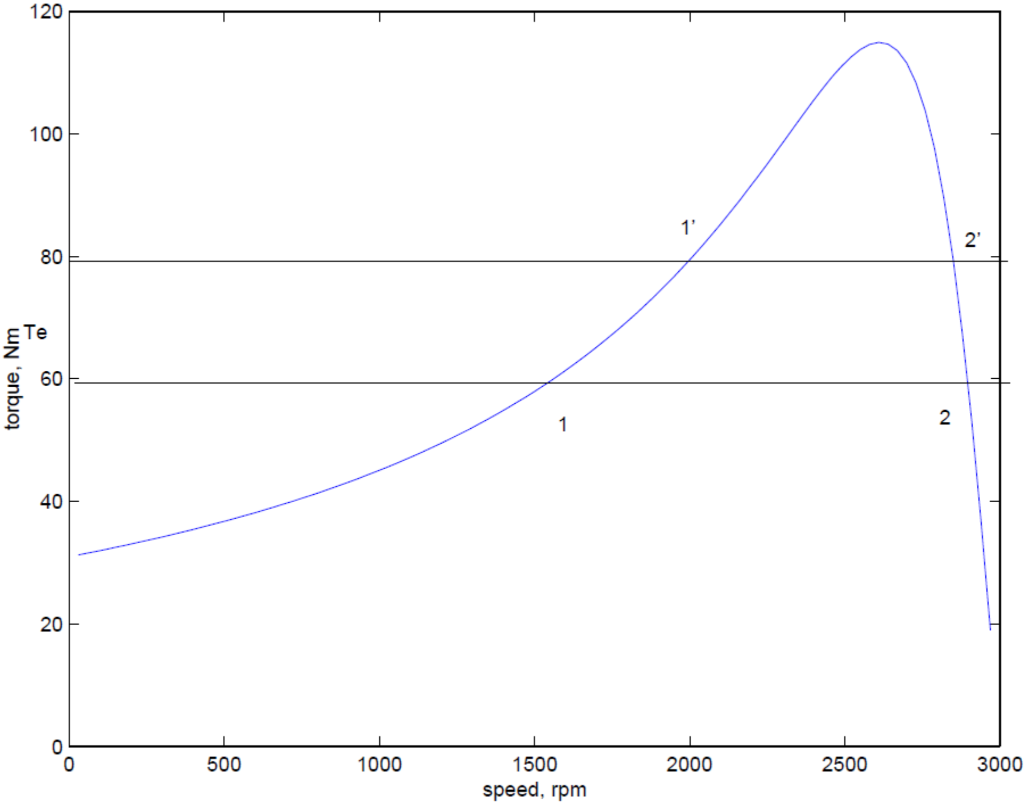


Fig: 3.22

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

3.14 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.

3.15 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.

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

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

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

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

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.

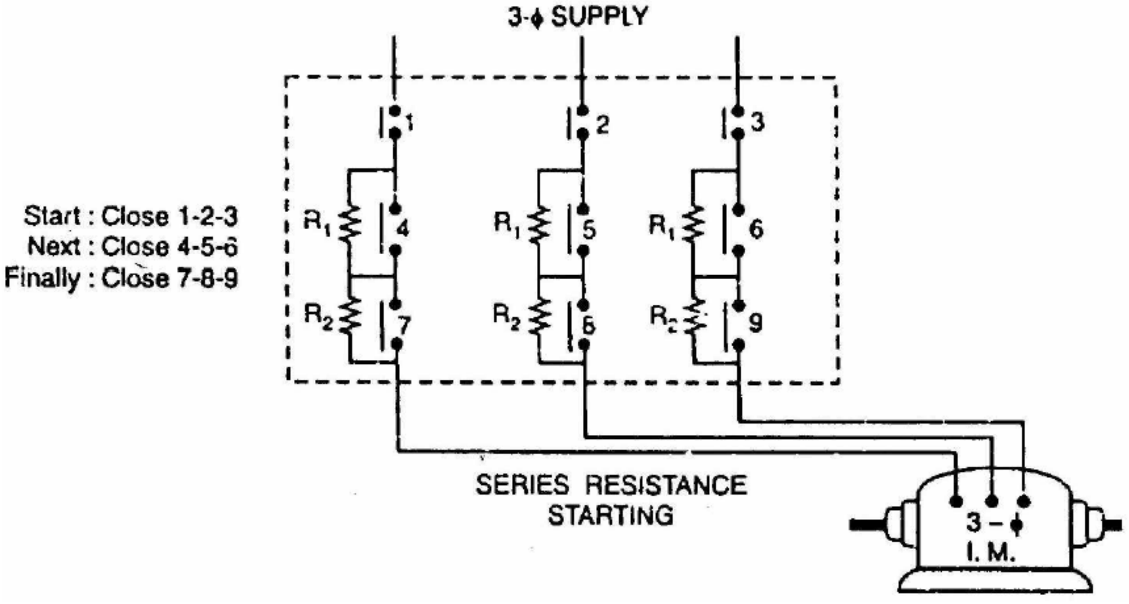


Fig: 3.23

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.

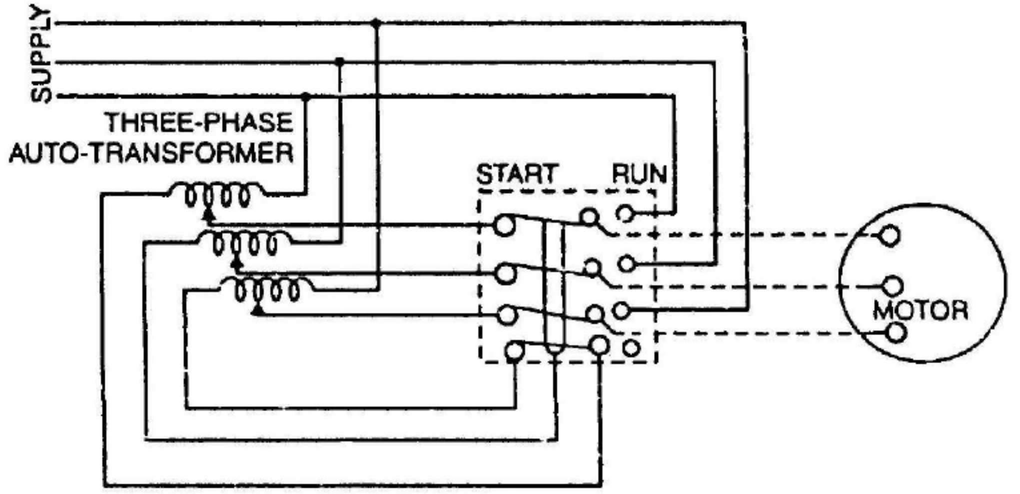


Fig: 3.24

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

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

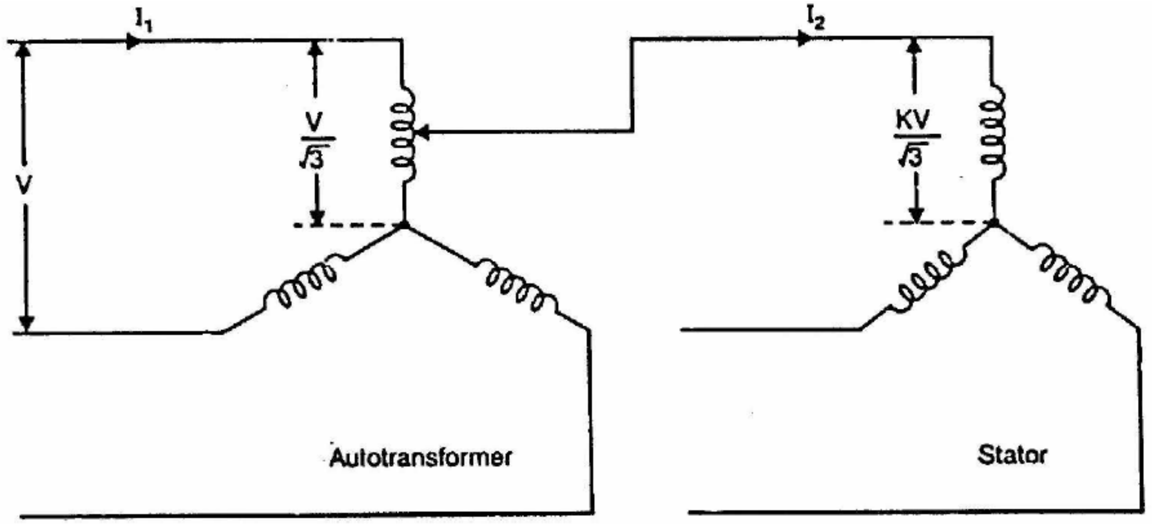


Fig: 3.25

The current taken from the supply or by autotransformer is $I_1 = KI_2 = K^2I_{sc}$. 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 $\left(1/\sqrt{3}\right)^2$ 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,

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

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)

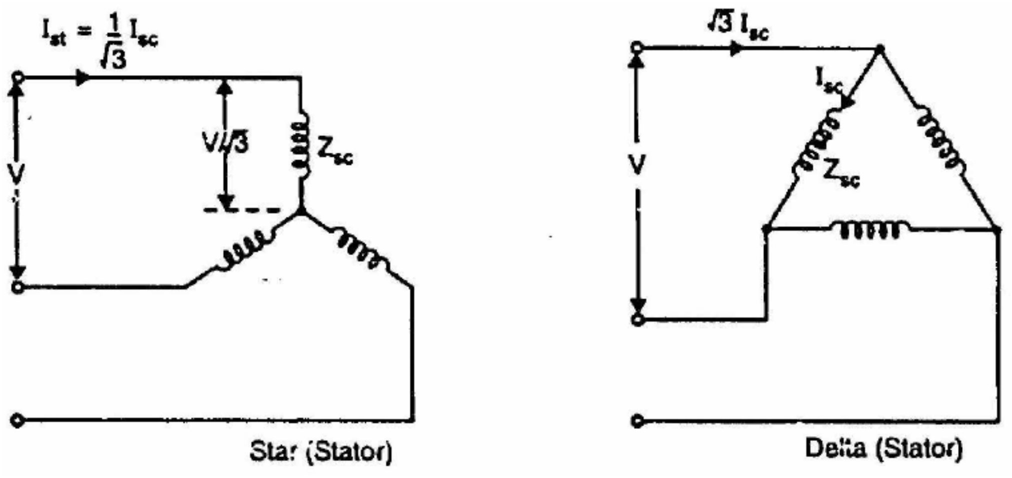


Fig: 3.26

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.

3.15.2 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.

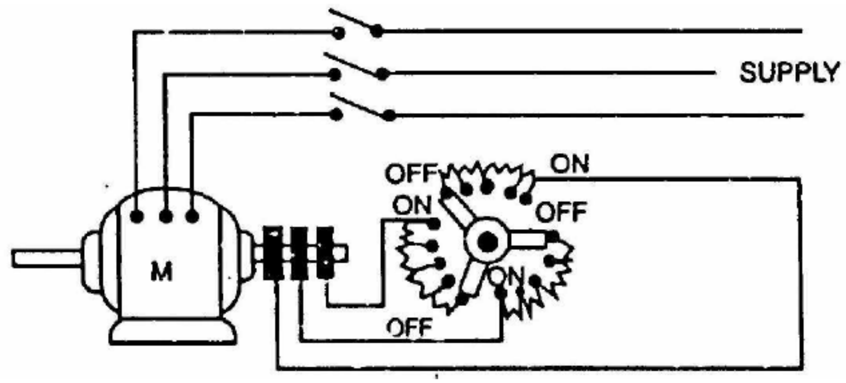


Fig: 3.27

(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.

3.16 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.

3.16.1 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 $\hat{s}$ 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 $T \propto \omega^2$.

Here one can see that it may be possible to run the motor to lower speeds within the range n_s to (1 − ˆs) 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.

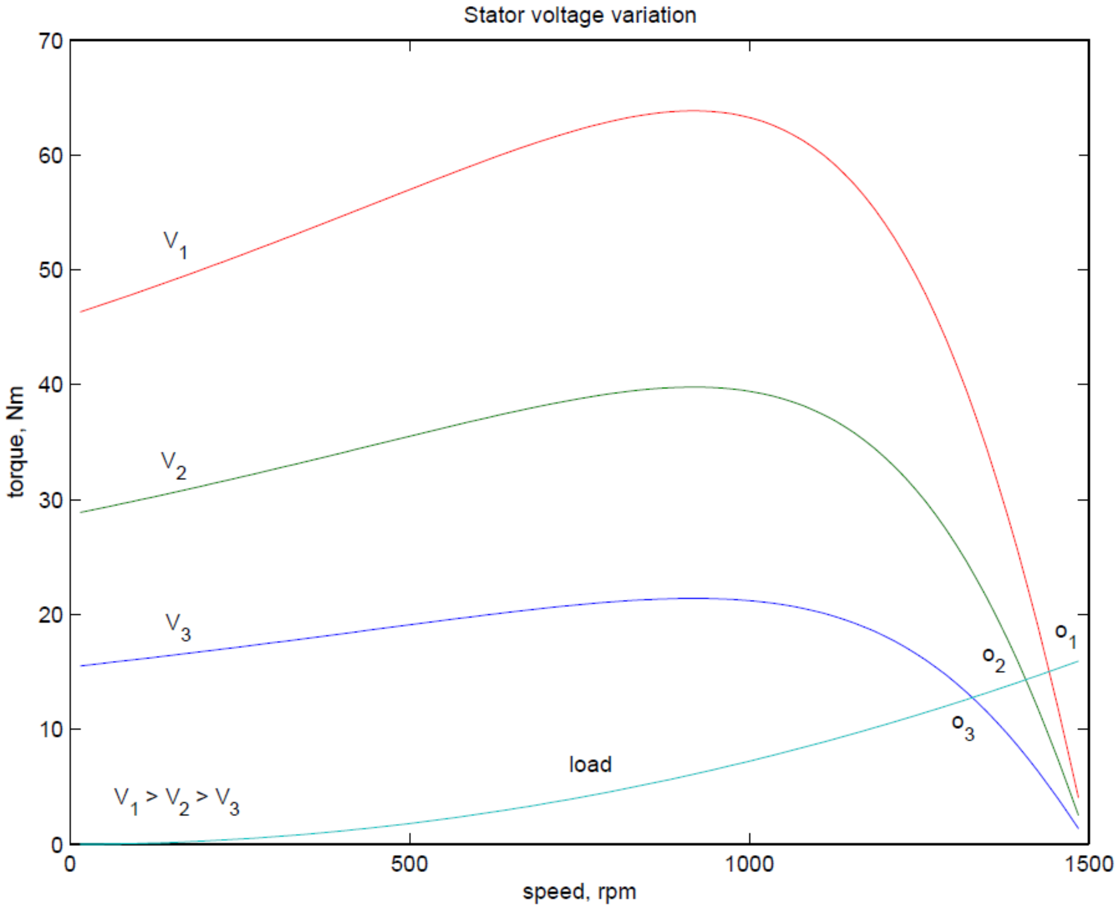


Fig: 3.28

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.

3.16.2 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.

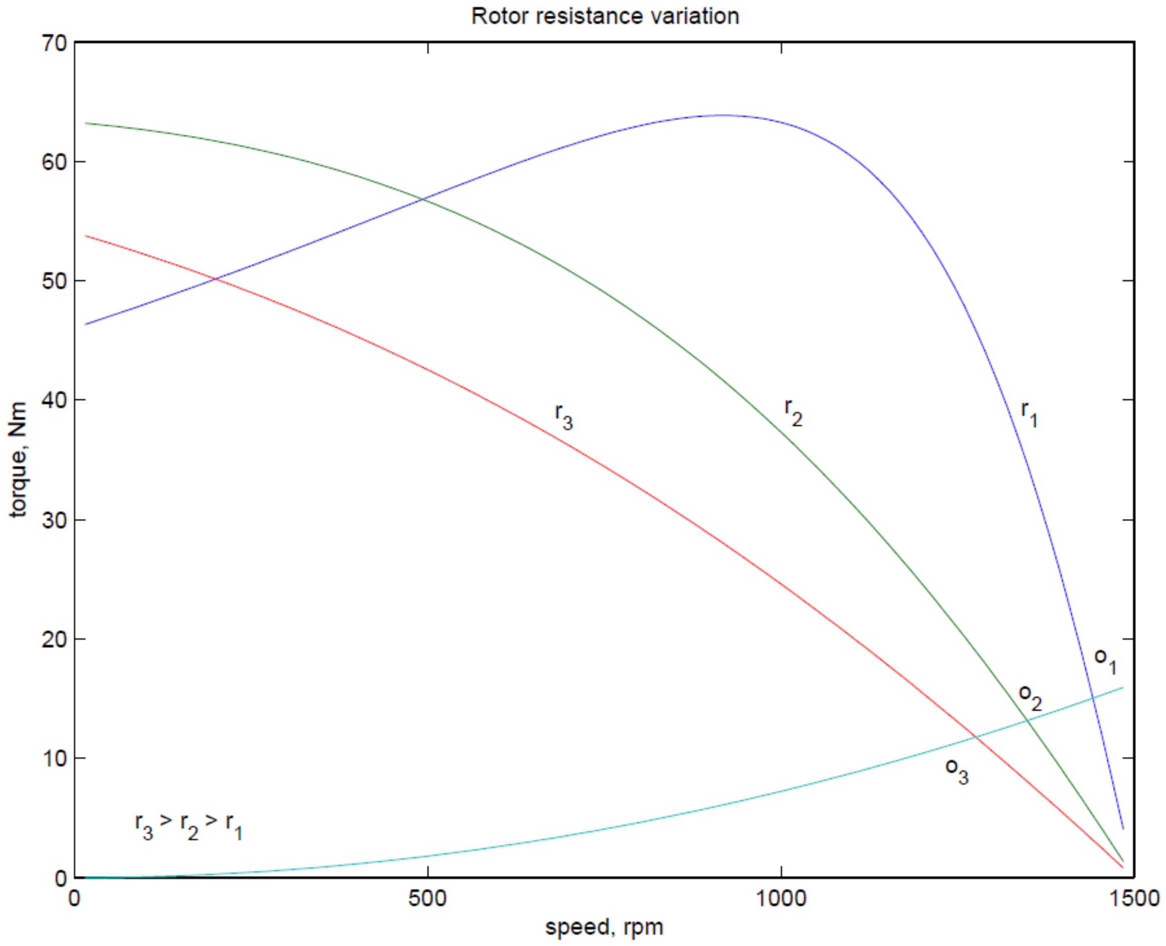


Fig: 3.29

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.

3.16.3 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,

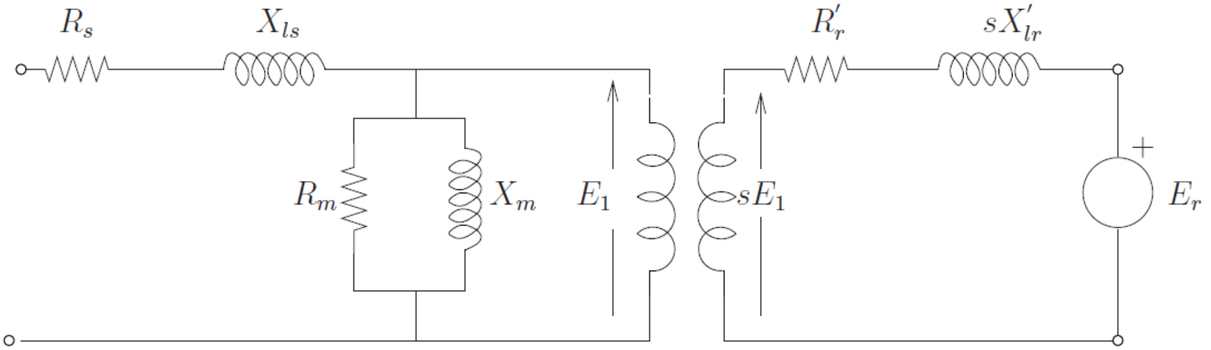
$$n = \frac{f_1}{p_1}(1 - s_1) = \pm\frac{s_1 f_1}{p_2}(1 - s_2).$$

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 results 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

$$sE_1I_2'\cos\phi_2 = I_2'R_2' + P_r.$$

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 $Pr = -I'^2_2\ R_2$ 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.

3.16.4 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.

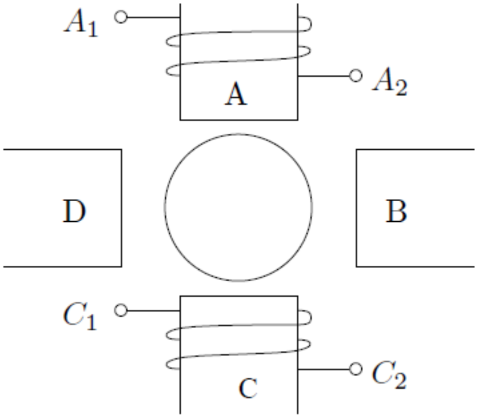


Fig: 3.31

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).

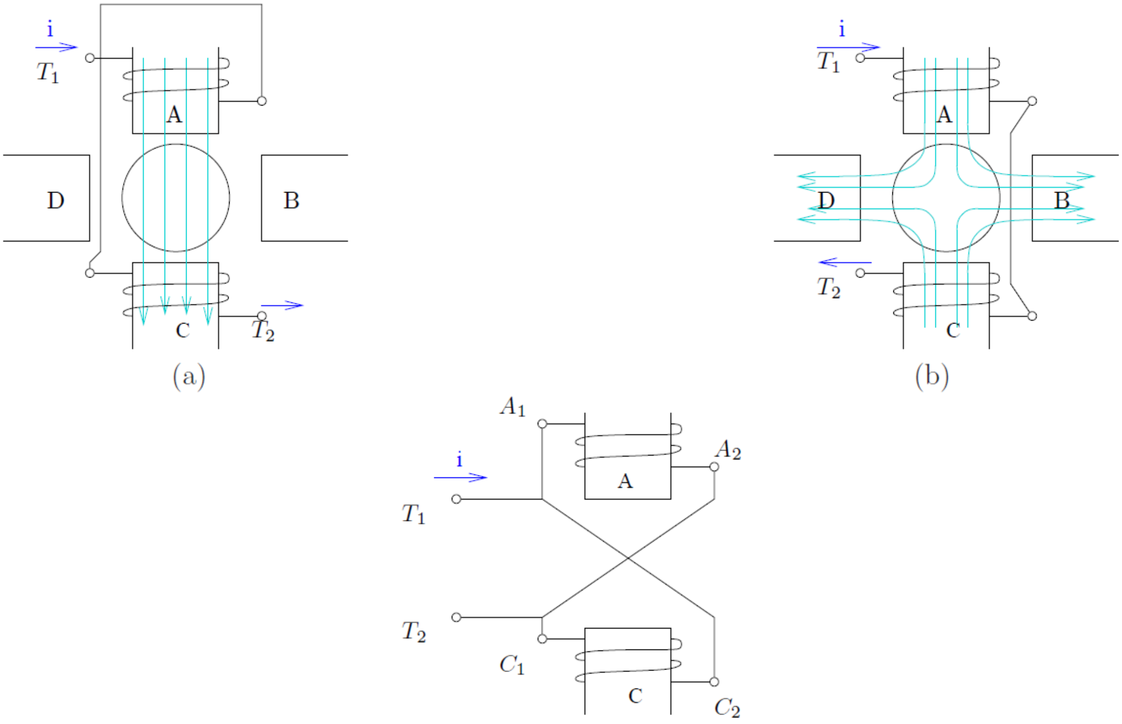


Fig: 3.32

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.

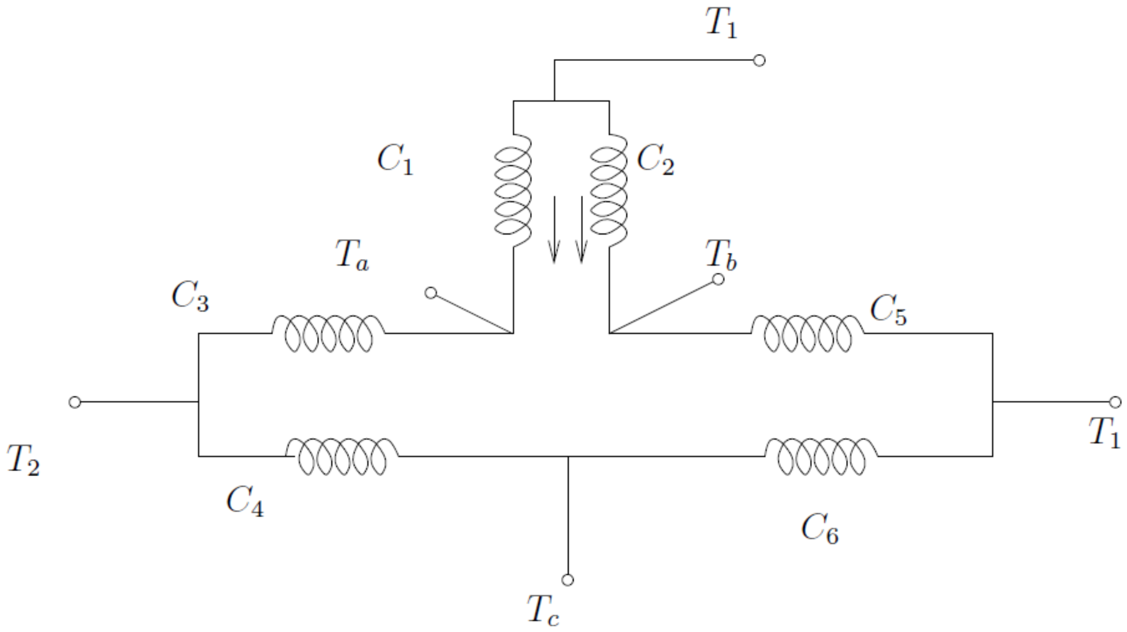


Fig: 3.33

3.16.5 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.

$$V = 4.44N\phi_m f$$

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.

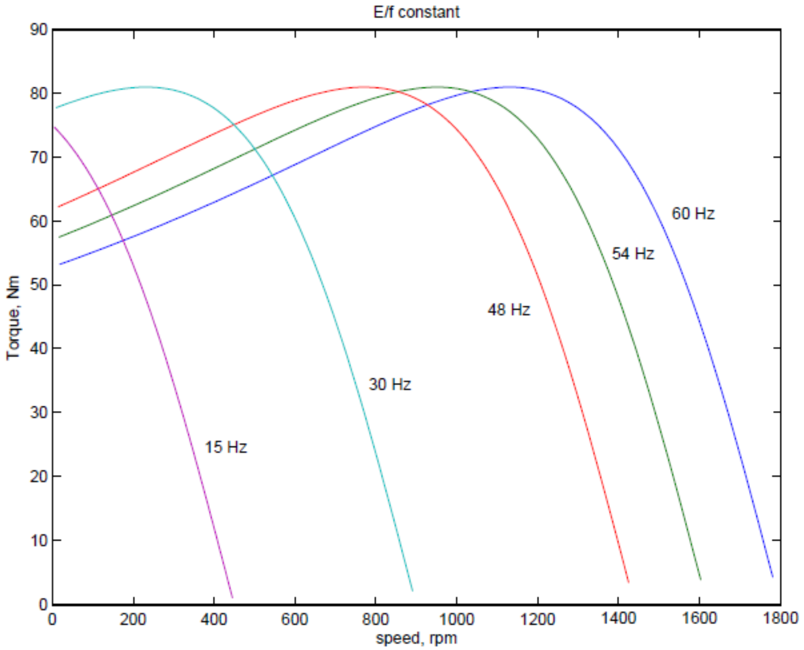


Fig: 3.34

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 $= 2\pi f$, 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 $\hat{s}$, we get $\hat{s} = \pm R'_r/(\omega L'_{lr})$. 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 $\hat{s}\omega$ 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.

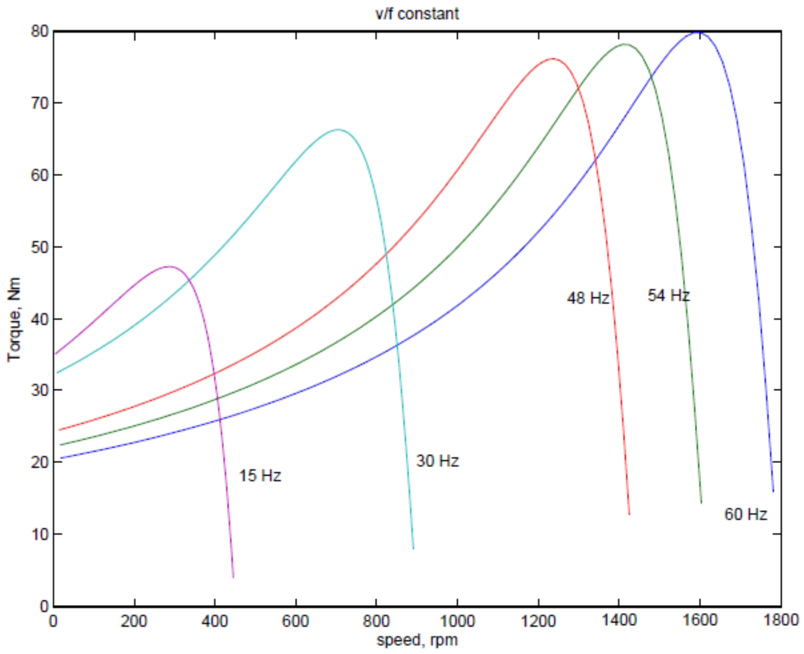


Fig: 3.35

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

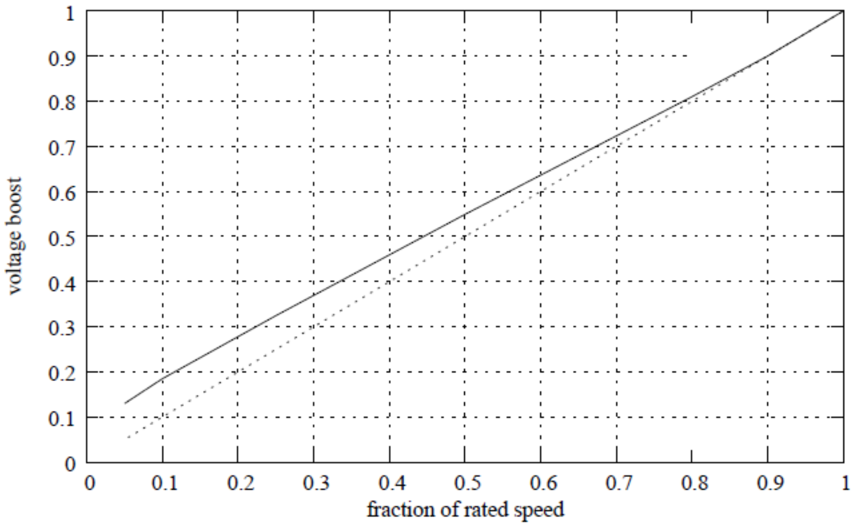


Fig: 3.36

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.

3.17 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.

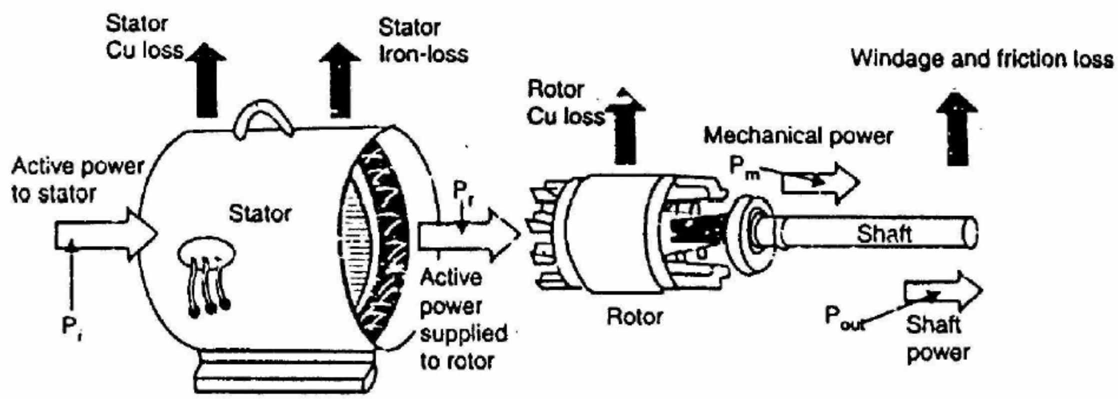


Fig: 3.37

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.

3.18 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.

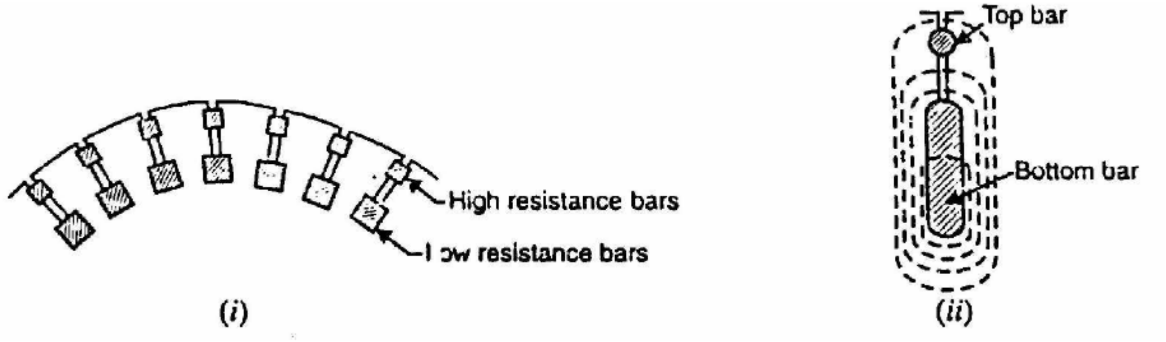


Fig: 3.38

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.

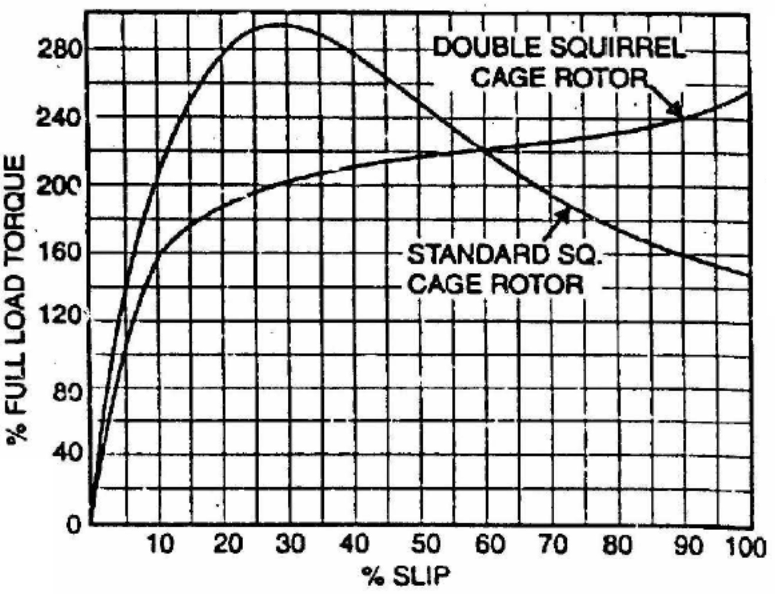


Fig: 3.39

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.

3.19 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*.

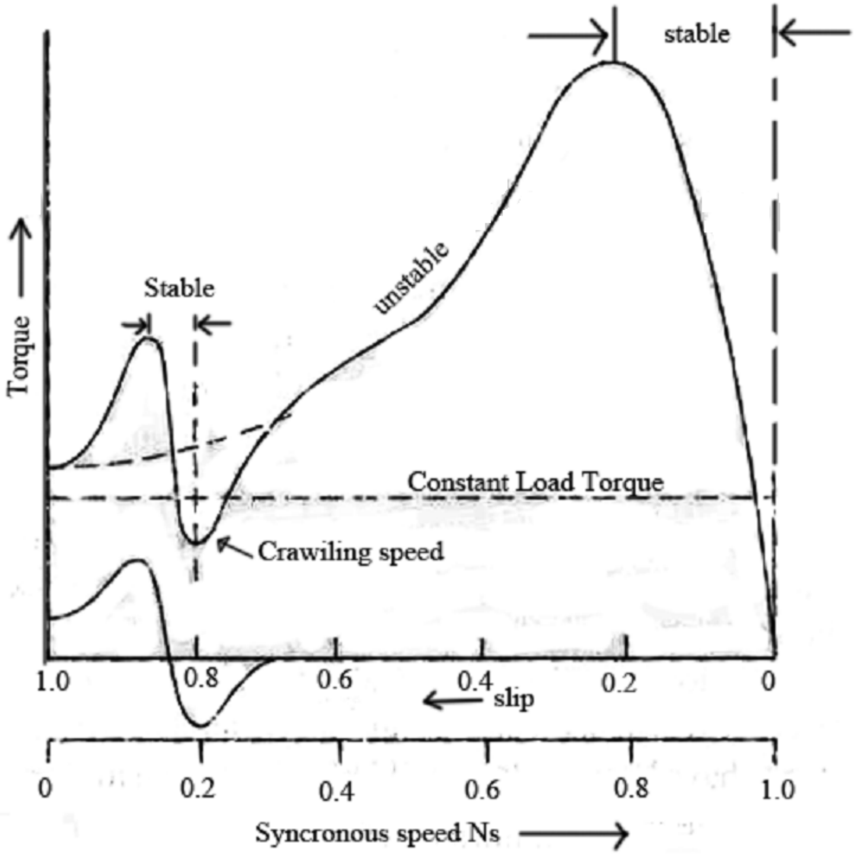


Fig: 3.40

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.

3.20 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.

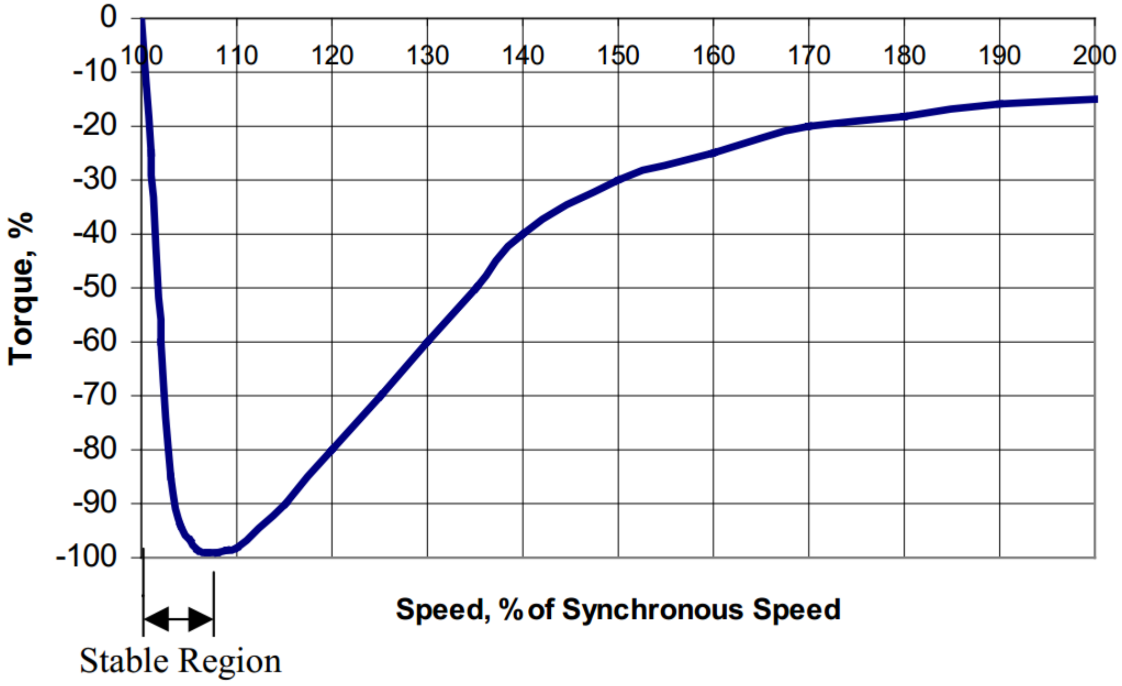


Fig: 3.41

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.

Module -IV

4. Single Phase Induction Motors

Single phase Induction motors perform a great variety of useful services at home, office, farm, factory and in business establishments. Single phase motors are generally manufactured in fractional HP ratings below 1 HP for economic reasons. Hence, those motors are generally referred to as fractional horsepower motors with a rating of less than 1 HP. Most single phase motors fall into this category. Single phase Induction motors are also manufactured in the range of 1.5, 2, 3 and up to 10 HP as a special requirement.

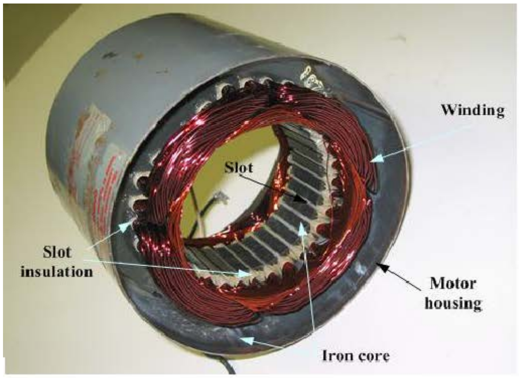


Fig: 4.1(a) Stator

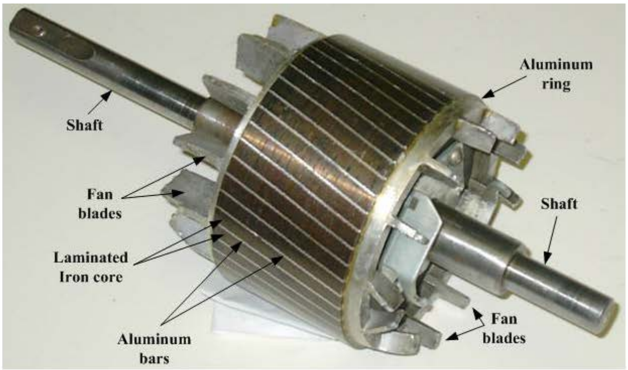


Fig: 4.1(b) Squirrel cage rotor

4.1 Theory of Operation

A single phase induction motor is similar in construction to that of a polyphase induction motor with difference that its stator has only one winding. If such a stator is supplied with single phase alternating current, the field produced by it changes in magnitude and direction sinusoidally. Thus the magnetic field produced in the air gap is alternating one but not rotating as a result these kind of motors are *NOT SELF STARTING*. Fig: 4.2 (a) shows the torque-speed characteristic of single phase induction motor.

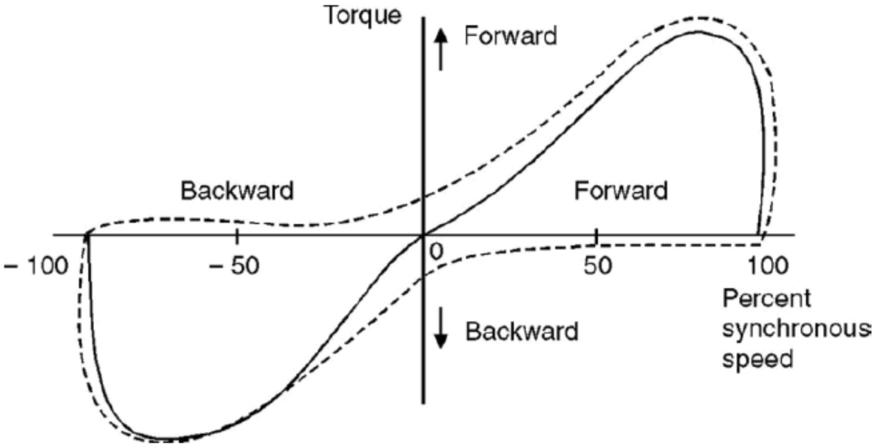


Fig: 4.2 (a)

Such an alternating filed is equivalent to two fields of equal magnitude rotating in opposite directions at equal speed as explained below:

4.1.1 *Double Revolving Field Theory of Single Phase Induction Motor*

Consider two magnetic fields represented by quantities OA and OB of equal magnitude revolving in opposite directions as shown in fig: 4.1.

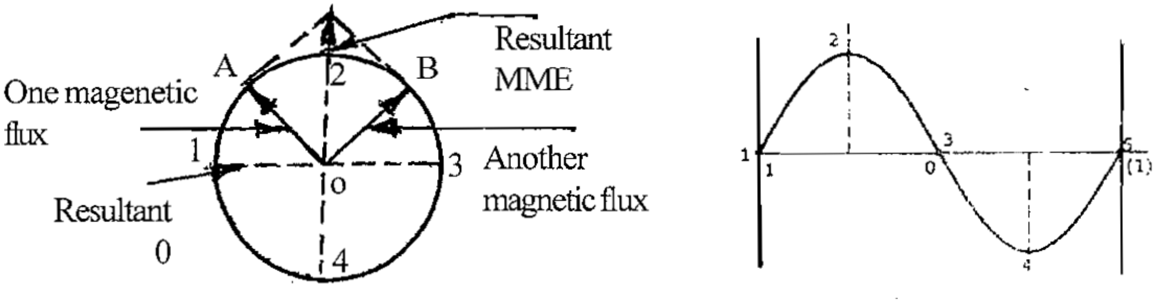


Fig: 4.2 (b)

The resultant of the two fields of equal magnitude rotating in opposite directions is alternating. Therefore an alternating current can be considered as having two components which are of equal in magnitude and rotating in opposite directions.

From the above, it is clear that when a single phase alternating current is supplied to the stator of a single phase motor, the field produced will be of alternating in nature which can be divided into two components of equal magnitude one revolving in clockwise and other in counter clockwise direction.

If a stationary squirrel cage rotor is kept in such a field equal forces in opposite direction will act and the rotor will simply vibrate and there will be no rotation.

But if the rotor is given a small jerk in any direction in this condition, it will go on revolving and will develop torque in that particular direction. It is clear from the above that a single phase induction motor when having only one winding is not a self-starting. To make it a self-starting anyone of the following can be adopted.

(i) Split phase starting.
(ii) Repulsion starting.
(iii) Shaded pole starting.

4.2 EQUVALENT CIRCUIT OF SINGLE PHASE INDUCTION MOTOR

The equivalent circuit of single phase induction motor is shown below (Fig: 4.3)

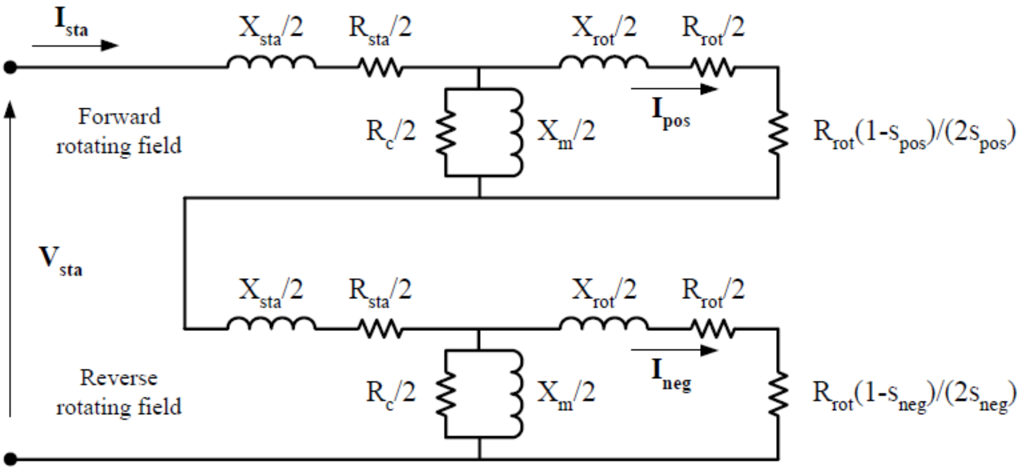


Fig: 4.3

4.2.1 **Determination of Equivalent Circuit Parameters of Single Phase Induction motor**

It is possible to find the parameters of the equivalent circuit of the single phase induction motor experimentally as shown in Fig.4.4. For this purpose, three tests should be conducted:

1- The DC Test:

The DC resistance of the stator can be measured by applying DC current to the terminals of the main winding and taking the reading of the voltage and the current (or using ohmmeter) and determine the DC resistance as follows:

$$R_{DC} = \frac{V_{DC}}{I_{DC}}$$

Then, the AC resistance is given by:

$$R_{AC} = 1.25\ R_{DC}$$

2-The Blocked Rotor Test:

When the rotor is locked (i.e. prevented from running), $\mathbf{S_b = S_f = 1}$. The secondary impedances become much less than the magnetizing branches and the corresponding equivalent circuit becomes that of Fig: 4.5.

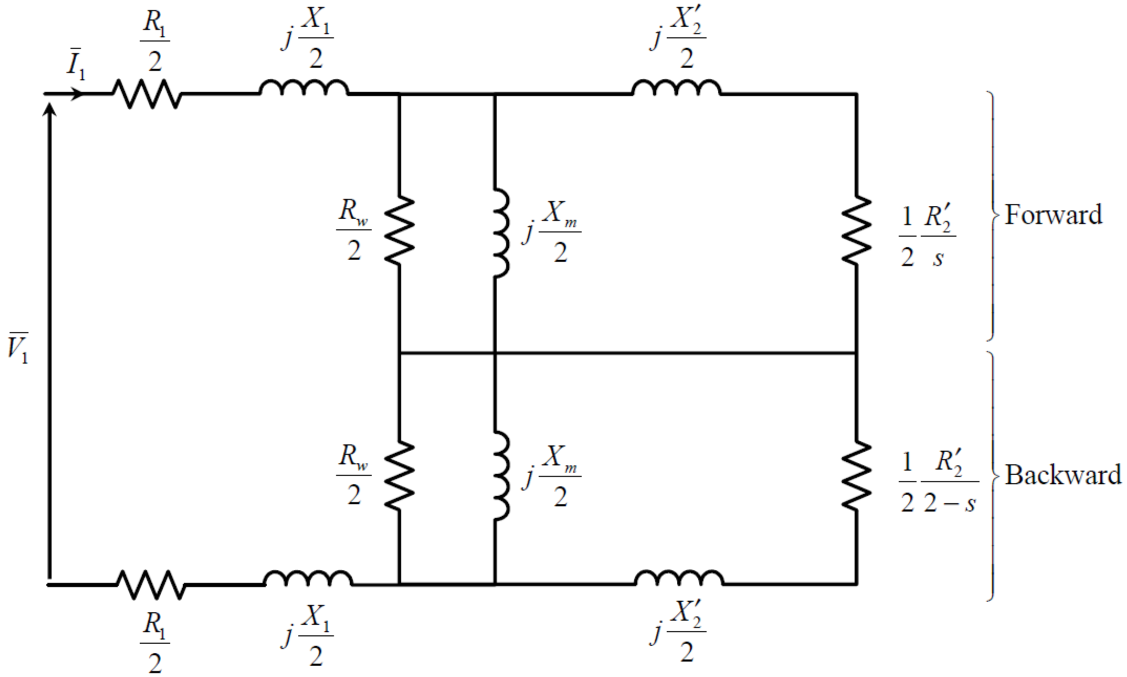


Fig: 4.4 Equivalent circuit of single phase induction motor.

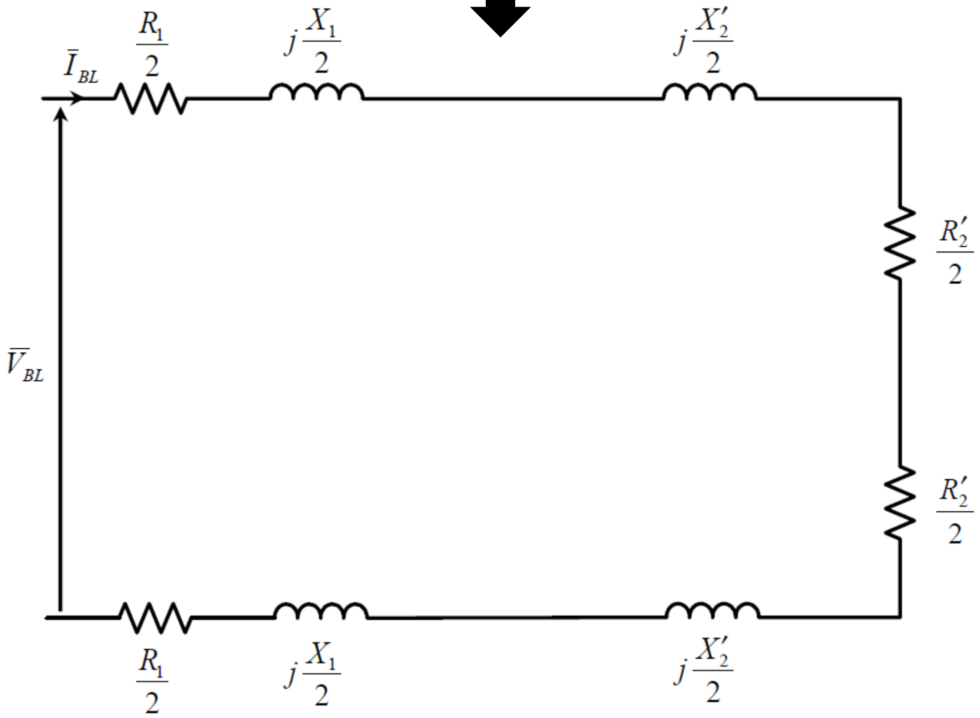


Fig: 4.5(a) Approximate equivalent circuit of the single phase induction motor at standstill.

The circuit in Fig: 4.5 (a) can be rearranged to the equivalent circuit that is shown in Fig: 4.5(b).

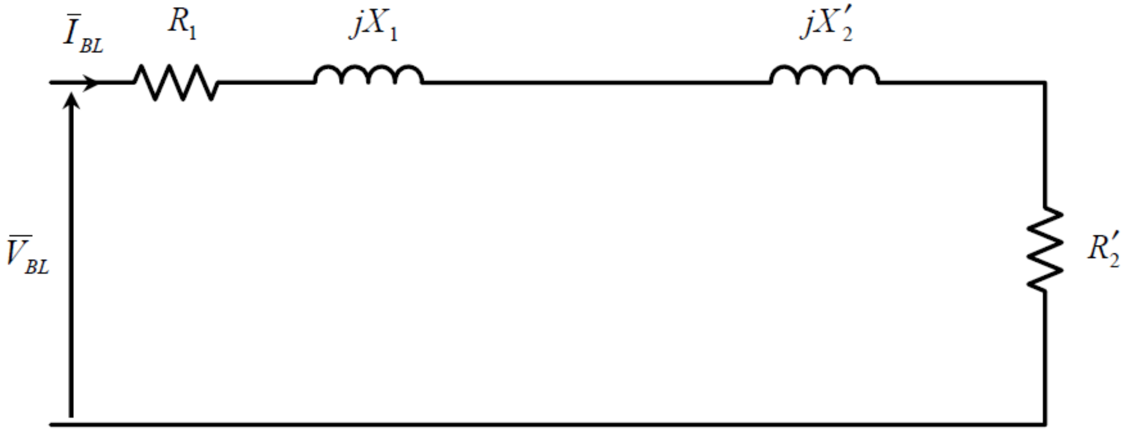


Fig: 4.5(b) Rearranged approximate equivalent circuit of the single phase induction motor at standstill.

The readings to be obtained from this test are:

a) Single phase power P_{BL}

b) Phase voltage V_{BL}

c) Phase current I_{BL}

Then, R_{eq}, Z_{eq}, and X_{eq} can be obtained using the following equations:

$$R_{eq} = \frac{P_{BL}}{I_{BL}^2}$$

$$Z_{eq} = \frac{V_{BL}}{I_{BL}}$$

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

Separation of X_1, X'_2, R_1, and R'_2 can be done as follows:

$$X_1 = X'_2 = \frac{1}{2} X_{eq}$$

$$R'_2 = R_{eq} - R_1$$

3-The No Load Test:

When the induction motor is allowed to run freely at no load, the forward slip **S_f** approaches zero and the backward slip **S_b** approaches 2 (**$S_f = s$, $S_b = 2-s$**). The secondary forward impedance becomes very large with respect to the magnetizing branch, while the secondary backward impedance becomes very small if compared with the magnetizing branch. Accordingly, the equivalent circuit corresponding to these operating conditions can be approximated by that of Fig: 4.6.

The readings to be obtained from this test are:

d) Single phase power P_{NL}

e) Phase voltage V_{NL}

f) Phase current I_{NL}

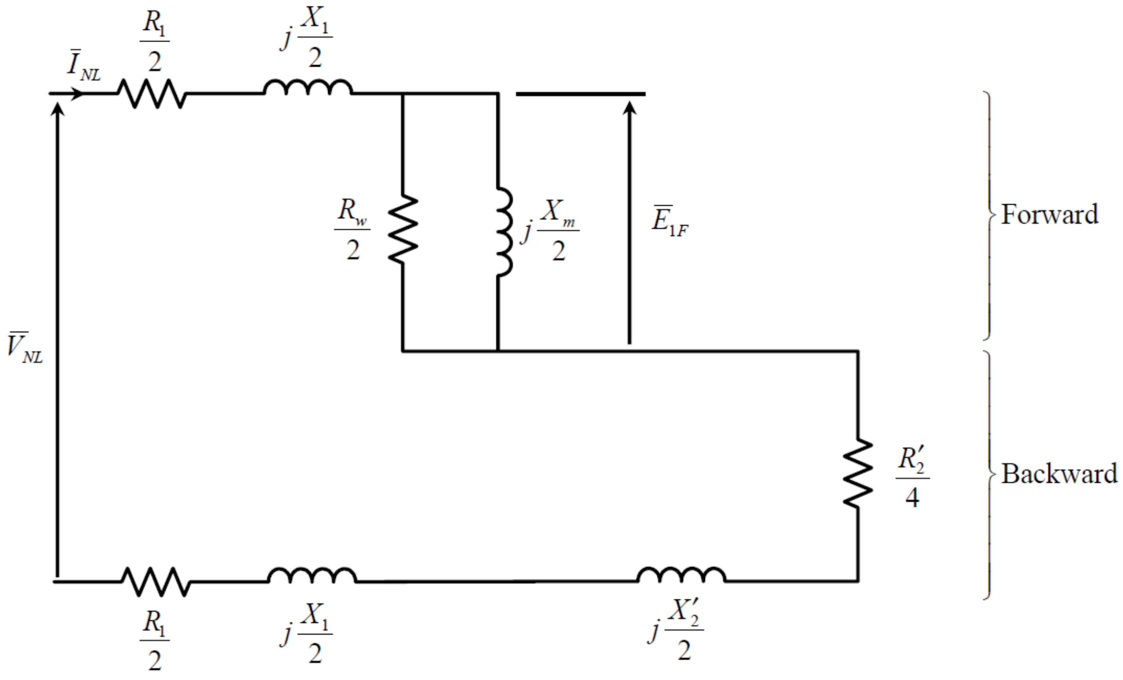


Fig: 4.6 (a) Approximate equivalent circuit of the single phase induction motor at no load.

⬇

The circuit in Fig: 4.6 (a) can be rearranged to the equivalent circuit that is shown in Fig: 4.6 (b)

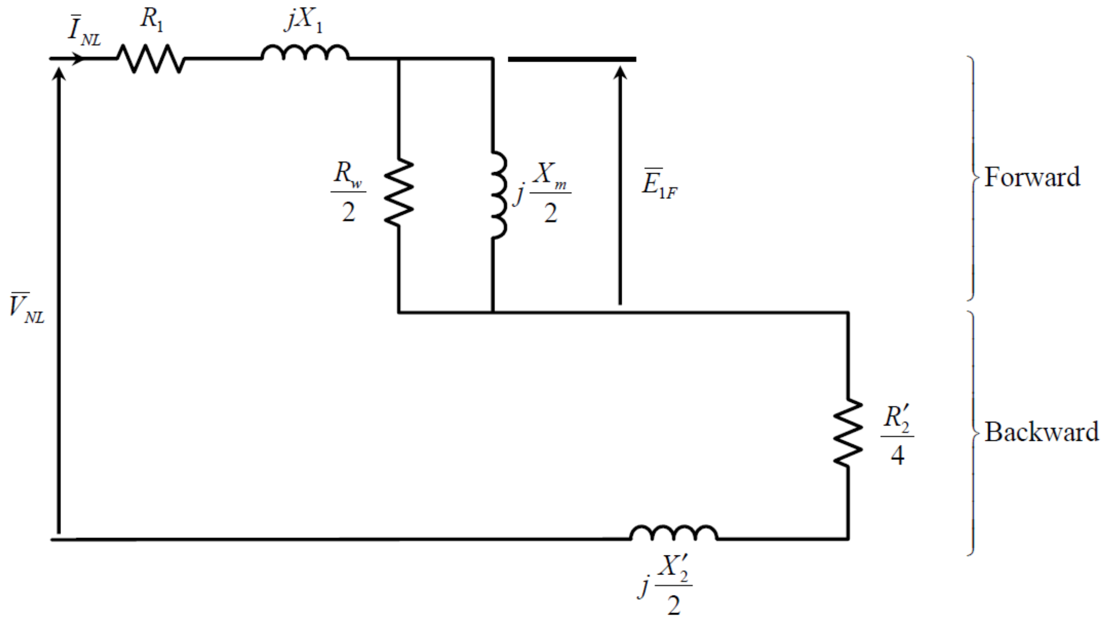


Fig: 4.6 (b) Rearranged approximate equivalent circuit of the single phase induction motor at no load

Then, R_w, and X_m, can be obtained as fallows:

$$P_{core+mechanical} = P_{NL} - I_{NL}^2\left(R_1 + \frac{R_2'}{4}\right)$$

$$\bar{E}_{1F} = \bar{V}_{NL} - \bar{I}_{NL}\left(\left(R_1 + \frac{R_2'}{4}\right) + j\left(X_1 + \frac{X_2'}{2}\right)\right)$$

Note: $(\bar{I}_{NL} = I_{NL}\angle -\theta, \quad \theta = \cos^{-1}\frac{P_{NL}}{V_{NL}\, I_{NL}})$

$$R_w = 2\frac{|E_{1F}|^2}{P_{core+mechanical}}$$

$$I_w = \frac{|E_{1F}|}{\left(\frac{R_w}{2}\right)} = 2\frac{|E_{1F}|}{R_w}$$

$$I_m = \sqrt{I_{NL}^2 - I_w^2}$$

$$X_m = 2\frac{|E_{1F}|}{I_m}$$

4.3 **Methods of Starting**

It is clear from previous discussion that a single phase induction motor when having only one winding and it is not self-starting. To make it a self-starting anyone of the following can be adopted.

(1) Split phase starting.

(2) Repulsion starting.

(3) Shaded pole starting.

4.3.1 PRINCIPLE OF SPLIT PHASE INDUCTION MOTOR

The basic principle of operation of a split phase induction motor is similar to that of a polyphase induction motor. The main difference is that the single phase motor does not produce a rotating magnetic field but produces only a pulsating filed.

Hence, to produce the rotating magnetic field for self-starting, phase splitting is to be done to make the motor to work as a two phase motor for starting.

4.3.1 ***Working of Split Phase Motor***

In split phase motor two windings named as main winding and starting winding are provided. At the time of starting, both the main and starting windings should be connected across the supply to produce the rotating magnetic field.

The rotor is of a squirrel cage type and the revolving magnetic field sweeps part the stationary rotor, inducing emf in the rotor. As the rotor bars are short-circuited, a current flows through them producing a magnetic field.

This magnetic field opposes the revolving magnetic field and will combine with the main filed to produce a revolving filed. By this action, the rotor starts revolving in the same direction of the rotating magnetic field as in the case of a squirrel cage induction motor.

Hence, once the rotor starts rotating, the starting winding can be disconnected from the supply by some mechanical means as the rotor and stator fields from a revolving magnetic field. There are several types of split phase motors.

4.3.2 TYPES OF SPLIT-PHASE INDUCTION MOTORS

1. Resistance-start, induction-run motors
2. Capacitor-start, induction-run motors
3. Capacitor-start, capacitor-run motors
4. Shaded pole motors.

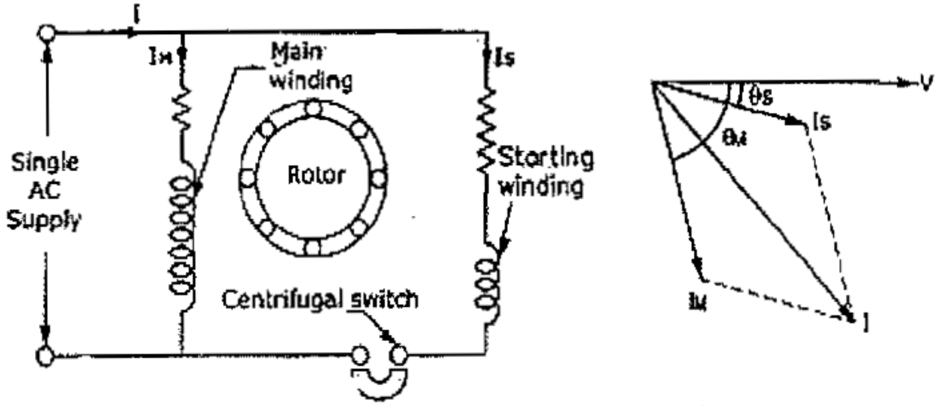
1. RESISTANCE-START, INDUCTION-RUN MOTORS

As the starting torque of this type of motor is relatively small and its starting current is high, these motors are most commonly used for rating up to 0.5 HP where the load could be started easily. The essential parts are shown in Fig: 4.7.

- Main winding or running winding.
- Auxiliary winding or starting winding
- Squirrel cage type rotor.
- Centrifugal switch.

CONSTRUCTION AND WORKING

The starting winding is designed to have a higher resistance and lower reactance than the main winding. This is achieved by using small conductors in the auxiliary winding than in the main winding. The main winding will have higher inductance when surrounded by more iron, which could be made possible by placing it deeper into the stator slots, it is obvious that the current would split as shown in Fig: 4.7(b).



a)Schamatic diagram

b)Vector diagram

Fig: 4.7

The starting current "I" start will lag the main supply voltage "V" line by 15 degree and the main winding current. "I" main lags the main voltage by about 80 degree. Therefore, these currents will differ in time phase and their magnetic fields will combine to produce a rotating magnetic field.

When the motor has come upto about 75 to 80% of synchronous speed, the starting winding is opened by a centrifugal switch and the motor will continue to operate as a single phase motor.

CHARACTERISTICS

At the point where the starting winding is disconnected, the motor develops nearly as much torque with the main winding alone as with both windings connected. This can be observed from, the typical torque-speed characteristics of this motor, as shown in Fig: 4.8.

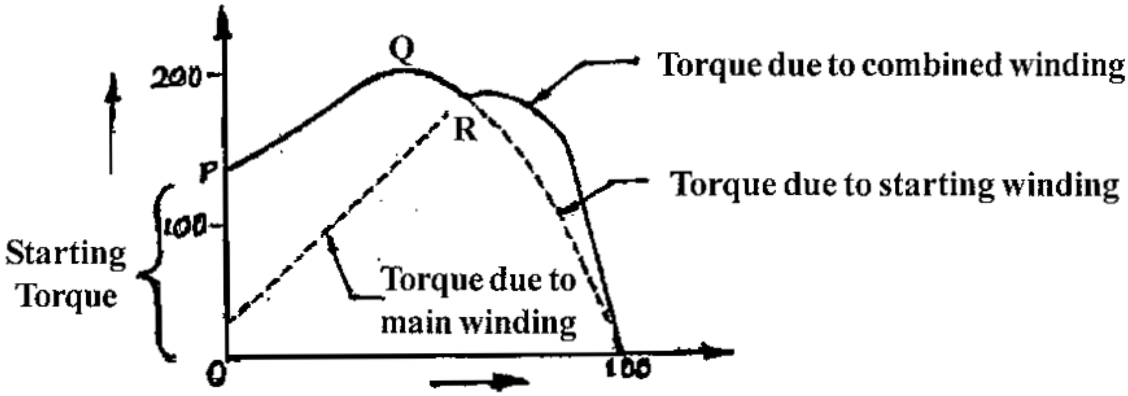


Fig: 4.8

The direction of rotating of a split-phase motor is determined by the way the main and auxiliary windings are connected. Hence, either by changing the main winding terminals or by changing the starting winding terminals, the reversal of direction of rotating could be obtained.

APPLICATIONS

These motors are used for driving fans, grinders, washing machines.

2. CAPACITOR-START, INDUCTION-RUN MOTOR

A drive which requires a large starting torque may be fitted with a capacitor-start, induction-run motor as it has excellence starting torque as compared to the resistance-start, induction-run motor.

CONSTRUCTION AND WORKING

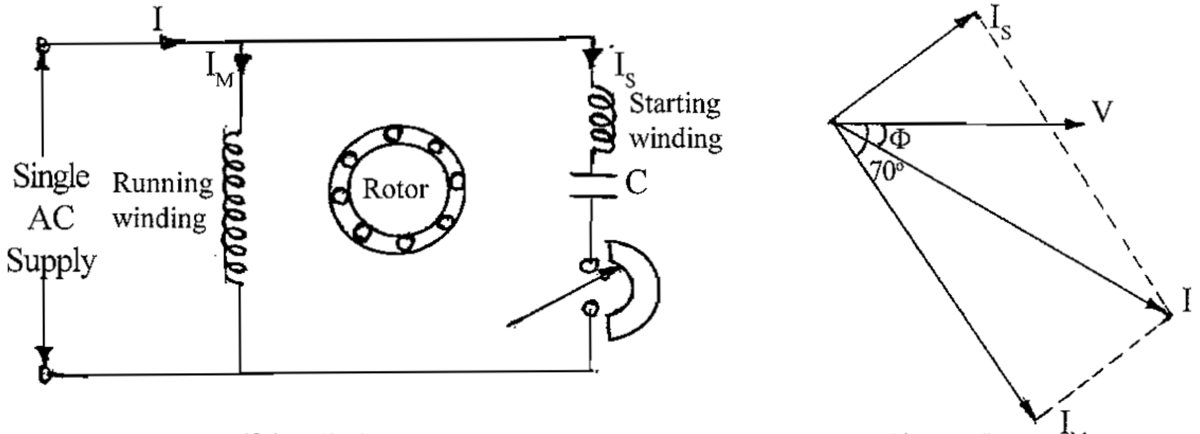
Fig: 4.9(a) shows the schematic diagram of a capacitor-start, induction-run motor. As shown, the main winding is directly connected across the main supply whereas the starting winding is connected across the main supply through a capacitor and centrifugal switch.

Both these windings are placed in a stator slot at 90 degree electrical apart, and a squirrel cage type rotor is used.

As shown in Fig: 4.9(b), at the time of starting the current in the main winding lags the supply voltages by 90 degrees, depending upon its inductance and resistance. On the other hand, the current in the starting winding due to its capacitor will lead the applied voltage, by say 20 degrees.

Hence, the phase difference between the main and starting winding becomes near to 90 degrees. This in turn makes the line current to be more or less in phase with its applied voltage, making the power factor to be high, thereby creating an excellent starting torque.

However, after attaining 75% of the rated speed, the centrifugal switch operates opening the starting winding and the motor then operates as an induction motor, with only the main winding connected to the supply.



a)Schamatic diagram b)Vector diagram

Fig: 4.9

As shown in Fig: 4.9(b), the displacement of current in the main and starting winding is about 80/90 degrees, and the power factor angle between the applied voltage and line current is very small. This results in producing a high power factor and an excellent starting torque, several times higher than the normal running torque as shown in Fig: 4.10.

CHARACTERISTICS

The torque-speed characteristics of this motor is shown in Fig: 4.10.

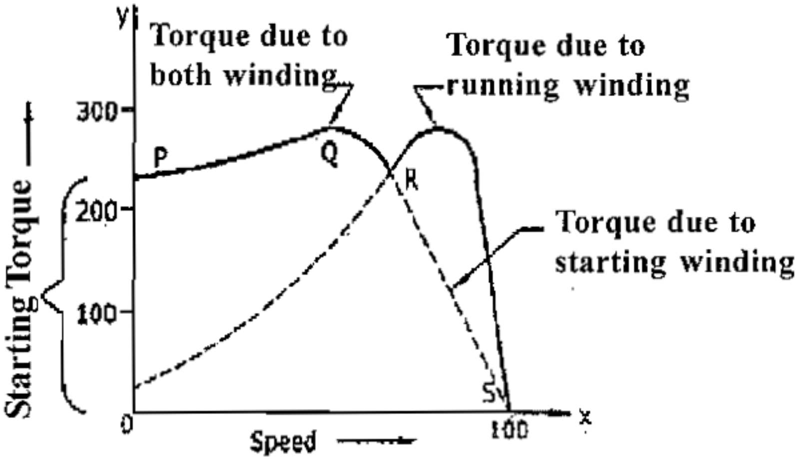


Fig: 4.10

In order to reverse the direction of rotation of the capacitor-start, induction-run motor, either the starting or the main winding terminals should be changed.

This is due to the fact that the direction of rotation depends upon the instantaneous polarities of the main field flux and the flux produced by the starting winding. Therefore, reversing the polarity of one of the field will reverse the torque.

APPLICATIONS

Due to the excellent starting torque and easy direction-reversal characteristics,

- Used in belted fans,
- Used in blowers dryers,
- Used in washing machines,
- Used in pumps and compressors.

3. CAPACITOR-START, CAPACITOR-RUN MOTORS

As discussed earlier, one capacitor-start, induction-run motors have excellent starting torque, say about 300% of the full load torque and their power factor during starting in high.

However, their running torque is not good, and their power factor, while running is low. They also have lesser efficiency and cannot take overloads.

CONSTRUCTION AND WORKING

The aforementioned problems are eliminated by the use of a two valve capacitor motor in which one large capacitor of electrolytic (short duty) type is used for starting whereas a smaller capacitor of oil filled (continuous duty) type is used for running, by connecting them with the starting winding as shown in Fig:4.11. A general view of such a two valve capacitor motor is shown in Fig: 4.11.

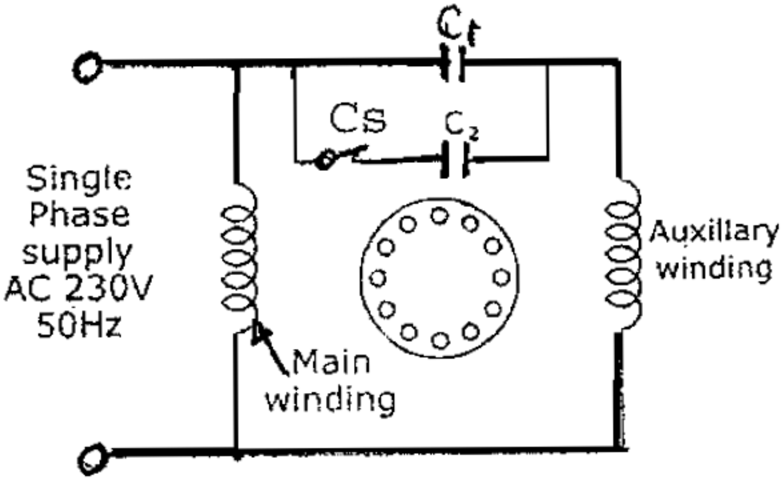


Fig: 4.11

This motor also works in the same way as a capacitor-start, induction-run motor, with exception, that the capacitor C1 is always in the circuit, altering the running performance to a great extent.

The starting capacitor which is of short duty rating will be disconnected from the starting winding with the help of a centrifugal switch, when the starting speed attains about 75% of the rated speed.

CHARACTERISTICS

The torque-speed characteristics of this motor is shown in Fig: 4.12.

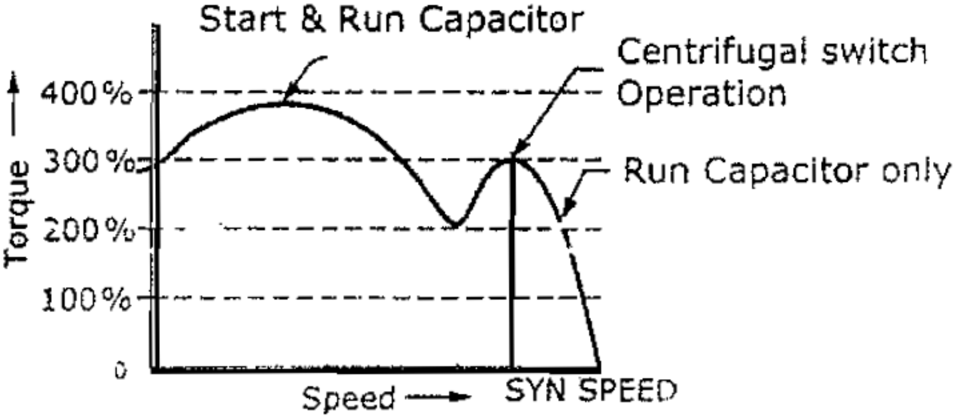


Fig: 4.12

This motor has the following advantages:

- The starting torque is 300% of the full load torque
- The starting current is low, say 2 to 3 times of the running current.
- Starting and running power factor are good.
- Highly efficient running.
- Extremely noiseless operation.
- Can be loaded upto 125% of the full load capacity.

APPLICATIONS

- Used for compressors, refrigerators, air-conditioners, etc.
- Higher starting torque.
- High efficiency, higher power factor and overloading.
- Costlier than the capacitor-start — Induction run motors of the same capacity.

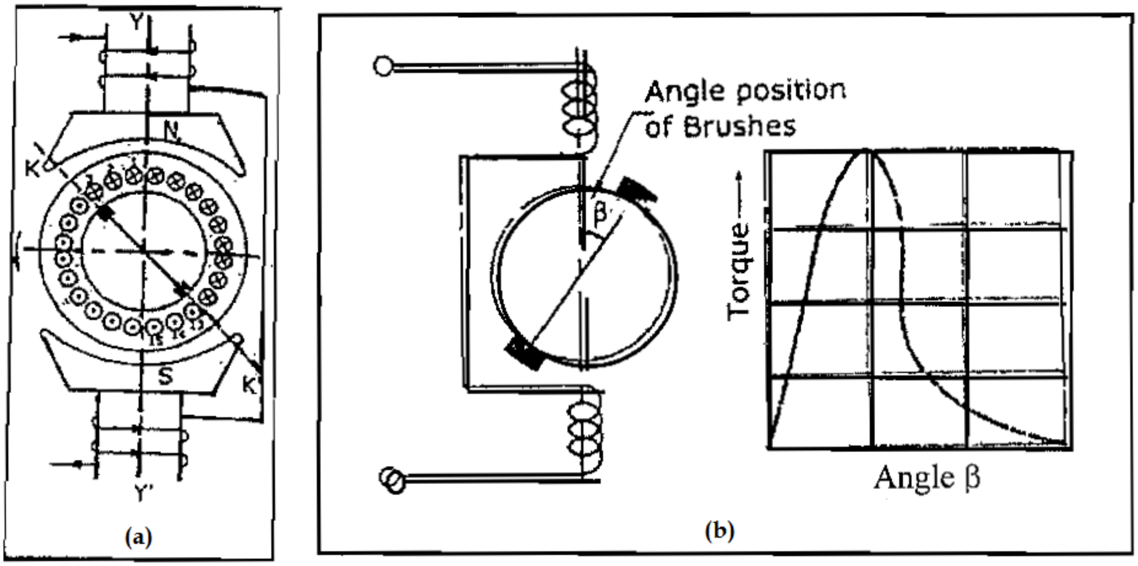
4.3.2 REPULSION STARTING

This type of starting need a wound rotor with brush and commutator arrangement like a dc armature Fig 4.13(a). The starting operation is based on the principle of repulsion and hence the name.

CONSTRUCTION AND WORKING

Repulsion starting, though complicated in construction and higher in cost, are still used in certain industries due to their excellent starting torque, low starting current, ability to withstand long spell of starting currents to drive heavy loads and their easy method of reversal of direction.

Now there is a condition that the rotor north pole will be repelled by the main north pole and the rotor south pole is repelled by the main south pole, so that a torque could be developed in the rotor. Now due to the repulsion action between the stator and the rotor poles, the rotor will start rotating in a clockwise direction. As the motor torque is due to repulsion action, this starting method is named as repulsion starting.



(a)

(b)

Fig: 4.13

To change the direction of rotation of this motor, the brush axis needs to be shifted from the right side as shown in Fig:4.13(b) to the left side of the main axis in a counter clockwise direction as shown in Fig:4.13(b).

CHARACTERISTICS

The torque developed in a repulsion motor will depend upon the amount of brush shaft as shown in Fig: 4.13 (b), whereas the direction of shift decides the direction of rotation.

Further, the speed depends upon the amount of brush shift and the magnitude of the load also on the relationship between the torque and brush-position angle.

Though the starting torque from 250 to 400% of the full load torque, the speed will be dangerously high during light loads. This is due to the fact that the speed of the repulsion motor start does not depend on frequency or number of poles but depends upon the repulsion principle.

Further, there is a tendency of sparking in the brushes at heavy loads, and the PF will be poor at low speeds. Hence the conventional repulsion motor start is not much popular.

4.3.3 SHAPED POLE STARTING

The motor consists of a yoke to which salient poles are fitted as shown in Fig: 4.14(a) and it has a squirrel cage type rotor.

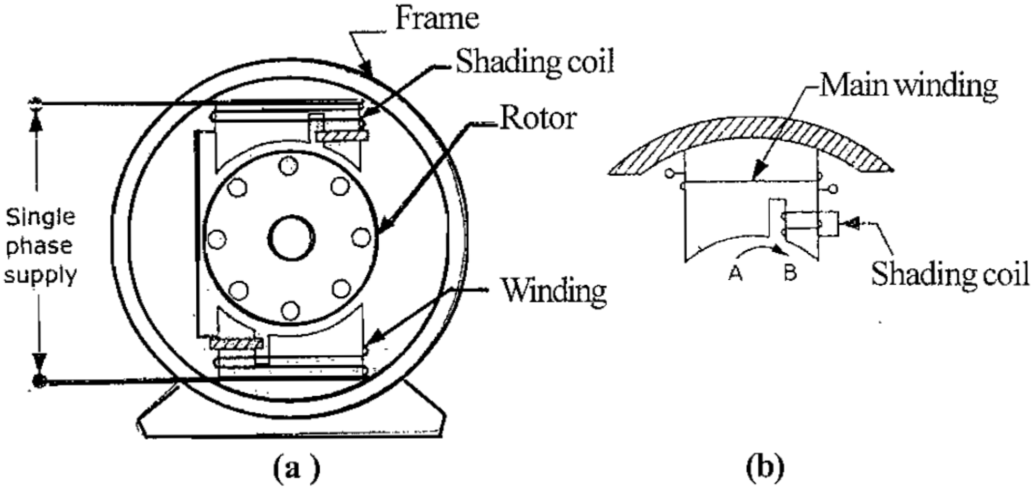


Fig: 4.14

A shaded pole made of laminated sheets has a slot cut across the lamination at about one third the distance from the edge of the pole.

Around the smaller portion of the pole, a short-circuited copper ring is placed which is called the shading coil, and this part of the pole is known as the shaded part of the pole. The remaining part of the pole is called the unshaded part which is clearly shown in Fig: 4.14(b).

Around the poles, exciting coils are placed to which an AC supply is connected. When AC supply is effected to the exciting coil, the magnetic axis shifts from the unshaded part of the pole to the shaded part as will be explained in details in the next paragraph. This shifting of axis is equivalent to the physical movement of the pole.

This magnetic axis, which is moving, cuts the rotor conductors and hence, a rotational torque is developed in the rotor.

By this torque the rotor starts rotating in the direction of the shifting of the magnetic axis that is from the unshaded part to the shaded part.

THE MAGNETIC FLUX SHIFTING

As the shaded coil is of thick copper, it will have very low resistance but as it is embedded in the iron case, it will have high inductance. When the exciting winding is connected to an AC supply, a sine wave current passes through it.

Let us consider the positive half cycle of the AC current as shown in Fig: 4.15.

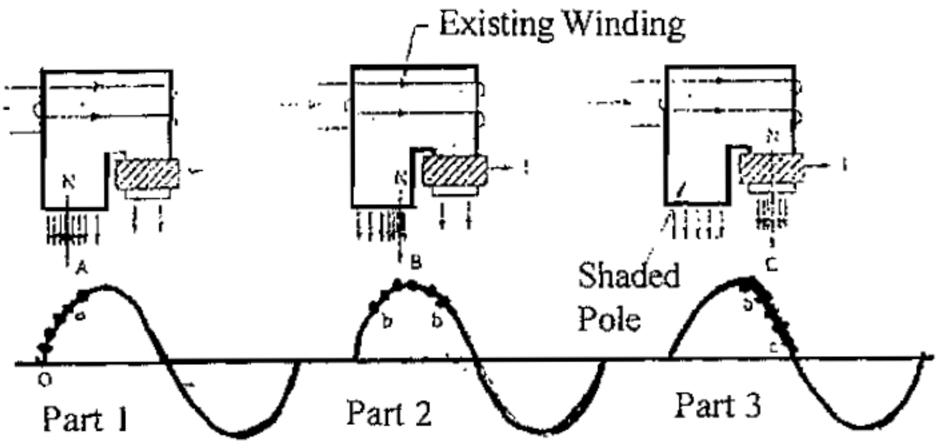


Fig: 4.15 Shifting of magnetic flux

When the current raises from "Zero" Value of point "0" to a point "a" the change in current is very rapid (Fast). Hence, it reduces an emf in the shaded coil on the basis of Faraday's law of electromagnetic induction.

The induced emf in the shaded coil produces a current which, in turn, produces a flux in accordance with Lenz Law. This induced flux opposes the main flux in the shaded portion and reduces the main flux in that area to a minimum value as shown in Fig: 4.15.

This makes the magnetic axis to be in the centre of the unshaded portion as shown by the arrow in part of Fig: 4.15. On the other hand as shown in part 2 of 3 when the current raises from point "a" to point "b" the change in current is slow the induced emf and resulting current in the shading coil is minimum and the main flux is able to pass through the shade portion.

This makes the magnetic axis to be shifted to the centre of the whole pole as shown in by the arrow in part 2 of Fig: 4.15.

In the next instant, as shown in part 3 of Fig: 4.15. When the current falls from "b" to "c" the change in current is fast but the change of current is from maximum to minimum.

Hence a large current is induced in the shading ring which opposes the diminishing main flux, thereby increasing the flux density in the area of the shaded part. This makes the magnetic axis to shift to the right portion of the shaded part as shown by the arrow in part.

From the above explanation it is clear the magnetic axis shifts from the unshaded part to the shaded part which is more or less a physical rotary movement of the poles.

Simple motors of this type cannot be reversed. Specially designed shaded pole motors have been constructed for reversing operations. Two such types:

a. The double set of shading coils method

b. The double set of exciting winding method.

Shaded pole motors are built commercially in very small sizes, varying approximately from 1/250 HP to 1/6 HP. Although such motors are simple in construction and cheap, there are certain disadvantages with these motor as stated below:

- Low starting torque.
- Very little overload capacity.
- Low efficiency.

APPLICATIONS

- Record players
- Fans
- Hair driers.

4.4 Single Phase Series Motor

The single-phase series motor is a commutator-type motor. If the polarity of the line terminals of a dc series motor is reversed, the motor will continue to run in the same direction. Thus, it might be expected that a dc series motor would operate on alternating current also. The direction of the torque developed in a dc series motor is determined by both filed polarity and the direction of current through the armature$[T \propto \phi I_a]$.

4.4.1 Operation

Let a dc series motor be connected across a single-phase ac supply. Since the same current flows through the field winding and the armature, it follows that ac reversals from positive to negative, or from negative to positive, will simultaneously affect both the field flux polarity and the current direction through the armature. This means that the direction of the developed torque will remain positive, and rotation will continue in the same direction. Thus, a series motor can run both on dc and ac.

However, a series motor which is specifically designed for dc operation suffers from the following drawbacks when it is used on single-phase ac supply:

1. Its efficiency is low due to hysteresis and eddy-current losses.
2. The power factor is low due to the large reactance of the field and the armature winding.
3. The sparking at the brushes is excessive.

In order to overcome these difficulties, the following modifications are made in a D.C. series motor that is to operate satisfactorily on alternating current:

1. The field core is constructed of a material having low hysteresis loss. It is laminated to reduce eddy-current loss.
2. The field winding is provided with small number of turns. The field-pole areas is increased so that the flux density is reduced. This reduces the iron loss and the reactive voltage drop.
3. The number of armature conductors is increased in order to get the required torque with the low flux.
4. In order to reduce the effect of armature reaction, thereby improving commutation and reducing armature reactance, a compensating winding is used.

The compensating winding is put in the stator slots. The axis of the compensating winding is 90 (electrical) with the main field axis. It may be connected in series with both the armature and field as shown in Fig: 4.16. In such a case the motor is conductively compensated.

The compensating winding may be short circuited on itself, in which case the motor is said to be inductively compensated shown in Fig: 4.17.

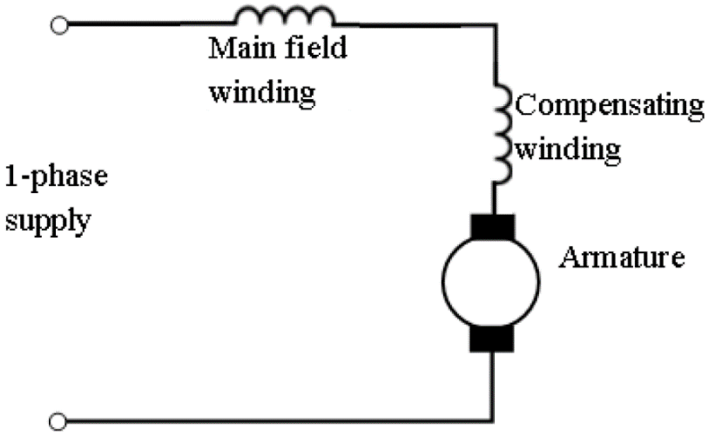


Fig: 4.16

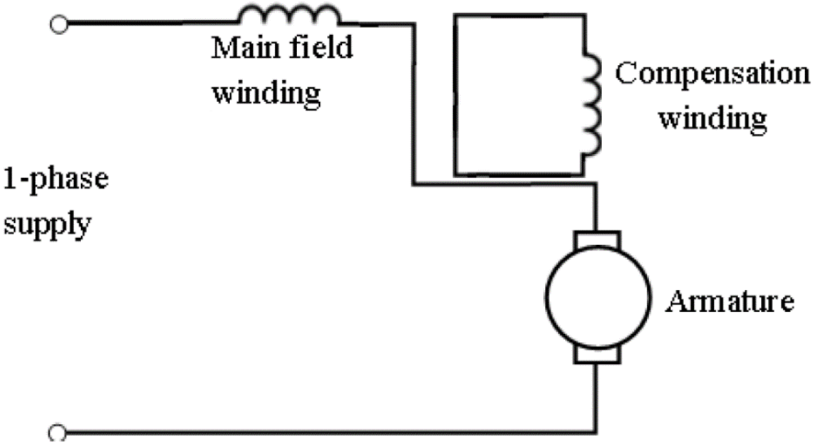


Fig: 4.17

The characteristics of single-phase series motor are very much similar to those of D.C. series motors, but the series motor develops less torque when operating from an a.c. supply than when working from an equivalent D.C. supply [Fig: 4.18]. The direction of rotation can be changed by interchanging connections to the field with respect to the armature as in D.C. series motor.

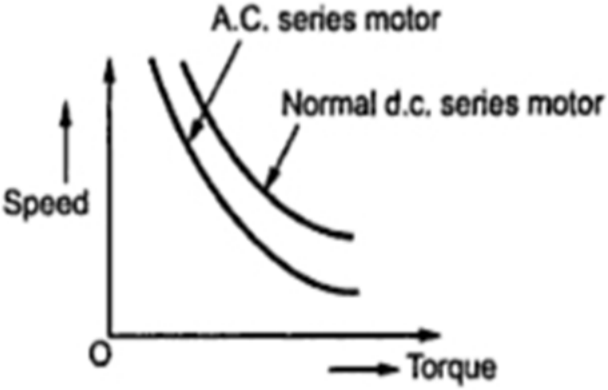


Fig: 4.18

Speed control of universal motors is best obtained by solid-state devices. Since the speed of these is not limited by the supply frequency and may be as high as 20,000 r.p.m. (greater than the maximum synchronous speed of 3000 r.p.m. at 50 Hz), they are most suitable for applications requiring high speeds.

4.4.2 Phasor Diagram of A.C Series Motor

The schematic diagram and phasor diagram for the conductively coupled single-phase ac series motor are shown in Fig: 4.19 and Fig: 4.20 respectively.

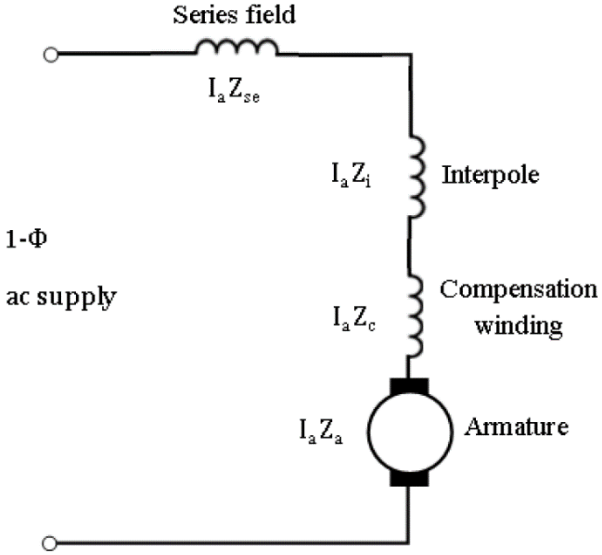


Fig: 4.19

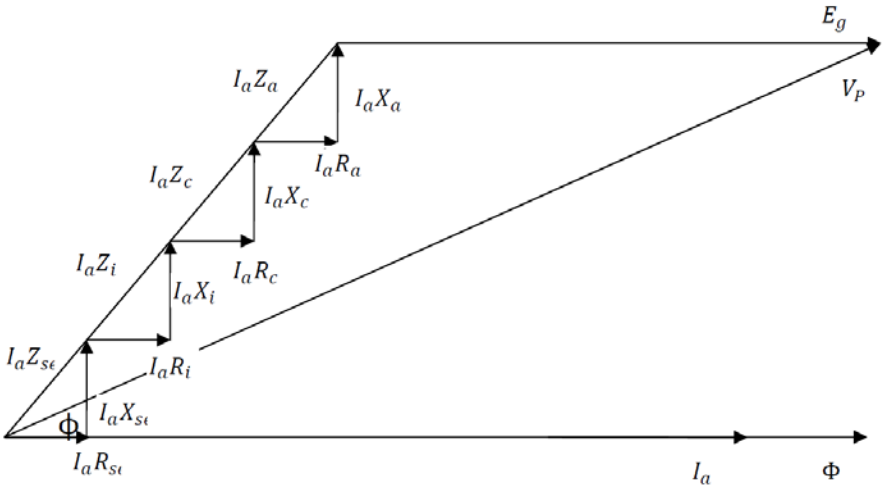


Fig: 4.20

The resistance I_aR_{se}, I_aR_i, I_aR_c and I_aR_a drops are due to resistances of series field, interpole winding, compensating winding and of armature respectively are in phase with armature current I_a. The reactance drops I_aX_{se}, I_aX_i, I_aX_c and I_aX_a are due to reactance of series field, interpole winding, compensating winding and of armature respectively lead current I_a by 90^0. The generated armature counter emf is E_g. The terminal phase voltage V_P is equal to the phasor sum of E_g and all the impedance drops in series.

$$V_p = E_g + I_aZ_{se} + I_aZ_i + I_aZ_c + I_aZ_a$$

The power factor angle between V_P and I_a is .

4.4.3 Applications

There are numerous applications where single-phase ac series motors are used, such as hair dryers, grinders, table-fans, blowers, polishers, kitchen appliances etc. They are also used for many other purposes where speed control and high values of speed are necessary.

4.5 Schrage Motor

Schrage motor is basically an inverted polyphase induction motor, with primary winding on the rotor and secondary winding on the stator. The primary winding on the rotor is fed through three slip rings and brushes at line frequency; secondary winding on the stator has slip frequency voltages induced in it.

The speed and power factor of slip ring induction motor can be controlled by injecting slip frequency voltage in the rotor circuit. If resultant rotor voltage increases, current increases, torque increases and speed increases. Depending on the phase angle of injected voltage, power factor can be improved. In 1911, K. H. Schrage of Sweden combined elegantly a SRIM (WRIM) and a frequency converter into a single unit.

4.5.1 Construction and Operation

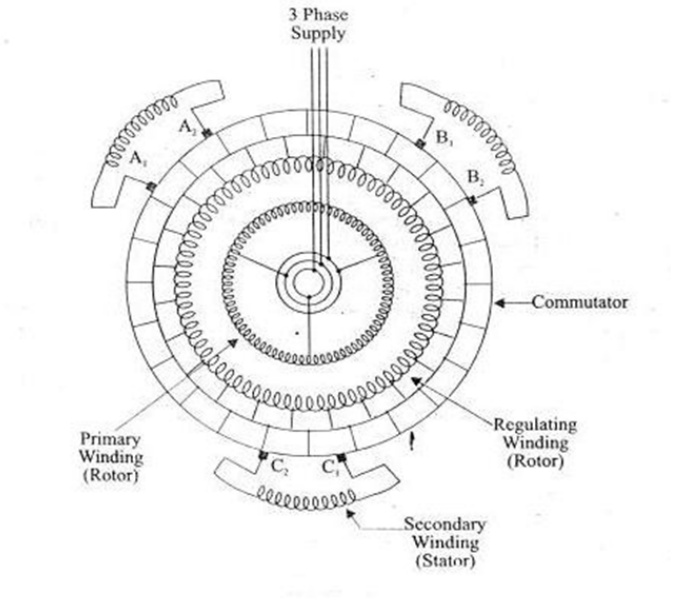


Fig: 4.21

Schrage motor has three windings- Two in Rotor and One in Stator.

Primary winding: Placed on the lower part of the slots of the Rotor. Three phase supply at line frequency is fed through slip rings and brushes which generates working flux in the machine.

Regulating winding: Placed on the upper part of the slots of the Rotor. These are connected to commutator segments in a manner similar to that of D.C. machine. Regulating windings are also known as *tertiary winding / auxiliary winding / commutator winding.*

Secondary winding: Same is phase wound & located on stator. Each winding is connected to a pair of brushes arranged on the commutator. Brushes are mounted on brush rockers. These are designed to move in opposite directions, relative to the centre line of its stator phase.

Brushes A_1, B_1 & C_1 move together and are 120^0 apart.

Brushes A_2, B_2 & C_2 also move together and are 120^0 apart.

Now the primary energized with line frequency voltage. Transformer action occurs between primary and regulating winding. Induction motor action occurs between primary and secondary windings. Commutator acting as a frequency converter converts line frequency voltage of regulating winding to slip frequency voltage and feeds the same to secondary winding on the stator.

Voltage across the brush pairs A_1 - A_2, B_1 - B_2 & C_1 - C_2 increases as brushes are separated.

Magnitude of voltage injected into the secondary winding depends on the angle of separation 'θ' of the brushes A_1 & A_2, B_1 & B_2, C_1 & C_2. ('θ' – Brush separation angle).

When primary is energized synchronously rotating field in clockwise direction is set up in the rotor core. Assume that the brushes are short circuited through commutator segment i.e. the secondary is short circuited. Rotor still at rest, the rotating field cuts the stationary secondary winding, induces an e.m.f. The stator current produce its own field. This stator field reacts with the rotor field thus a clockwise torque produced in the stator. Since the stator cannot rotate, as a reaction, it makes the rotor rotate in the counter clockwise direction.

Suppose that the rotor speed is N_r rpm. Rotor flux is rotating with N_S relative to primary & regulating winding. Thus the rotor flux will rotate at slip speed (N_S - N_r) relative to secondary winding in stator with reference to space.

4.5.2 Speed Control

Speed of Schrage Motor can be obtained above and below Synchronous speed by changing the Brush position i.e. changing “θ” (‘θ’ – Brush separation angle).

In Fig: 4.22 (a) Brush pair on the same commutator segment.i.e. the secondary winding short circuited. Thus the Injected voltage Ej = 0 and the machine operates as an Inverted Induction Motor so here $N_r < N_S$.

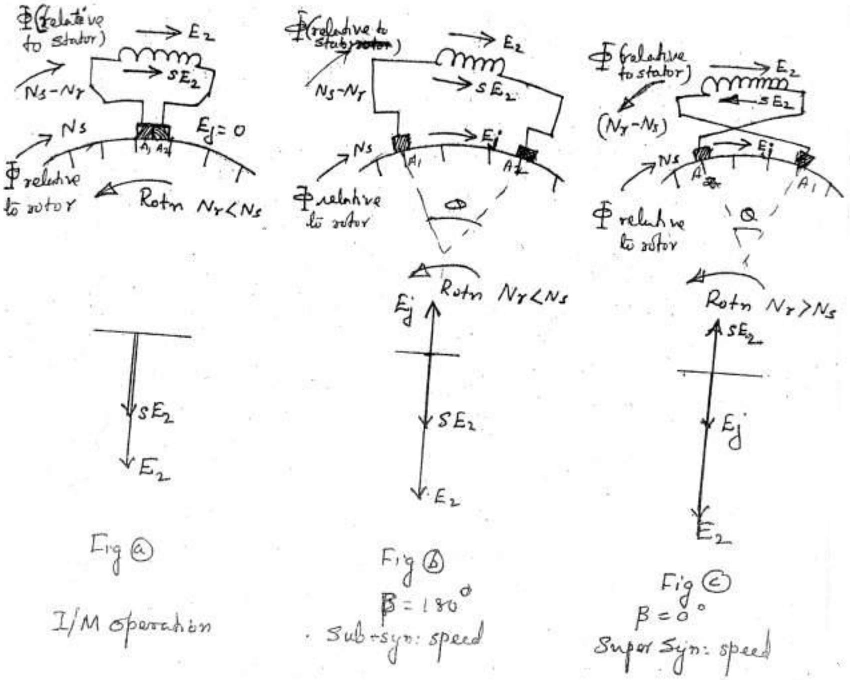


Fig: 4.22 (a) ,(b) & (c)

In Fig: 4.22 (b) Brushes parted in one direction which produces sub-synchronous speed. Injected voltage Ej, is obtained from the section of the regulating winding between them. If the centre line of this group of conductors is coincident with the centre line of the corresponding secondary phase, then E_2 and Ej are in phase opposition.

Neglecting impedance drop, sE_2 must be equal and opposite of Ej.

“β” is the angle between E_2 and Ej. $\beta=180^0$ and so here also $N_r < N_S$.

In Fig: 4.22 (c) Brushes parted in opposite direction which produces super-synchronous speed. Here Ej is reversed relative to E_2 i.e. $\beta=0^0$ & sE_2 must also be reversed.

This is occurring only because ‘s’ becoming negative i.e. The speed is thus above synchronous speed so $N_r > N_S$.

The commutator provides maximum voltage when the brushes are separated by one pole pitch. i.e. ‘θ’ = 180^0.

4.5.3 Power Factor Improvement

This can be obtained by changing the phase angle of the injected voltage into the secondary winding. In this case one set of brushes is advanced more rapidly than the other set. Now the two centre lines do not coincide, have an angle ‘ρ’ between them. (“ρ” – Brush shift angle).

In Fig: 4.22 (d) Brush set is moved against the direction of rotation of rotor. In this case Speed decreases and the p.f. is improved.

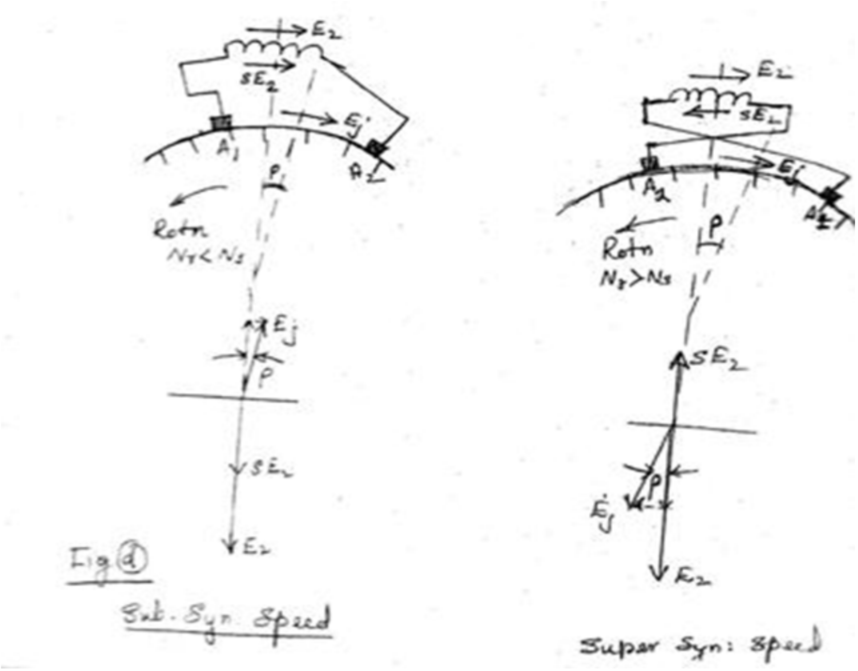


Fig: 4.22 (d) & (e)

In Fig: 4.22 (e) Brush set is moved in the same direction of rotation of rotor. In this case Speed increases, the p.f. is also improved.

Both p.f. and speed can be controlled by varying ‘θ’ & ‘ρ’.

Thus ‘Ej Cos ρ’ and ‘Ej Sin ρ’ effect the speed and p.f. respectively. Fig: 4.23 show Variation of no load speed with Brush Separation.

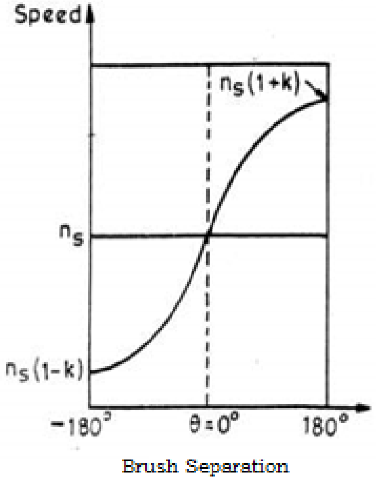


Fig: 4.23

4.5.4 Speed Torque Characteristics

Above discussion reveals that the Schrage Motor is almost a constant speed motor i.e. it has D.C Shunt motor characteristics. Figure 4.23 shows the typical speed-torque characteristics of Schrage motor.

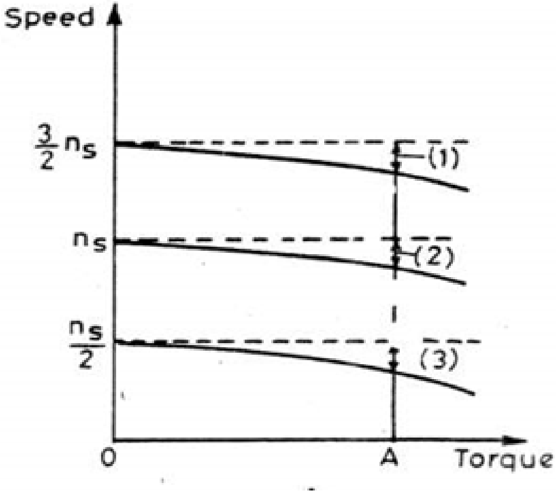


Fig: 4.23

4.5.5 Advantages & Shortcomings

Advantages:

- (i) Good Speed Regulation.
- (ii) High p.f. for high speed setting.

(iii) High efficiency at all speeds except N_S

Shortcomings:

(i) Operating voltage has to be limited to 700V because the power is to be supplied through slip rings.
(ii) Low p.f. at low speed settings.
(iii) Poor commutation.
(iv) High Cost.

4.5.6 Applications

Can be applied to any individual drive requiring variable speed, especially in knitting & Ring spinning applications, Cranes & Hoists Fans & Centrifugal Pumps, printing Machinery Conveyors, Packing machinery & Paper Mills etc.

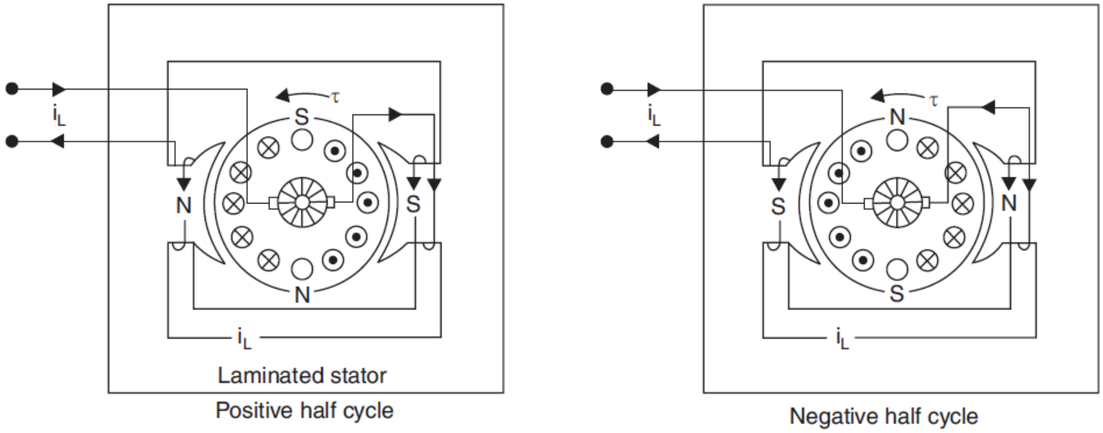
4.6 Universal Motors

It is also commutator type motor. A universal motor is one which operates both on AC and DC supplies. It develops more horsepower per Kg. weight than any other AC motor mainly due to its high speed.

The principle of operation is the same as that of a DC motor. Though a universal motor resembles a DC series motor, it required suitable modification in the construction, winding and brush grade to achieve sparkles commutation and reduced heating when operated on AC supply, due to increased inductance and armature reaction.

A universal motor could therefore be defined as a series or a compensated series motor [Fig: 4.24 & Fig: 4.25 (a), (b)]designed to operate at approximately the same speed and output at either direct current or single phase alternating current of a frequency not greater than 50Hz, and of approximately the same RMS voltage. Universal motor is also named as AC single phase series motor.

Fig: 4.24



(a) (b)

Fig: 4.25

The main parts of a universal motor are an armature, field winding, stator stampings, frame and plates and brushed. The increased sparking at the brush position in AC operation is reduced by the following means:

Providing commutating inter poles in the stator and connecting the interpole winding in series with the armature winding. Providing high contact resistance brushed to reduce sparking at brush positions.

4.6.1 Operation

A universal motor works on the same principles as a DC motor i.e. force is created on the armature conductors due to the interaction between the main field flux and the flux created by the current carrying armature conductors. A universal motor develops unidirectional torque regardless of whether it operated on AC or DC supply.

Fig: 4.25 (a),(b) & Fig: 4.26 shows the operation of a universal motor on AC supply. In AC operation, both field and armature currents change their polarities, at the same time resulting in unidirectional torque.

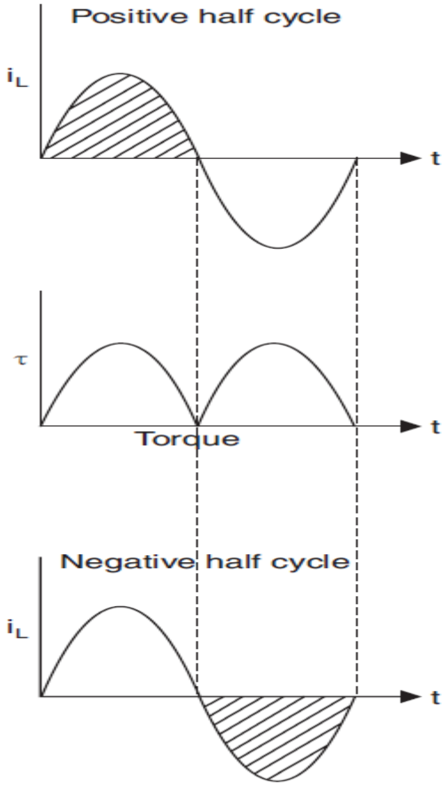


Fig: 4.26

4.6.2 Characteristic

The speed of a universal motor inversely proportional to the load i.e. speed is low at full load and high, on no load.

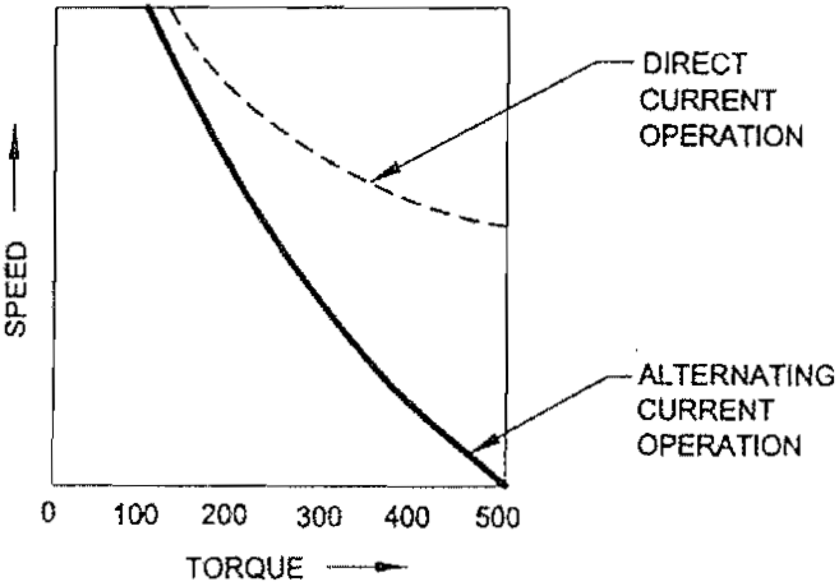


Fig: 4.27

The speed reaches a dangerously high value due to low field flux at no loads in fact the no load speed is limited only by its own friction and windage losses. As such these motors are connected with permanent loads or gear trains to avoid running at no load thereby avoiding high speeds.

Fig: 4.27 shows the typical torque-speed relation of a universal motor, both for AC and DC operations. This motor develops about 450 % of full load torque at starting, as such higher than any other type of single phase motor.

4.6.3 Applications

There are numerous applications where universal motors are used, such as hand drills, hair dryers, grinders, blowers, polishers, and kitchen appliances etc. They are also used for many other purposes where speed control and high values of speed are necessary like in vaccum cleaners, food mixers, portable drills and domestic sewage machines. Universal motors of a given horse power rating are significantly smaller than other kinds of a.c. motors operating at the same frequency.

UNIT-V
SYNCHRONOUS MACHINES

- **Introduction**
- **Constructional Features of round rotor and salient pole machines**
- **Armature windings**
- **Integral slot and fractional slot windings**
- **Distributed and concentrated windings**
- **Distribution, pitch and winding factors**
- **E.M.F Equation.**
- **Armature reaction, leakage reactance, synchronous reactance and impedance - Experimental determination**
- **Equivalent Circuit & Phasor diagrams**
- **Load characteristics &Voltage regulation .**
- **Regulation by synchronous impedance method, M.M.F. method and Z.P.F. method**
    - **Illustrative examples**
    - **Important questions**

Introduction:

The most commonly used machine for generation of electrical power for commercial applications is the synchronous generator. Such a synchronous generator is also called an alternator since it generates alternating voltage. A Synchronous Machine has two main parts, viz. the stator and the rotor just like a DC Machine or an Induction Machine

Synchronous Machine Vs Induction Machine:

There are two major types of AC machines: Synchronous machines and Induction machines. In both of them:

A three-phase system of currents supplied to a system of three coils spaced120 degrees apart on a stator will produce a uniform rotating magnetic field within the stator. The *direction of rotation* of the magnetic field can be *reversed* by simply swapping the connections to any two of the three phases. This is the working principle of both Induction and Synchronous Motors. Conversely, a rotating magnetic field will produce a three-phase set of voltages within such a set of coils. This is the working principle of both Induction and Synchronous generators.

The principal difference between the two types is that synchronous machines require a DC field current to be supplied to their rotors, while induction machines have the field current induced in their rotors by transformer action.

In both Synchronous and Induction machines the speed of the rotating magnetic field & electrical frequency and electrical phase angle & mechanical angle are related to the number poles in the machines are related the same way as below.

In stators of more than two poles, one complete mechanical rotation of the magnetic field produces more than one complete electrical cycle. For such a stator, one mechanical rotation produces *PI2* electrical cycles. Therefore, the electrical angle of the voltages and currents in such a machine is related to the mechanical angle of the magnetic fields by:

$$\theta_e = (P/2)\theta_m$$

The relationship between the electrical frequency of the stator and the mechanical rate of rotation of the magnetic fields is given by: $\boldsymbol{f_e = PN_m /120}$

Synchronous Generator Vs. DC Generator:

We know that in the case of a DC Generator basically the type of induced e.m.f generated in the armature conductors is AC only. It is converted to DC by using commutator. If they are removed and the voltage available from the armature conductors is directly collected, then the output would be AC only. Such a machine without commutator which provides AC output is called an Alternator. But in the case of an alternator to draw the AC output Slip rings and Brushes are used. Further in the case of Synchronous Generator three armature windings spatially separated by 120^0 are placed in the Stator.

Basic principle of operation of a Synchronous Generator:

In a synchronous generator, a DC current is applied to the rotor winding, which produces a rotor magnetic field. The rotor of the generator is then turned by a prime mover, producing a rotating magnetic field within the machine. This rotating magnetic field induces a three-phase set of voltages within the stator windings of the generator.

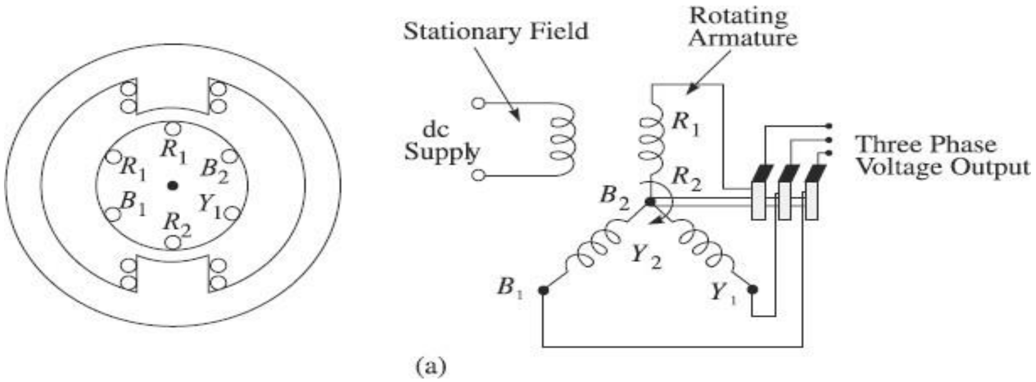
Two terms commonly used to describe the windings on an Electric Machine are ***'field windings'*** and ***'armature windings'.*** In general, the term "field windings" applies to the windings that produce the main magnetic field in a machine, and the term "armature windings" applies to the windings where the main voltage is induced.

For synchronous machines, the field windings are on the rotor, so the terms "***rotor windings"*** *and* ***"field windings***" are used interchangeably. Similarly, the terms "***stator windings***" and "***armature windings***" are used interchangeably.

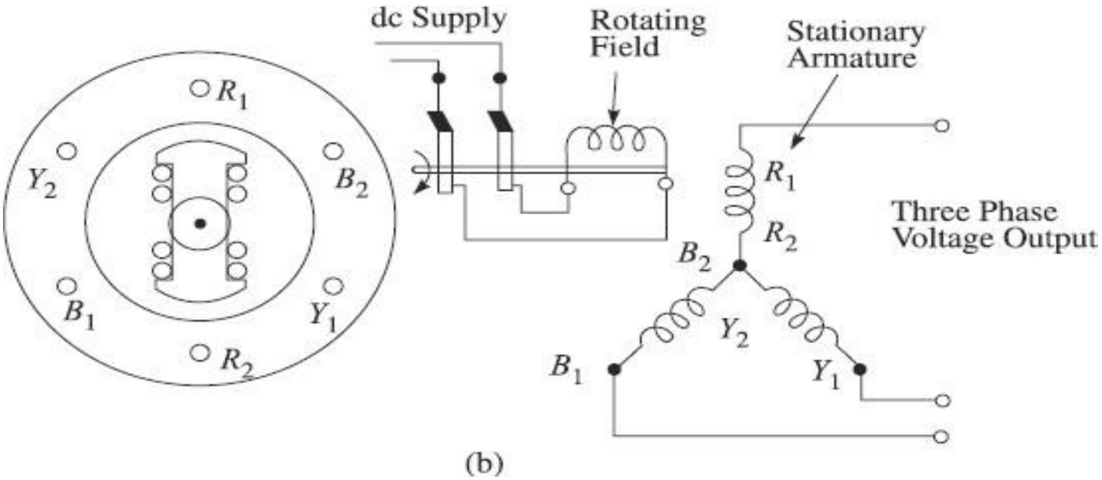
Constructional details of a three phase Synchronous Machine:

A synchronous machine works as a generator when the rotor is rotated and as a motor when a three-phase supply is connected across its armature. The basic construction of a synchronous generator and a synchronous motor is the same. In a dc machine, the field system is stationary and the-armature winding is placed on the rotor. The same arrangement can be done in a synchronous machine also. But in a synchronous machine, due to a number of advantages, the field system is made rotating and the armature winding is placed in stator slots. These two possible arrangements of armature and field system are shown in the figure below.

In synchronous machine construction, two arrangements are possible: the arrangement shown in figure (a) below in which the field is stationary and the armature is rotating has limited applications. In almost all commercial synchronous machines, rotating field and stationary armature system as shown in figure (b) is used for the following reasons.



(a) Stationary field and rotating armature system as in a DC machine,



(b) Rotating field and stationary armature system as in an alternator

Advantages of Rotating Field and Stationary Armature System:

The following are the main reasons why a stationary armature and rotating field construction for three-phase synchronous machines is used in all commercial applications.

(a) Ease of Construction: For large three-phase synchronous machines, the armature winding is more complex than the field winding. The coil and phase connections of the windings can be done more easily and securely on a stationary structure, i.e., on the stator than on the rotor.

(b) Number of Slip-rings required: Referring to the figure (a) above it is seen that when armature winding is made rotating, at least three slip-rings are needed to receive the generated power for the output circuit from the synchronous generator. For large synchronous machines rated in MVAs and voltage ratings in kilo volts (generally11 kV) transferring power through brush and slip-ring arrangement is very difficult. It is also difficult to insulate the slip-rings from the rotating shaft for high voltage. The distance between the slip-rings is to be kept sufficiently large so that flash-over does not take place.

With the stationary armature and rotating field arrangement, none of these problems occur. Only two slip-rings of much smaller size are required to supply excitation current to the rotating windings, as power required for excitation is much less and is supplied at a low voltage.

(c) Better Insulation to Armature: Large size commercial synchronous machine armature coils carry heavy currents at high voltage. It is easier to insulate the armature coils from the core, if the windings are placed on the stator instead of on the rotor. It is comparatively easier to insulate the low voltage DC winding placed on the rotor.

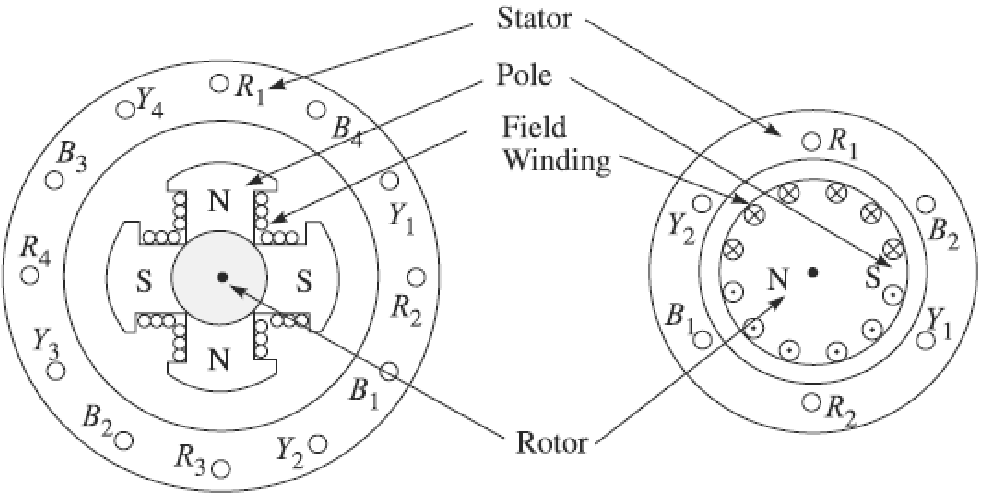
(d) Reduced Rotor Weight and Rotor Inertia: The weight of the field system placed on the rotor is comparatively much lower than the armature winding placed on the stator. This is because the field windings are made with thinner wires and are required to be insulated for a lower voltage. The inertia of the rotor is, therefore reduced. With rotating field system, the rotor will take comparatively less time to come up to the rated speed.

Hence all the large synchronous machines built today have stationary armature and rotating field structure as shown in the figure (b) above.

Types of Rotor Construction:

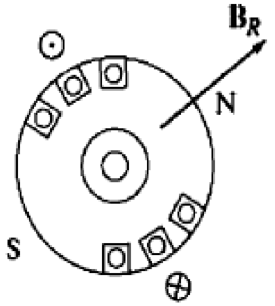
The rotor of a synchronous generator is essentially a large electromagnet. The magnetic poles on the rotor can be of either ***salient*** or ***nonsalient*** construction.

The term *salient* means "protruding" or "sticking out" and a "*salient pole*" is a magnetic pole that sticks out from the surface of the rotor. On the other hand a *nonsalient pole* is a magnetic pole constructed flush with the surface of the rotor. Both types of rotors are shown in the figures below. Nonsalient-pole rotors are normally used for two- and four-pole rotors, while salient-pole rotors are normally used for rotors with four or more poles. Because the rotor is subjected to changing magnetic fields, it is constructed of thin laminations to reduce eddy current losses.

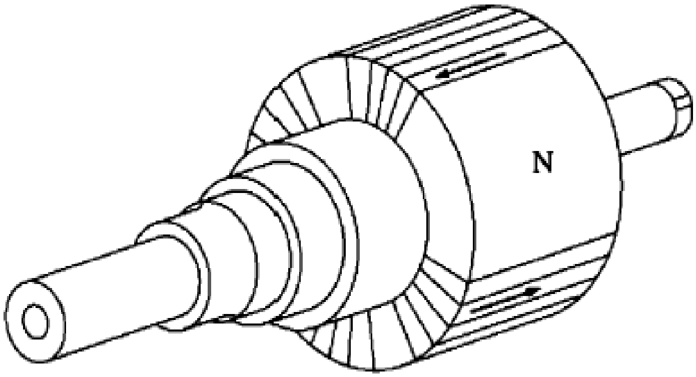


(a) (b)

Figure (a) Salient type rotor (b) Non-salient or cylindrical type rotor



End View



Side View

Figure: A Nonsalient two-pole Rotor for a Synchronous machine

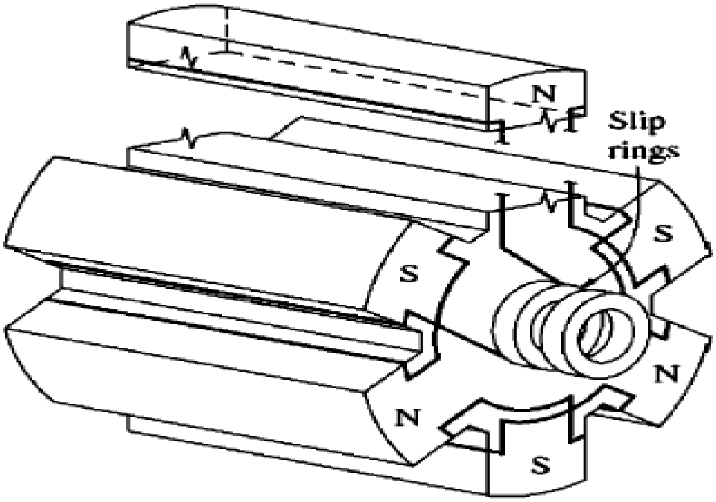


Figure: A Salient Six pole Rotor for a Synchronous Machine

Type of rotor construction also depends upon the type of prime mover used to drive the synchronous generator and is explained in detail below. .

Salient Type Rotor for Alternators Driven at Low Speeds

Alternators driven at low speeds by prime movers like water turbines will have salient pole rotors. This is because, to generate electricity at 50 Hz with the rotor rotate at slow speeds, the number of rotor poles required becomes large. It is convenient to build a rotor having large number of poles in projected pole, i.e., salient pole construction. The diameters of such rotors become bigger than their lengths.

Nonsalient Type Rotor for Alternators Driven at High Speeds

For alternators using high-speed turbines (3000 rpm) like steam turbines as Prime movers, the number of rotor poles required to generate electricity at 50 Hz is only two. To reduce the centrifugal force developed on the rotor winding at high-speed, the rotor diameter is to be kept small. Nonsalient, i.e., cylindrical type rotor construction is made for such synchronous generators. The length of such generators is more than their diameters. For alternators using medium-speed prime mover, like diesel engines, the number of rotor poles is more than two and the rotor is made salient type.

Excitation for Rotating Field System:

A DC current must be supplied to the field circuit on the rotor. Since the rotor is rotating, a special arrangement is required to get the DC power to its field windings. There are two common approaches to supplying this DC power:

I. Supply the DC power from an external DC source to the rotor by means of *slip rings* and *brushes.* This is used for small size generators.
2. Supply the DC power from a special DC power source mounted directly on the shaft of the synchronous generator thus avoiding slip rings and brushes totally. This is called *Brush less exciter* and used for large size Generators.

Brushless exciter: It is a small AC generator with its Field circuit mounted on the stator and its Armature circuit mounted on the rotor shaft as shown in the figure below.

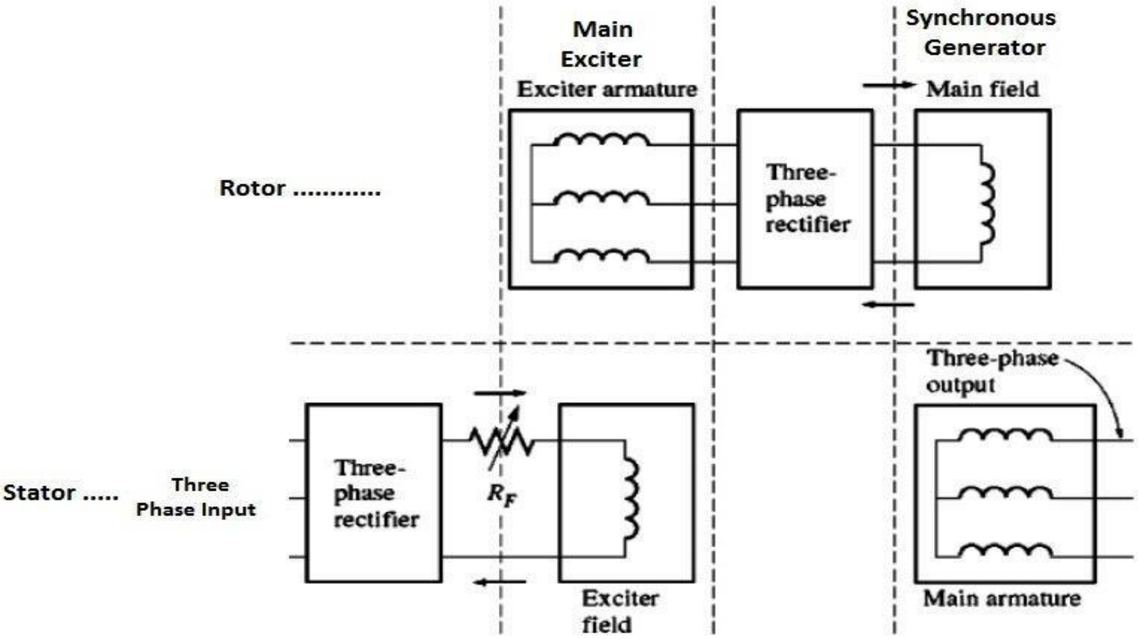


Figure: A brush less exciter circuit. A small three-phase current is rectified and

used to supply the field circuit of the exciter which is located on the stator. The output of the armature circuit of the exciter (on the rotor) is then rectified and used to supply the field current of the main machine

The three-phase output of the exciter generator is rectified to direct current by a three-phase rectifier circuit also mounted on the shaft of the generator, and is then fed into the main DC field circuit. By controlling the small DC field current of the exciter generator (located on the stator), it is possible to adjust the field current on the main machine *without slip rings and brushes.*

A Synchronous machine rotor with a brushless exciter mounted on the same shaft is shown in the figure below. Since no mechanical contacts ever occur between the rotor and the stator, a brushless exciter requires much less maintenance than an exciter with slip rings and brushes.

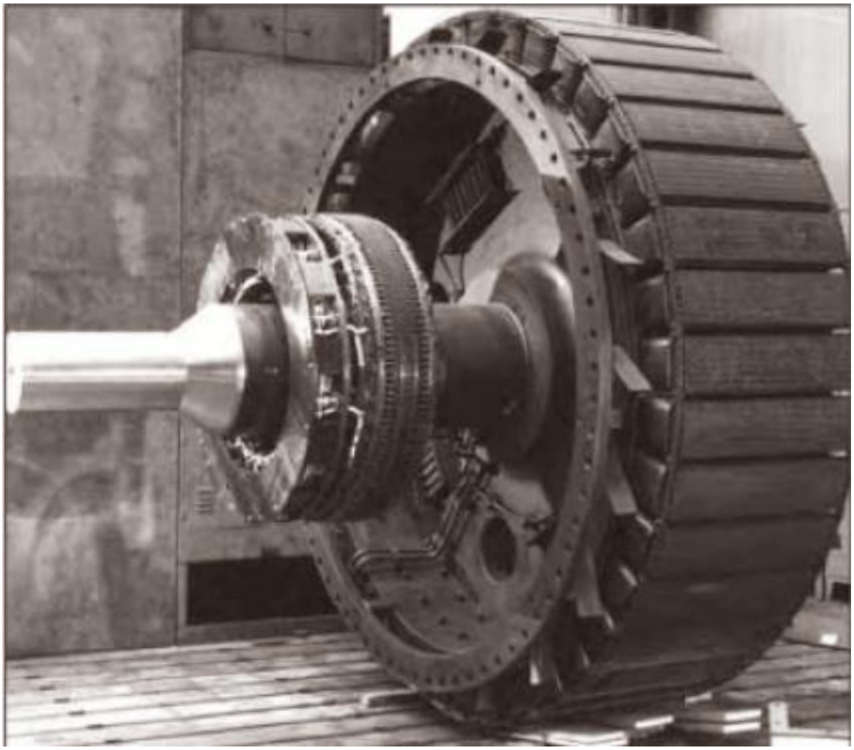


Figure: Photograph of a synchronous machine rotor with a brush less exciter mounted on the same shaft. Notice the rectifying electronics visible next to the armature of the exciter.

Brush less exciter with a Pilot exciter: To make the excitation of a generator *completely* independent of any external power sources, a small pilot exciter is often included in the system. *A pilot exciter* is a small ac generator with *permanent magnets* mounted on the rotor shaft and a three-phase winding on the stator as shown in the figure below. It produces the power for the field circuit of the exciter, which in turn controls the field circuit of the main machine. If a pilot exciter is included on the generator shaft, then *no external electric power* is required to run the generator.

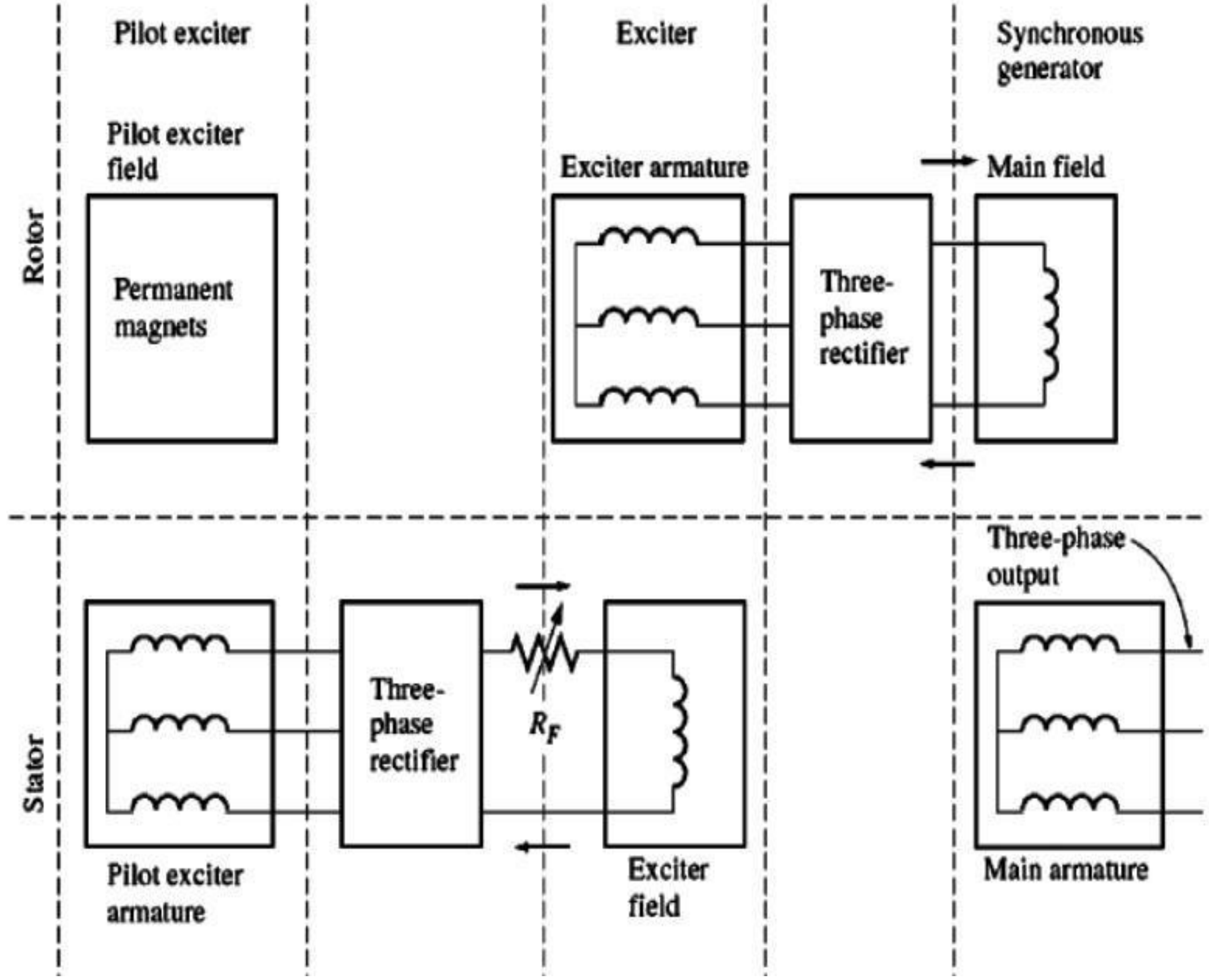


Figure: A brushless excitation scheme that includes a pilot exciter. The permanent magnets of the pilot exciter produce the field current of the exciter which in turn produces the field current of the main machine.

A cutaway diagram of a complete large synchronous machine is shown in the *figure below. This figure shows an eight-pole salient-pole rotor, a stator with distributed double-layer windings, and a brushless exciter.*

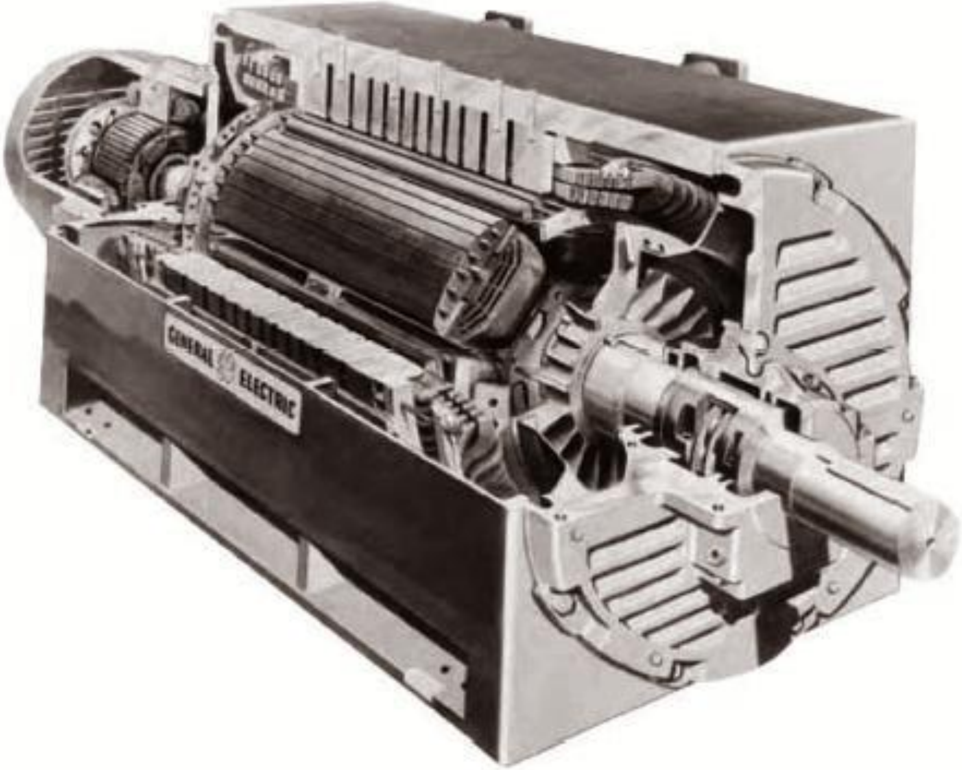


Figure: A cutaway diagram of a large synchronous machine. Note the salient pole construction and the onshaft exciter.

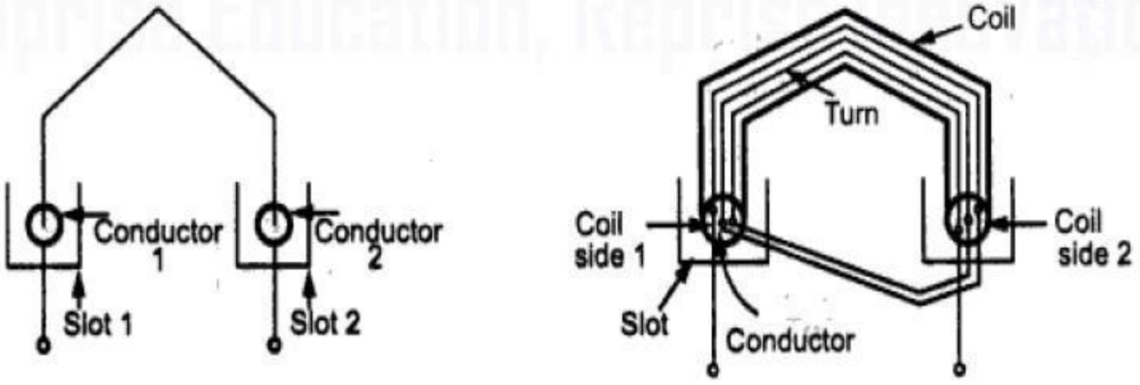
Armature Winding

Armature winding of alternators is different from that of DC machines. Basically, three phase alternators carry three sets of windings arranged in the slots in such a way that there exists a Phase difference of 120° between the induced e.m.f.s in them. In D.C machine, Winding is closed while in alternators winding is open i.e. two ends of each set of winding is brought out. In three phase alternators, the six terminals are brought out which are finally connected in star or delta and then the three terminals are brought out. Each set of windings represents winding per phase and induced e.m.f. in each set is called induced e.m.f. per phase denoted as E_{ph}. All the coils used for one phase must be connected in such a way that their e.m.f.s add to each other. And overall design should be in such a way that the waveform of an induced e.m.f. is almost sinusoidal in nature.

Winding Terminology

1) Conductor: The part of the wire, which is under the influence of the magnetic field and responsible for the induced e.m.f. is called a conductor and its length is called active length of the conductor. The conductors are placed in the armature slots.

2) Turn: A conductor in one slot, when connected to a conductor in another slot forms a turn. So two conductors constitute one turn. This is shown in the figure below.



(a)Turn

(b)Multiturn coil

3) Coil: As there are number of turns, they are all grouped together to form a coil. Such a coil is called multiturn coil. A coil may consist of a single turn in which case it is called a single turn coil. Figure (b) above shows a multiturn coil.

4) Coil Side: Since coil consists of many turns part of the coil in each slot is called coil side of a coil as shown in the figure (b) above.

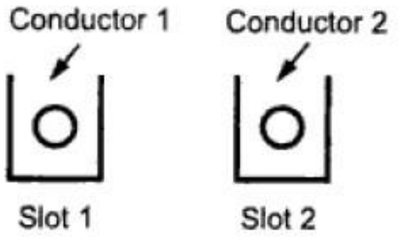
5) Pole pitch: It is the *centre to centre* distance between the two adjacent poles measured in terms of number of slots or electrical degrees. We have seen that for one rotation of the conductor, 2 poles are responsible for $360^0$of electrical induced emf, 4 poles are responsible for 720^0 and so on. So, 1 pole is responsible for 180^0 electrical in induced e.m.f.

Practically how many slots are under one pole which are responsible for 180^0 electrical voltage are measured to specify the pole pitch.

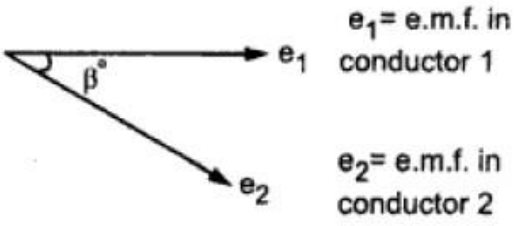
e.g., Consider 2 pole, 18 slots armature of an alternator. Then under 1 pole there are 18/2 i.e., 9 slots. So, pole pitch is 9 slots or 180^0 electrical. This means 9 slots are responsible to produce a phase difference of 180^0 between the e.m.f.s. induced in different conductors.

Pole pitch = 180^0 electrical
= slots per pole (no. of. Slots/P) = n

6) Slot angle (β): The phase difference contributed by one slot in degrees electrical is called slot angle β.As the number of slots per pole which contribute to a phase of 180^0 is denoted by 'n' , slot angle $\beta = 180^0/n$
In the above example, $n = 18/2 = 9$ and so slot angle $\beta = 180^0/n = 180^0/9 = 20^0$
This means that if we consider the induced e.m.f.in the conductors which are placed in the slots which are adjacent to each other, there exists a phase difference of β^0in between them. Similarly e.m.f. induced in the conductors which are placed in slots which are 'n' slots distance away, there exists a phase difference of 180^0 between them.



(a) Adjacent slots



(b) Indication of phase difference

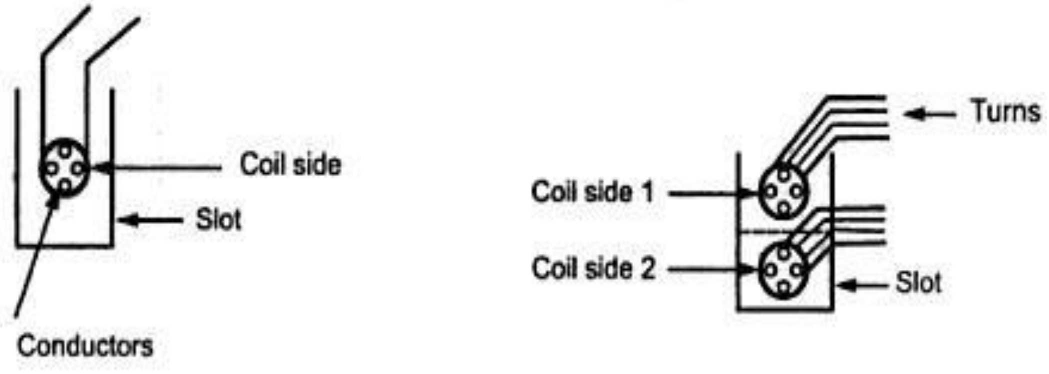
Types of Armature Windings:

In general armature windings are classified as:

1. Single layer and double layer winding
2. Full pitch and short pitch winding.
3. Concentrated and distributed winding.

Single Layer and Double Layer Winding

If a slot consists of only one coil side as shown in the figure (a) below thewinding is said to be single layer. If there are two coil sides per slot, one at the bottom and one at the top as shown in the figure (b) below, the winding is called double layer winding.



(a) Single layer

(b) Double layer

A lot of space gets wasted in single layer windings and hence in practice generally double layer winding is only preferred.

Full Pitch and Short Pitch Winding

As seen earlier, one pole pitch is always 180° electrical. The value of 'n', slots per pole indicates how many slots are contributing to 180° of electrical phase difference. So, if coil side in one slot is connected to a coil side in another slot which is one pole pitch distance away from first slot, the winding is said to be full pitch winding and coil is called full pitch coil.
For example, in a 2 pole, 18 slots alternator, the pole pitch is n = 18/2 = 9 slots. So, if coil side in slot No. 1 is connected to coil side in slot No. 10 such that two slots No. 1 and No. 10 are one pole pitch or n slots or 180° electrical apart, the coil is called full pitch coil. Here we can define one more term related to a coil called coil span.

Coil Span

It is the distance on the periphery of the armature between two coil sides of a coil. It is usually expressed in terms of number of slots or degrees electrical. So, if coil span is 'n' slots or 180^0 electrical the coil is called full pitch coil. This is shown in the figure below.

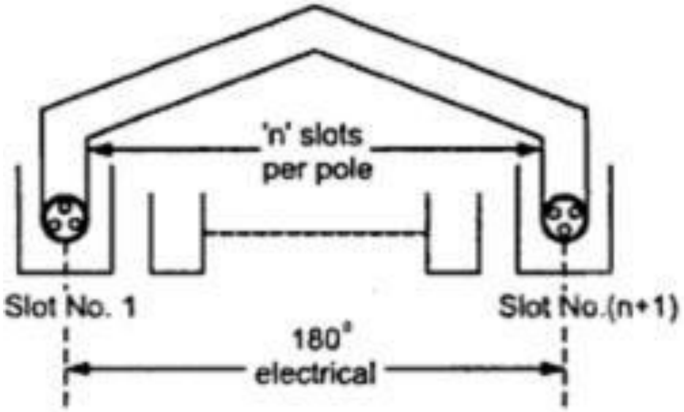


Figure: Full pitch coil

As against this if coils are used in such a way that coil span is slightly less than a pole pitch i.e., less than 180^0 electrical, the coils are called, ***short pitched coils*** or ***fractional pitched coils***. Generally, coils are shorted by one or two slots

So, in 18 slots, 2 pole alternator instead of connecting a coil side in slot No. 1 to slotNo.10, it is connected to a coil side in slot No.9 or slot No. 8, coil is said to be short pitched coil and winding is called short pitch winding. This is shown in the figure below.

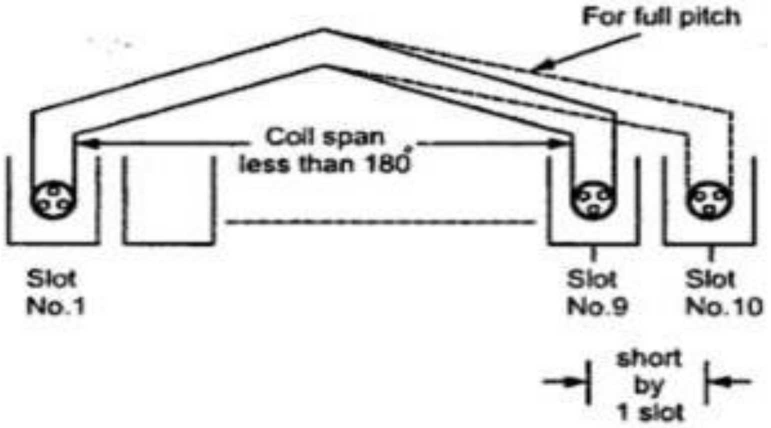


Figure: Short pitch coil

Advantages of Short Pitch Coils:

In actual practice, short pitch coils are used as it has the following advantages:

- The length required for the end connections of coils is less i.e., inactive length of winding is less. So, less copper is required. Hence economical.
- Short pitching eliminates high frequency harmonics which distort the sinusoidal nature of e.m.f. Hence waveform of induced e.m.f is more sinusoidal due to short pitching.
- As high frequency harmonics get eliminated, eddy current and hysteresis losses which depend on frequency also get minimised. This increases the efficiency.

Concentrated and Distributed Winding:

Concentrated winding: In three phase alternators, we know that there are three different sets of windings, one for each phase. So, depending upon the total number of slots and number of poles, we have certain slots per phase available under each pole. This is denoted as **'m'**.
‘m’ = Slots per pole per phase= n/number of phases
= n/3 (since generally no. of phases is 3)
For example, in 18 slots, 2 pole alternator we have,n =18/2 = 9and hence
m= 9/3 = 3
So, we have 3 slots per pole per phase.
Now let **‘x’**be the number of conductors per phase which are to be placed under one pole. And we have 3 slots per pole per phase available. But if all ‘x' conductors per phase are placed in one slot keeping remaining 2 slots per poleper phase empty then the winding is called ***concentrated winding***.
So in concentrated winding all conductors or coils belonging to a phase are placed in one slot under every pole.

Distributed winding: But in practice, an attempt is always made to use all the 'm’ slots per pole per phase available for distribution of the winding. So, if all the **‘x’** conductors per phase are distributed amongst the 3 slots per phase available under every pole, the winding is called ***distributed winding***. So, in distributed winding all the coils belonging to a phase are distributed over all the ‘**m**’ slots per phase available under every pole. Distributed winding makes the waveform of the induced e.m.f more sinusoidal in nature. Also, in concentrated winding due to large number of conductors per slot, heat dissipation is poor.

So, in practice, double layer, short pitched and distributed type of armature windings are used in the alternators.

Integral Slot Winding

The value of 'm' = slots/ pole / phase decides the class of the winding. *When the value of 'm'is an integer, then the winding is called* ***Integral slot winding.***

Consider a 2 pole, 12 slots alternator: n = slots / pole = $\frac{12}{2} = 6$

Then Pole pitch = 180^0 = 6 slots and 'm' = $\frac{n}{3} = \frac{6}{3} = 2$

As 'm' is integer, this type of winding is known as ***'Integral slot winding'***. This winding can be full pitch winding or short pitch winding.

Fractional Slot Winding

This is another class of winding which depends on the value of **'m'**. *The winding in which* ***slots per pole per phase (m)*** *is a fractional number is called fractional slot winding.* In such a winding, the number of slots (S) must be divisible by 3. Thus, the number of slots per phase is an integer which is necessary to obtain symmetrical three phase winding. But slots per Pole (n) and slots per pole per phase (m) both are fractional. As 'n' is a fraction, the coils cannot be full Pitch. Thus, if there are 54 slots and 8 poles then the slots per pole n = 54/8 = 6.75 hence coil Span can be 7 or 6. Generally short pitch coils are used. Such a fractional slot winding can be easily achieved with double layer winding.

Advantages of Fractional Slot Winding:

1. Though appear to be complicated, easy to manufacture.
2. The number of armature slots (S) need not be integral multiple of number of poles (P).
3 The number of slots can be selected for which notching gear is available, which is economical.
4. There is saving in machine tools.

5. High frequency harmonics are considerably reduced.
6. The voltage waveform available is sinusoidal in nature.

E.M.F. Equation of an Alternator:

Let Φ = Flux per pole, in Wb

P = Number of poles

N_s = Synchronous speed in r.p.m.

f = Frequency of induced e.m.f in H_z

Z = Total number of conductors

Z_{ph}= Conductors per phase connected in series

$Z_{ph}=Z/3$ as number of phases = 3.

Let us consider a single conductor placed in a slot.

The average value of e.m.f induced in a conductor = $\frac{d\emptyset}{dt}$

For one revolution of a conductor,

e_{avg} per conductor = $\frac{Flux\ cut\ in\ one\ revolution}{Time\ taken\ for\ one\ revolution}$

Total flux cut in one revolution is ø x P.

Time taken for one revolution is ($60/N_S$) seconds.

e_{avg} per conductor $= \frac{\emptyset P}{\left(\frac{60}{N_S}\right)} = \emptyset \frac{PN_s}{60}$ … (1)

But we know that 'f' = ($PN_S/120$)

Hence ($PN_S/60$) = $2f$

Substituting this in equation (1),

e_{avg} per conductor = **$2f\Phi$** volts

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

Then e.m.f. per turn = 2 × (e.m.f. per conductor) =**2 × (2fΦ)= 4 fΦ** volts.

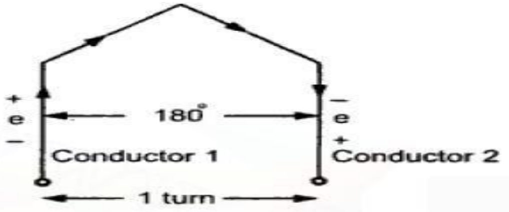


Figure: One Turn of full pitch coil

Let 'T_{ph}' be the total number of turns**(=$Z_{ph}/2$)** per phase connected in series. Assuming **concentrated winding,** we can say that all are placed in single slot per pole per phase. So induced e.m.f.s in all turns will be in phase as they are placed in a single slot. Hence the net e.m.f per phase will be algebraic sum of the e.m.f. s per turn.

∴ Average $E_{ph} = T_{ph} \times$ **(Average e.m.f. per turn)**

∴ Average $E_{ph} = T_{ph} \times 4 f \Phi$

But in a.c. circuits R.M.S. value of an alternating quantity is used for the analysis. The form factor K_f(RMS/Average) = 1.11 for sinusoidal parameters.

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

∴ $E_{phrms} = 1.11 \times 4 f \Phi T_{ph} = 4.44 f \Phi T_{ph}$ volts

This is the basic e.m.f. equation for the induced e.m.f. per phase for 'full pitch', 'concentrated' type of winding

But as mentioned earlier, the winding used for the alternators is ***distributed*** and ***short pitch***. Hence e.m.f induced gets affected. Hence we have to see the effect of ***distributed*** and ***short pitch*** type of windings on the e.m.f. equation.

Pitch factor or Coil Span Factor (K_c):

In practice short pitch coils are preferred. So,coil is formed by connecting one coil side to another which is less than one pole pitch away. So actual coil span is less than 180^0. The coil is generally short pitched by one or two slots.

Angle by which coils are short pitched is called angle of short pitch denoted as ***'α'.*** Slot angle is **ß** and the angle of short pitch is always a multiple of the slot angle **ß**.

α = β x number of slots by which the coils are short pitched

or $\alpha = 180^0$- Actual coil span of the coils

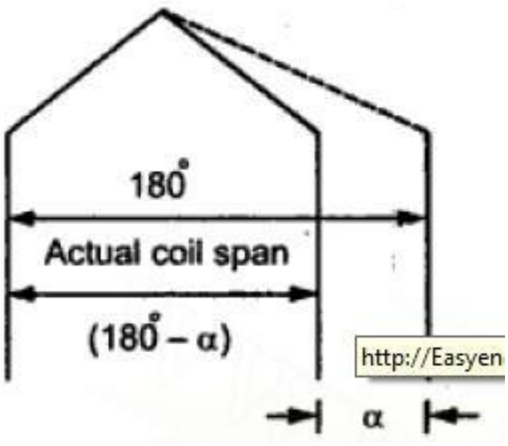


Figure: Angle of short pitch

Derivation of expression for 'Pitch factor or Coil Span Factor '(K_c)':

Now let **E** be the induced e.m.f. in each coil side. If the coil is a full pitch coil, the induced e.m.f. in each coil side help each other. Coil connections are such that both will try to set up a current in the same direction in the external circuit. Hence the resultant e.m.f. across a coil will be algebraic sum of the two.

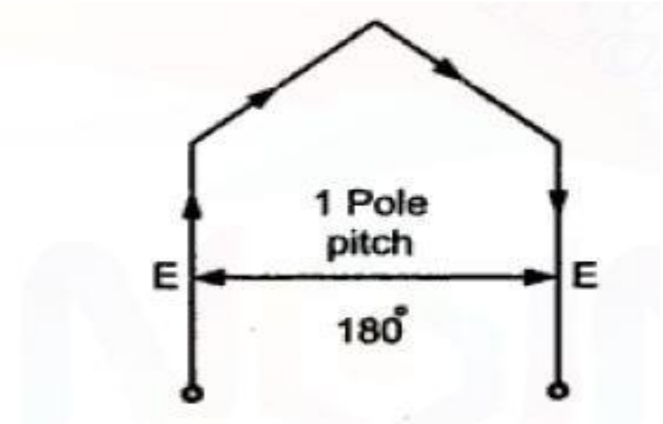


Figure :Full pitch coil

Hence $\mathbf{E_R = E + E = 2E}$

But if the coil is short pitched by an angle **'α'**, the two e.m.fs in the two coil sides no longer remain in phase. Hence the resultant e.m.f. also no longer remains algebraic sum of the two but becomes a phasor sum of the two as shown in the figure below. Obviously, **E_R** in such a case will be less than what it is in the case of a full pitched coil **(2E)**.From the geometry of the figure below we can show that the resultant e.m.f is given by:

$$E_R = 2\ E \cos(\alpha/2)$$

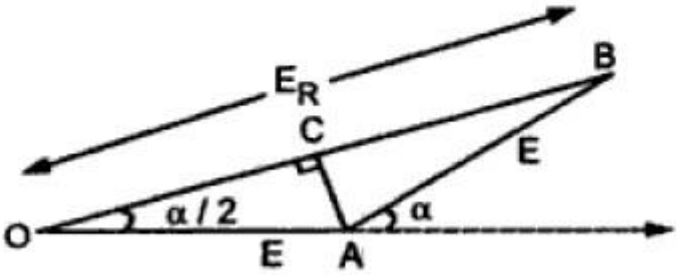


Figure: Phasor sum of the two e.m.fs with a Short pitched coil

Now the factor by which, induced e.m.f in the coil gets reduced due to short pitching is called ***pitch factor*** *or* ***coil span factor*** *denoted by* K_C*. It is defined as the ratio of resultant e.m.f. when coilis short pitched to the resultant e.m.f. when coil is full pitched. It is always less than one.*

$$\therefore \qquad K_C = \frac{E_R \text{ when coil is short pitched}}{E_R \text{ when coil is full pitched}} = \frac{2\,E\cos(\frac{a}{2})}{2\,E}$$

$$= K_C = \cos(\alpha/2)$$

Where **α=Angle of short pitch**

Distribution Factor (K_d)

Similar to full pitch coils, concentrated winding is also rare in practice. Attempt is made to use all the slots available under a pole for the winding which makes the nature of the induced e.m.f. more sinusoidal. Such a winding is called a distributed winding.

Consider **18 slots, 2 pole** alternator. So, **slots per pole** i.e. **n = 9**.

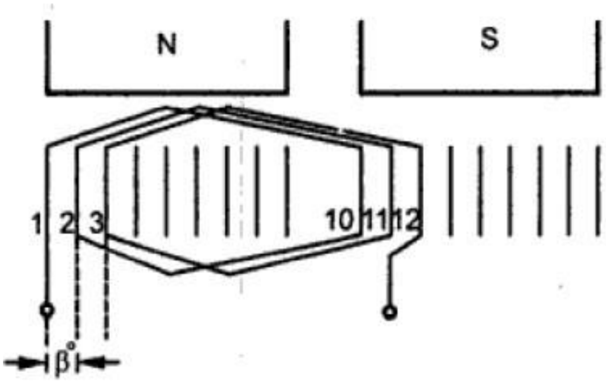
m = Slots per pole per phase **= 3**

$\beta = 180^0 / 9 = 20^0$

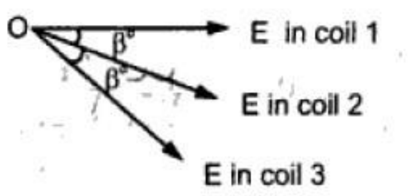
Let **E** = induced e.m.f per coil and there are 3 coils per phase.

In concentrated type all the coil sides will be placed in one slot under a pole. So induced e.m.f. in all the coils will achieve maxima and minima at the same time i.e., all of them will be in phase. Hence resultant e.m.f. after connecting coils in series will be algebraic sum of all the e.m.fs as all are in phase.

AS against this, in distributed type, coil sides will be distributed, one each in the 3 slots per phase available under a pole as shown in the figure (a) below .



(a) Distributed winding



(b) Phase difference between induced e.m.f.

Though the magnitude of e.m.f. in each coil will be same as **'E'**, as each slot contributes phase difference of **β^0 i.e.20^0** in this case, there will exist a phase difference of **β^0** with respect to each other as shown in the figure (b) above. Hence resultant e.m.f. will be phasor sum of all of them as shown in the figure below. So due to distributed winding resultant e.m.f. decreases.

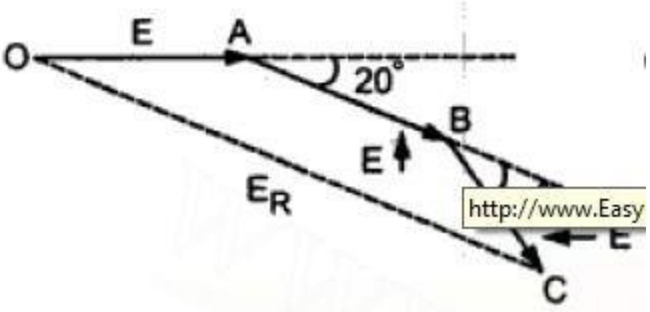


Figure: Phasor sum of e.m.fs in distributed (3 per phase) conductors

The factor by which there is a reduction in the e.m.f. due to distribution ofcoils is *called ‘**distribution factor’** denoted as ‘*$\mathbf{K_d}$*’*

Derivation of expression for *‘distribution factor’‘K_d’* :

Let there be **'n’** slots per pole and **'m’** slots per pole per phase. So, there will be **‘m’** coils distributed under a pole per phase, connected in series. Let ‘**E’** be the induced e.m.f. per coil. Then all the **'m’** e.m.f.s induced in the coils will have successive phase angle difference of **$\beta = 180^0/n$**. While finding out the phasor sum of all of them, phasor diagram will approach a shape of a 'm' equal sided polygon circumscribed by a semicircle of radius **‘R’.**

This is shown in the figure below. **AB, BC, CD** etc., represent e.m.f. per coil. All the ends are joined at **'O’** which is centre of the circumscribing semicircle of radius **'R’.** We know that *‘**distribution factor**’ ‘**K_d**’* **is defined as:**

$$K_d = \frac{E_R whencoilsaredistributed}{E_R whencoilsareconcentrated}$$

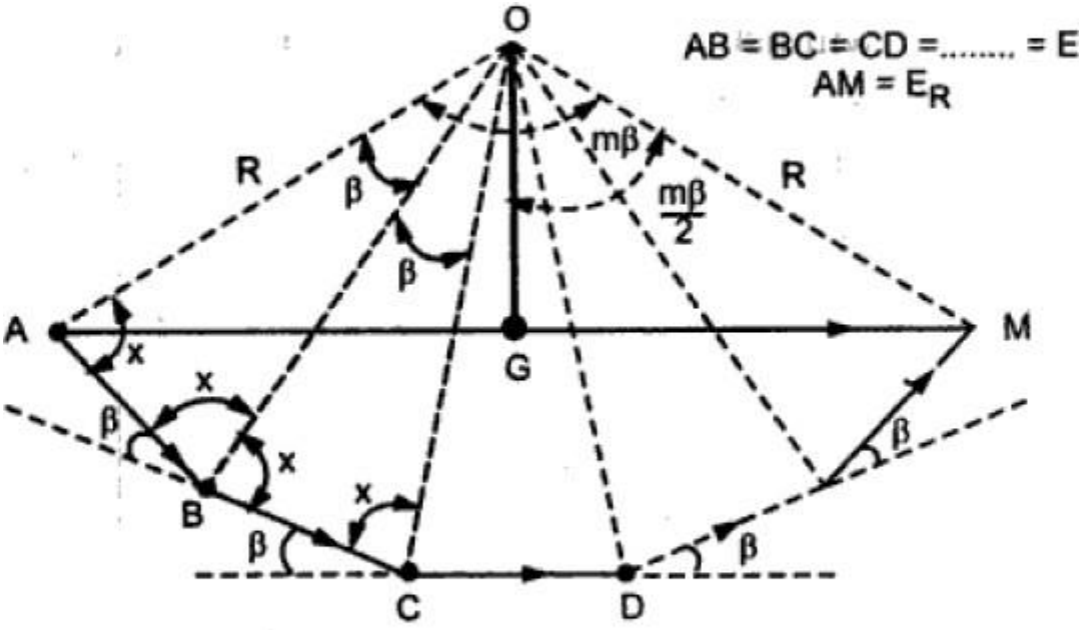


Figure: Phasor sum of ‘m’ e.m.fs in distributed conductors

By a careful study of the above figure and application of the relevant

trigonometric relations we can show that:
The resultant e.m.f. when coils are concentrated is given by:

$$\mathbf{E_R = 2\ m\ R\ \sin(\beta/2)}$$

And the resultant e.m.f. when the coils are distributed is given by:

$$\mathbf{E_R = 2\ R\ \sin(m\beta/2)}$$

And thus finally the ***'distribution factor'*** will be :

$$K_d = \frac{E_R whencoilsaredistributed}{E_R whencoilsareconcentrated} = \frac{\sin(\frac{mQ}{2})}{m \sin(\frac{Q}{2})}$$

……

Detailed Proof:

Angle subtended by each phasor at the origin 'O' is β^0. *This can be proved as below. All the triangles OAB, OBC... are similar and isosceles, as AB = BC = … = E. Let the base angles be 'X'. In the Above figure <OAB = <OBA = < OBC = … = x*

And $\angle AOB = \angle BOC = \ldots = y$ *say*

In Δ *OAB,* $2x + y = 180^0$

While in the polygon $\angle OBA + \angle OBC + \beta = 180^0$

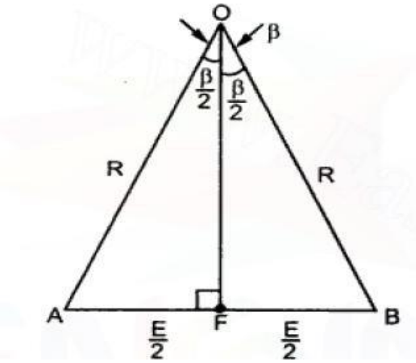
i.e. $2x + \beta = 180^0$

Comparing the above two equations $y = \beta$

So $\angle AOB = \angle BOC = \angle COD = \ldots = \beta$

If 'M' is the last point of the last phasor, $\angle AOM = m \times \beta = m\beta$ *and* $AM = E_R$ = *Resultant of all the e.m.f.s.*

Consider the Δ *OAB separately as shown in the figure below.*



Let OF be the perpendicular drawn on AB bisecting the angle AOB at apex 'O' as β/2.

l(AB) = E ∴ l(AF) = $\frac{E}{2}$ *and let l(OA) = R.*

(Here prefix 'l' represents 'length')

∴ $\sin(\frac{\beta}{2}) = \frac{AF}{OA} = \frac{E/2}{R}$

∴ **$E = 2R \sin(\frac{Q}{2})$ ………….(3)**

*Now consider Δ OAM as shown in the above figure -1 and OG is the perpendicular drawn from 'O' on its base bisecting <AOM (**m** Q)*

∴ $<AOG = < GOM = \frac{m\beta}{2}$

∴ $l(AM) = E_R$

∴ $l(AG) = \frac{E_R}{2}$

∴ $\sin(\frac{m\beta}{2}) = \frac{AG}{OA} = \frac{\frac{E_R}{2}}{R}$

∴ **$E_R = 2R \sin(\frac{mQ}{2})$ ……………………….(4)**

This is the resultant e.m.f. when coils are distributed.

If all 'm' coils are concentrated all would have been in phase giving E_R as algebraic *sum of all the e.m.f.s.*

∴ $$E_R = m \times E$$ *…. For concentrated*

From equation (3), $E = 2\,R\,\sin\left(\frac{\beta}{2}\right)$

∴ $$\boldsymbol{E_R = 2\,m\,R\,\sin\left(\frac{Q}{2}\right)}$$

This is resultant e.m.f. when coils are concentrated.

This distribution factor is defined as the ratio of the resultant e.m.f. when coils are distributed to the resultant e.m.f. when coils are concentrated. It is always less than one.

∴ $$K_d = \frac{E_R \text{ when coils are distributed}}{E_R \text{ when coils are concentrated}} = \frac{2\,R\,\sin\left(\frac{m\beta}{2}\right)}{2\,m\,R\,\sin\left(\frac{\beta}{2}\right)}$$

∴ $$\boxed{K_d = \frac{\sin\left(\frac{m\beta}{2}\right)}{m\,\sin\left(\frac{\beta}{2}\right)}}$$

Where *m = Slots per pole per phase*

B = *Slot angle* = $\frac{180^0}{n}$

N = Slots per pole.

Generalized Expression for E.M.F. Equation of an Alternator

Considering full pitch and concentrated winding we have earlier obtained the expression for induced emf in a Generator as:

$$\mathbf{E_{ph} = 4.44\ f\ \emptyset\ T_{ph}\ volts}$$

But due to short pitch& distributed winding used in practice, this **E_{ph}** will reduce by factors **K_c** and **K_d**. So generalized expression for e.m.f. equation can be written as : **$E_{ph} = 4.44\ K_cK_d\ f\ \emptyset\ T_{ph}$ volts**

For full pitch coil, **K_c = 1.**

For concentrated winding **K_d = 1**.

For short pitch and distributed winding K_c and K_d are always less than unity.

Armature reaction, leakage reactance, synchronous reactance and Synchronous Impedance - Experimental determination:

Armature resistance: Every armature winding has its own resistance which is designated armature resistance per phase **R_a Ω/Ph.** It can be measured by a simple ***multi meter*** which gives DC resistance. But due to skin effect the AC resistance at 50 Hz (Applicable to us) will be higher by approximately 1.6.

Armature leakage resistance: When armature carries a load current it produces its own flux, part of which does not cross the air-gap and links with itself. Such a flux is called leakage flux. This leakage flux makes the armature winding inductive in nature. So effectively the armature winding has an inductive reactance in addition to a resistance. If **L** is the value of the leakage inductance in Henrys per phase then, the leakage reactance **X_L** per phase is given by **$X_L = \omega L = 2\pi fL$ Ω /Ph.** In Synchronous machines also like in DC machines the value of leakage reactance is much larger than armature resistance **R_a**.

Armature Reaction:

When a synchronous generator is running on no-load, there will be no current flowing through the armature windings. The flux produced in the air-gap will be due to the field ampere-turns only. When load is connected across the armature terminals, current will flow through the armature windings. These three-phase currents will produce a rotating magnetic field in the air-gap. The effect of the armature flux on the main flux produced by the field ampere-turns is called ***Armature Reaction***. The armature flux will distort, oppose or help the field flux causing reduction or increase in the air gap flux depending upon the power factor of the load.

When a synchronous generator is loaded, there will be a change in the terminal voltage due to a voltage drop in armature resistance and armature leakage reactance. *There will be some change in terminal voltage due to armature reaction effect also and it can be viewed as a reactance voltage drop. The corresponding reactance is designated as* **X_{ar}**.

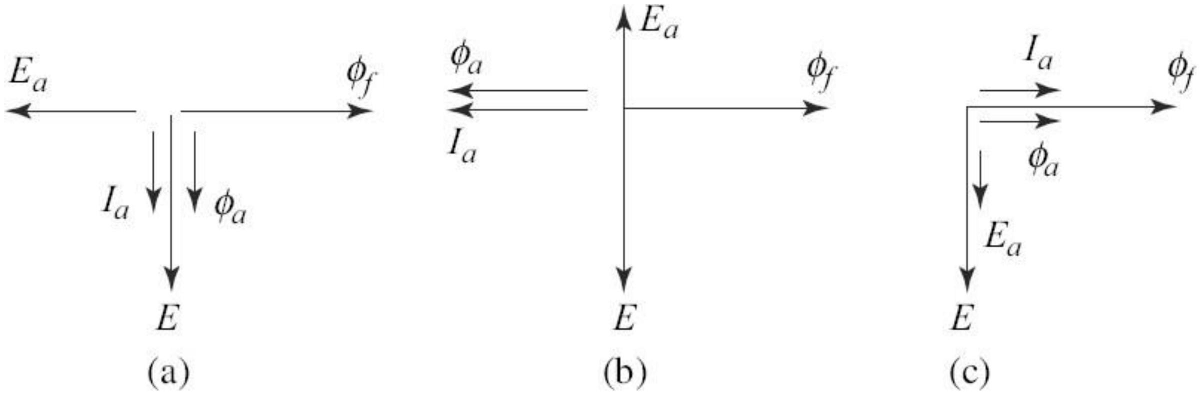
Synchronous Reactance & Synchronous Impedance: The vector sum of Armature leakage reactance X_L and the apparent reactance due to the effect of Armature reaction **X_{ar}** is called *Synchronous Reactance* **X_S**. *Finally the vector sum of* **R_a** and **X_S** is called *Synchronous Impedance* **Z_S**.

Armature reaction explained in detail along with phase relationships between all the important parameters in a Synchronous Generator:

The change in terminal voltage due to armature reaction effect can also be viewed as a reactance voltage drop. This can be understood from the following explanation:

The rotor field flux **φ_f** *produces an induced emf* **E** *in the armature winding. When loaded, this emf causes an armature current,* I_a *to flow through the winding and the load. The armature ampere-turns produce a flux,* **φ_a** *in the air gap. This flux* **φ_a** *produces another emf* **E_a** *in the armature windings.*

The phase relationship between the field flux **φ_f** *, armature induced emf due to field flux* **E** *, the armature current* **I_a** *the flux produced by armature current* **φ_a**, *and the emf induced* **E_a** *in the armature due to armature flux at different power-factor loads are shown in the figure below. Induced emf* **E** *will lag the field flux* **φ_f** *as shown in the figure.*



(a) (b) (c)

Figure: Phase relationship between the various quantities on (a) Resistive load (unity power factor), (b) Inductive load (zero power factor lagging) (c) Capacitive load (zero power factor leading)

The phase relationship between the induced emf **E** *and the current flowing* *through the armature winding **I_a** will depend upon the power factor of the load. At unity power-factor load **I_a** will be in phase with **E**. At zero lagging power-factor load **I_a** will lag **E** by 90° whereas at zero leading power-factor load, **I_a** will lead **E** by*

90°. Flux, $\boldsymbol{\varphi_a}$ produced by armature current $\mathbf{I_a}$ will be in time-phase. Emf induced $\mathbf{E_a}$ in the armature windings due to $\boldsymbol{\varphi_a}$ will lag $\boldsymbol{\varphi_a}$ by 90°. A component of the generated voltage that would be necessary to overcome this armature reaction voltage must act in the opposite direction.

Since the armature reaction induced voltage always lags the armature current and the flux producing it by 90°,the component of the voltage drop necessary to overcome this generated voltage will always lead the armature current by 90°. This voltage drop is similar to the component of applied voltage needed to overcome leakage reactance drop due to emf of self-induction. Thus the voltage induced due to armature reaction effect can be considered as a reactance drop in the armature winding of the synchronous generator. This fictitious reactance due to armature flux, $\boldsymbol{\varphi_a}$ is called $\mathbf{X_{ar}}$. Reactance due to armature leakage flux, as mentioned earlier, is called leakage reactance $\mathbf{X_L}$. The sum of $\mathbf{X_{ar}}$ and $\mathbf{X_L}$ is called ***synchronous reactance*** $\mathbf{X_S}$.

Equivalent circuit and corresponding Phasor diagrams:

We know that in non-salient, i.e., cylindrical rotor type Synchronous generators, the air-gap between the stator and the rotor is uniform. The synchronous reactance, $\mathbf{X_S}$ which is the sum of leakage reactance $\mathbf{X_L}$ and a fictitious reactance which replaces the effect of armature reaction $\mathbf{X_{AR}}$ is the same throughout the entire air-gap between the stator and the rotor. The armature winding resistance $\mathbf{R_a}$ is very small as compared to synchronous reactance $\mathbf{X_S}$. The equivalent circuit of a non-salient pole synchronous generator and its phasor diagram with these parameters are shown in the figure (a) below. Figure (b) below shows the approximate equivalent circuit and the corresponding phasor diagram with the armature resistance $\mathbf{R_a}$ neglected.

Here **V** is the terminal voltage and $\mathbf{I_a}$ is load current with a phase angle of **ϕ.** The angle **δ** between the induced emf **E** and the terminal voltage **V** is called the **Power angle** about which we will learn in more detail in the next unit.

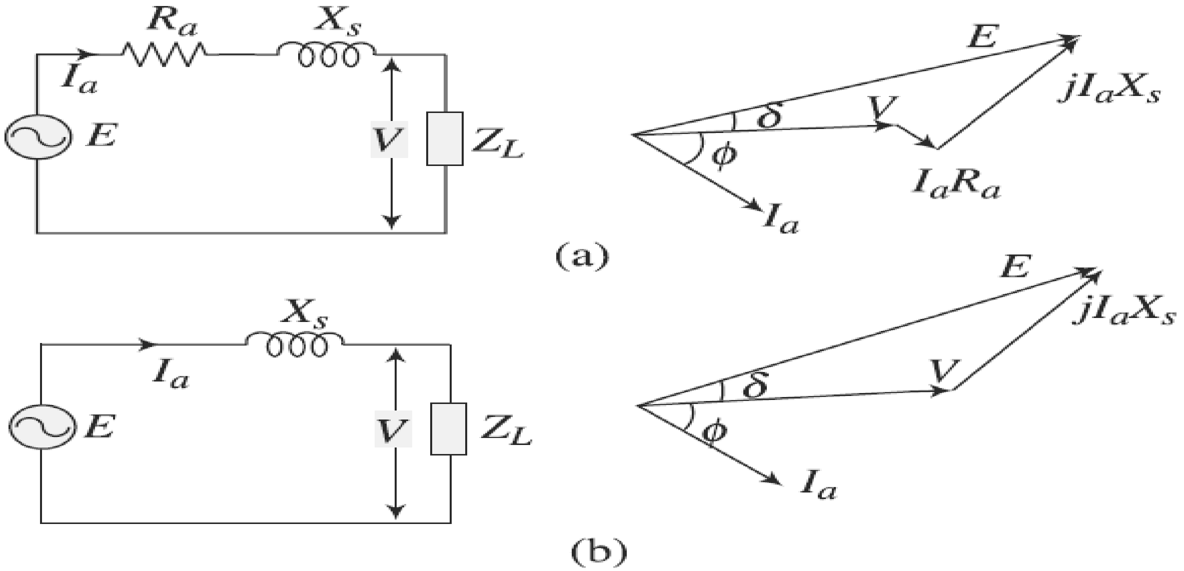


Figure: (a) Equivalent circuit and phasor diagram of a synchronous generator (b) Equivalent circuit and phasor diagram with R_a negelected

The phasor diagrams representing the various quantities of a synchronous generator at different power-factor loads are also shown in the figure below.

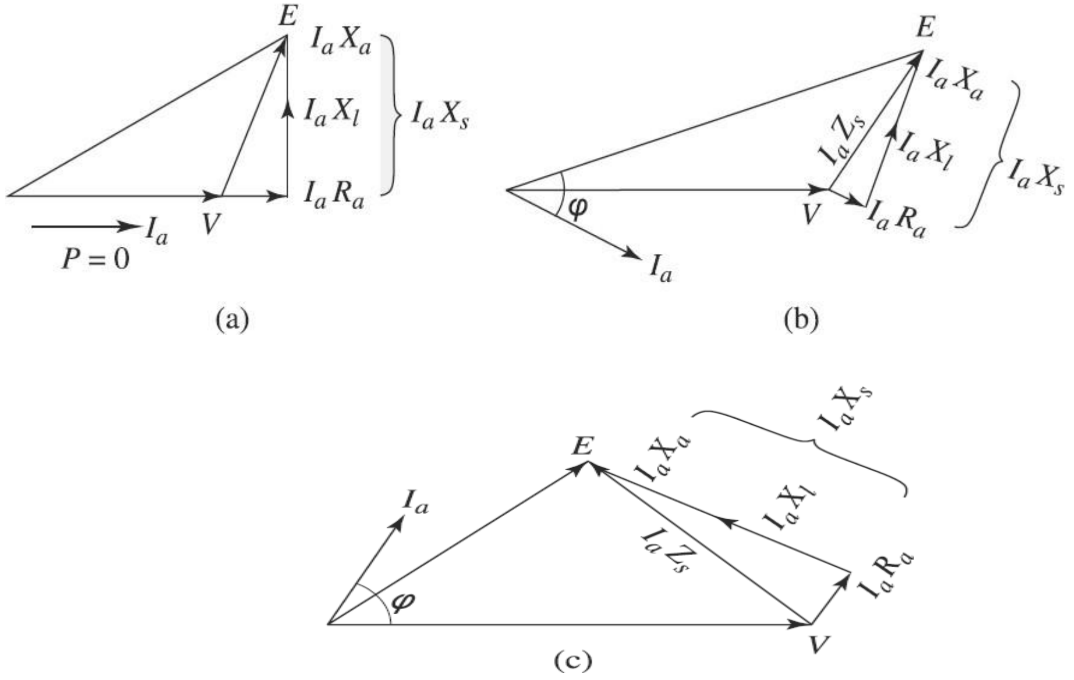


Figure: Phasor diagrams at (a) Unity pf load, (b) Lagging pf load, (c) Leading pf load

Load Characteristics & Voltage regulation of a synchronous generator:

When an alternator is loaded, there will be a voltage drop due to $\mathbf{I_a R_a}$ which is in phase with $\mathbf{I_a}$ and due to $\mathbf{I_a X_s}$, which is leading $\mathbf{I_a}$ by **90°**. The difference between the terminal voltage **V** and induced emf **E** is due to voltage drops in the resistance and reactance, $\mathbf{I_a R_a}$ and $\mathbf{I_a X_s}$. The relationship between induced emf **E** and the terminal voltage **V** is given by:

$$\mathbf{E = V + I_a R_a + I_a (X_L + X_a)}$$
$$\mathbf{\text{or } E = V + I_a R_a + I_a X_s}$$
$$\mathbf{\text{Or } E = V + I_a(R_a + X_s)}$$
$$\mathbf{\text{Therefore } E = V + I_a Z_s}$$
$$\mathbf{\text{Or } V = E - I_a Z_s}$$

The above expression for **V** is a function $\mathbf{I_a}$ and it's plot is known as the Load Characteristics and shown below for various power factor loads.

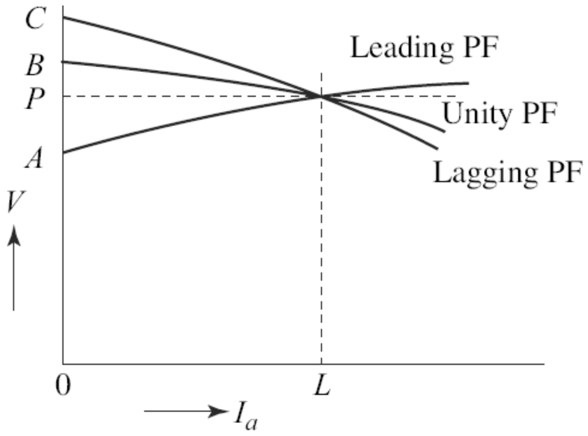


Figure: Effect of armature reaction on terminal voltage of a synchronous Generator at various power factor loads

It has been explained that the terminal voltage of a synchronous generator changes on application of load across its output terminals. The change is due to voltage drop in the windings (in the armature reactance $\mathbf{R_a}$ and Leakage reactance

L_a) in addition to the effect of armature reaction. The change in terminal voltage due to armature reaction effect depends upon the magnitude and power factor of the load.

At lagging power-factor load the armature reaction effect is just opposite to that of leading power-factor load. Figure below shows the relationship between terminal voltage and load current of a synchronous generator at different power-factor loads.

Let **OL** be the rated load on the generator. At this load, **OP** is the terminal voltage. If this load of unity power factor is removed, keeping speed and excitation of the alternator constant, the terminal voltage will rise to **OB**, whereas if the load is of lagging power-factor, the terminal voltage will rise to **OC**. For leading power-factor load, terminal voltage however will fall to **OA**. It can be noticed that the change of terminal voltage from full-load to no-load is more in case of lagging or leading power-factor load as compared to unity power-factor load. This is because of the demagnetizing or magnetizing effect of armature reaction on the main field flux.

The variation of terminal voltage from no-load to full-load expressed per unit or percentage of full-load voltage is called regulation of a synchronous generator. The per unit regulation of a Generator is expressed as:

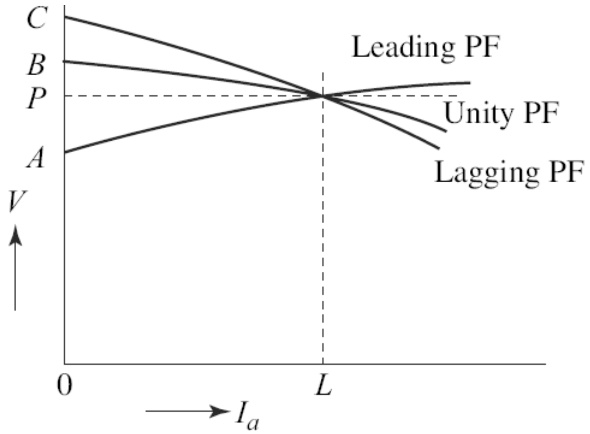


Figure: Variation of terminal voltage of a synchronous generator at different power factor loads

Per unit regulation:

= (Change of terminal voltage from NL to FL)/ FL terminal voltage)

= (OB – OP)/ OP = BP/OP *at unity pf load*

= (OC – OP)/ OP = CP/OP *at lagging pf load*

= (OA – OP)/ OP = AP/OP *at leading pf load*

It can be noticed that at leading power-factor load, the regulation is negative. Since Regulation of an alternator depends on the load and the load power-factor, it is, therefore, necessary to mention power factor also while expressing regulation at a particular load.

An expression for voltage regulation is derived from the phasor diagram of a loaded synchronous generator at a lagging power-factor load shown in the figure below.

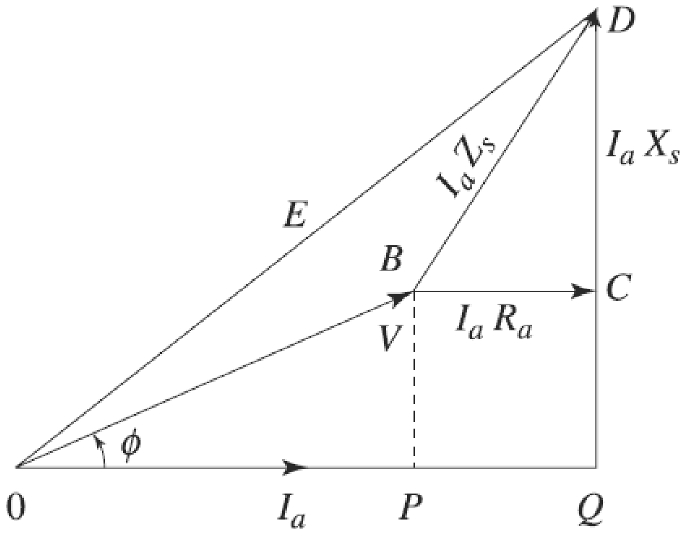


Figure: Phasor diagram of a Synchronous Generator at lagging power factor load

From the triangle **OQD** of figure above we can see that:

$$\mathbf{OD^2 = (OQ)^2 + (QD)^2}$$
$$\mathbf{= (OP+PQ)^2 + (QC+CD)^2}$$
$$\mathbf{Or\ \ E^2 = (V \cos \phi + I_aR_a)^2 + (V \sin \phi + I_aX_s)^2}$$
$$\mathbf{Or\ \ E = \sqrt{}*(V \cos \phi + I_aR_a)^2 + (V \sin \phi + I_aX_s)^2]}$$

No-load voltage, **E** corresponding to a particular load current **I_a** can be calculated if the values of terminal voltage on load, load power-factor angle, armature resistance $\mathbf{R_a}$ and synchronous reactance $\mathbf{X_s}$ are known.

For a leading power-factor load, the expression for **E** can be similarly derived and can be expressed as:

$$E \quad = \surd\ *(V \text{ Cos } \phi + I_aR_a)^2 + (V \text{ Sin } \phi - I_aX_s)^2]$$

Thus, in general, the expression for no-load voltage **E** can be written as,

$$E \quad = \surd\ *(V \text{ Cos } \phi + I_aR_a)^2 \pm (V \text{ Sin } \phi + I_aX_s)^2]$$

Where, + sign is for lagging power-factor load and, – sign is for leading power factor load.

Determination of Regulation of a Synchronous Generator:

Commercial generators are manufactured in ratings as high as 500 MVA. To determine voltage regulation directly, such high capacity generators are to be loaded. Loading of such generators to determine their regulation or efficiency in the test laboratory will be a difficult task. Moreover, the prime mover required for driving such a generator may not be available in the test laboratory. It is, therefore, a common practice to test such large machines indirectly by simulating the load conditions.

Such indirect methods will consume only a small amount of power as compared to the power consumed in direct loading method.

We will study the three important methods of determining regulation of an alternator.

Determination of Voltage Regulation by Synchronous Impedance Method:

In this method of determination of regulation, two tests are required to be per formed on the machine, namely the open-circuit test and the short-circuit test. Open-circuit test is performed by running the alternator on no-load and at rated speed. The terminal voltage on no-load is measured at different values of excitation current. The relationship between no-load voltage and excitation current gives the open-circuit characteristics (OCC).

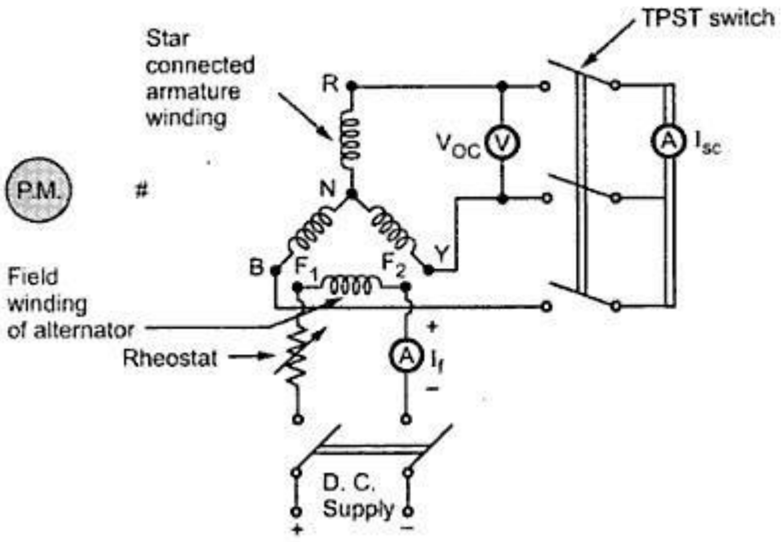


Figure: Open circuit and Short circuit test setup for an Alternator

Short-circuit test is performed by running the alternator at rated speed. Keeping the output terminals short-circuited through an ammeter, reduced excitation current is allowed to flow through the field winding. The relationship between armature current, **I_a** and the field current **I_f** gives the short-circuit characteristics (SCC). Test setup for conducting Open circuit and short circuit tests are shown in the figure below.

The OCC and SCC of an alternator are shown in the figure below.

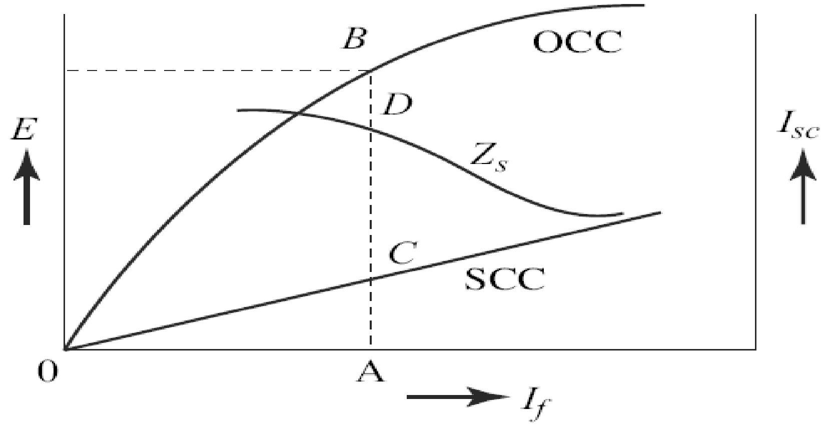


Figure: Open Circuit and Short Circuit Characteristics of a Synchronous Generator

At any particular value of **I_f** the ratio of open-circuit voltage and short-circuit armature current gives the synchronous impedance **Z_s**. Referring to the above figure, **Fig. 5.31** at a field current of say **OA**, the induced emf is **AB**. With this excitation, if the armature terminals are short-circuited, a current **AC** will flow through the armature windings. The emf induced, **AB** on open circuit is regarded as being responsible for circulating a short-circuit current of **AC** through the synchronous impedance of the winding. Thus the value of synchronous impedance **Z_s** at this excitation is given by:

$$Z_s = \text{OC Voltage/SC Current} \qquad (\textit{at the same excitation})$$
$$= [\, A\,B\,(V)/\,AC\,(A\,) + \Omega$$

To calculate per-phase value of **Z_s**, the values of emf and current should be taken as their per-phase values. Because of the non-linear nature of the OCC, the ratio of open-circuit voltage and short-circuit current at various values of excitation currents are different. If the values of **Z_s** at different excitation are calculated and plotted, we will get a curve for **Z_s** as shown in the above figure. It is seen that at lower values of excitation current, the value of **Z_s**, is more than its value at higher excitations. We know that:

$$E \quad = \surd *(V \cos \phi + I_a R_a)^2 \pm (V \sin \phi + I_a X_s)^2]$$

So to find out **E** we need to have the values of **R_a** and **X_s.** The dc resistance **R_a** of the stator winding can be directly measured by ammeter-voltmeter method. Then AC resistance is calculated multiplying DC resistance by a factor of 1.5. The synchronous reactance **X_S** can be calculated from the relation: **$X_S = \surd\, Z_S^2 - R_a^2$.**
After calculating **E, *% Regulation*** can be calculated as:

$$\% \text{ Regulation} = [(E-V)/V] \times 100$$

We know that under short-circuit test, small amount of field current is necessary to circulate full load current through the winding. The induced emf corresponding to this excitation is small. The value of synchronous impedance calculated from open-circuit and short circuit test data is, therefore, more than its value under actual loading condition.

The regulation calculated using this value of synchronous impedance will, therefore, be more (poorer) than the actual value of regulation. Hence this method gives a very ***pessimistic result.***

Example 1: In a 2000 V. single-phase synchronous generator, a full-load current of 100 A is produced on short-circuit by a field excitation of 2.5 and an emf of 500 V is produced on open-circuit by the same excitation. The armature resistance is 0.8 W. Determine the voltage regulation when the generator is delivering a current of 100 A at (a) unity power factor, (b) 0.71 power factor lagging; and (c) 0.8 power factor leading.

Solution

$$\text{Synchronous impedance, } Z_s = \frac{\text{OC Voltage}}{\text{SC Current}} = \frac{500}{100} = 5\ \Omega$$

$$X_s = \sqrt{Z_s^2 - R_a^2} = \sqrt{5^2 - 0.8^2} = 4.935\ \Omega$$

$$\text{Induced emf} \qquad E = \sqrt{(V\cos\phi + I_a R_a)^2 + (V\sin\phi + I_a X_s)^2}$$

$$\text{(a) At unity pf} \qquad E = \sqrt{(V\cos\phi + I_a R_a)^2 + (V\sin\phi + I_a X_s)^2}$$

$$= \sqrt{(2000 \times 1 + 100 \times 0.8)^2 + (2000 \times 0 + 100 \times 4.935)^2}$$

$$= \sqrt{(2080)^2 + (4.935)^2} = 2138\ \text{V}$$

$$\text{Regulation} = \frac{E - V}{V} \times 100 = \frac{(2138 - 2000)}{2000} \times 100 = 6.9\%$$

(b) At 0.71 pf lagging, ($\cos\phi = 0.71$, $\sin\phi = 0.704$)

$$E = \sqrt{(2000 \times 0.71 + 100 \times 0.8)^2 + (2000 \times 0.704 + 100 \times 4.935)^2}$$

$$= \sqrt{(1420 + 80)^2 + (1408 + 493.5)^2} = 2422\ \text{V}$$

$$\text{Regulation} = \frac{E - V}{V} \times 100$$

$$= \frac{2422 - 2000}{2000} \times 100 = 21.1\%$$

(c) At 0.8 pf leading, ($\cos\phi = 0.8$, $\sin\phi = 0.6$)

$$E = \sqrt{(2000 \times 0.8 + 100 \times 0.8)^2 + (2000 \times 0.6 - 100 \times 4.935)^2}$$

$$= \sqrt{(1680)^2 + (706.5)^2} = 1822.5 \text{ V}$$

$$\text{Regulation} = \frac{E - V}{V} \times 100$$

$$= \frac{(1822.5 - 2000)}{2000} \times 100 = -8.87\%$$

Note that the regulation is negative at this leading power factor load.

Voltage Regulation by MMF Method:

This method of determining the regulation of an alternator is also called Ampere-turn method or **Rothert's M.M.F. method**. This method is also based on the results of open circuit test and short circuit test on an alternator like Synchronous impedance method.

In mmf (magneto motive force) method, the mmf required to produce an emf of **$E' = V + I_aR_a$** is obtained by adding vectorially **I_aR_a** drop to the terminal voltage **V.** The mmf in terms of field current to get this voltage is found out from the OCC. From the short circuit characteristic, the field current necessary to send rated armature current is determined. The mmf representing this field current is assumed to be necessary to send rated current through the armature leakage reactance and at the same time overcome armature reaction. These mmfs or ampere-turns are produced by field currents say **I_{f1}** and **I_{f2}** respectively. **I_{f1}** is found out from OCC and **I_{f2}** is found out from SCC as shown in the figure (a) below.

I_{f1} produces **E'** which lags behind **I_{f1}** by 90°. **I_{f2}** produces an emf which will be able to circulate the rated current through the armature on short circuit. This emf is equal to the voltage drop in the armature due to synchronous reactance and hence is drawn in phase opposition to **I_a**.

The phasor sum of **I_{f1}** and **I_{f2}** gives the total field current **I_f** required to induce an emf **E.** The value of **E** corresponding to **I_f** is found from the OCC and voltage regulation is calculated as: **%Voltage regulation = [(E - V)/V] x 100**

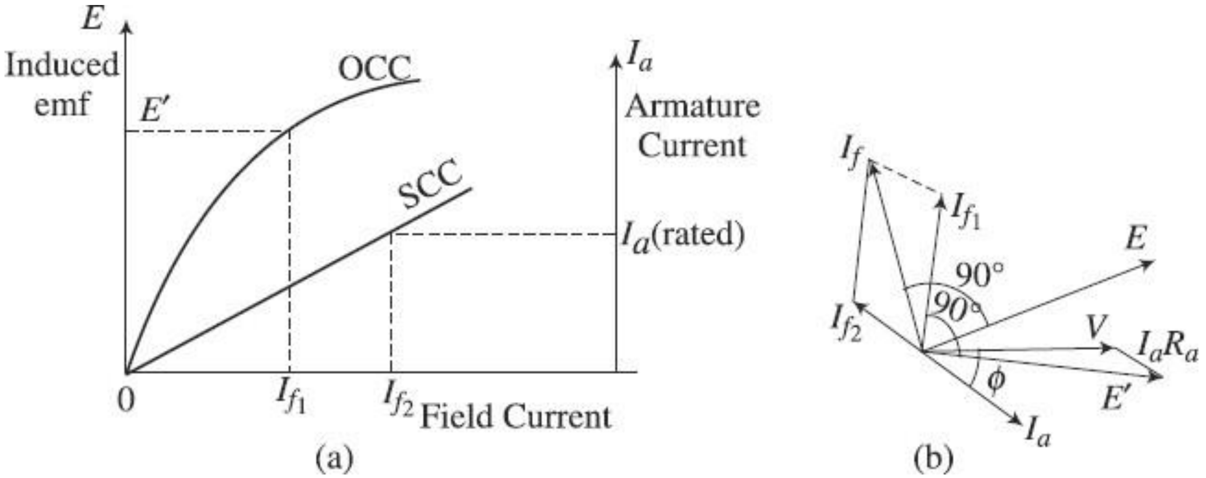


Figure: (a) OCC and SCC of a Synchronous Generator (b) Phasor diagram for determining resultant field current.

Step by step procedure for calculation of voltage regulation by mmf method is given below.

1. Open-circuit & Short Circuit tests are conducted and OCC & SCC are drawn just like in EMF method.
2. Armature resistance is measured by ammeter-voltmeter method by applying a low voltage DC. Then AC resistance $\mathbf{R_A}$ is calculated as 1.5 times the DC resistance.
3. The procedure basically involves reading the data from the OCC &SCC and then drawing the Phasor diagram step by step alternately.
4. Armature rated voltage **V** is drawn to scale as reference phasor in the phasor diagram. Let us assume that regulation is required to be calculated at an armature current of $\mathbf{I_a}$ and power factor angle of $\boldsymbol{\phi}$. Then phasor $\mathbf{I_a}$ is drawn making a lag angle of $\boldsymbol{\phi}$ with the **V-**axis. Then $\mathbf{I_a}$ $\mathbf{R_a}$ drop is added vectorially (in phase with $\mathbf{I_a}$) to **V** to get the no load induced voltage **E'**. For this voltage **E'** to be induced the required field current $\mathbf{I_{f1}}$ is read from the **OCC**. This value of $\mathbf{I_{f1}}$ is drawn to scale such that the induced emf **E'** lags $\mathbf{I_{f1}}$ by 90° (see phasor diagram in figure **b** above).
5. The field current $\mathbf{I_{f2}}$ required to circulate the rated current through the armature on short-circuit is read from the **SCC**. This is the field current required to induce an emf which will balance the synchronous reactance voltage drop, $\mathbf{I_a}$ $\mathbf{X_s}$. Then $\mathbf{I_{f2}}$ is drawn to scale in phase opposition to $\mathbf{I_a}$**.** Then finally the resultant of $\mathbf{I_{f1}}$ and $\mathbf{I_{f2}}$ is drawn to give $\mathbf{I_f}$ as shown in the phasor diagram.

6. From the phasor diagram using the field current scale factor, **I**$_f$ is obtained in amperes. From the OCC the value of induced emf **E** corresponding to this net field

current of I_f is read. Using this value of emf **E** and the rated terminal voltage **V,** voltage regulation is calculated using the formula

$$\%\text{Voltage regulation} = [\ (E - V)/V\ ] \times 100$$

The value of regulation found out by mmf method is lower than the actual regulation of the alternator and hence is an ***Optimistic method***.

Zero Power Factor (ZPF) Method:

This method is also called **Potier** method. In the operation of any alternator, the armature resistance drop I_aR_a, and armature leakage reactance drop I_aX_L are actually e.m.f. quantities while the armature reaction is basically a m.m.f. quantity. In the synchronous impedance method all the quantities are treated as e.m.f. quantities where as in M.M.F method all are treated as m.m.f. quantities. Hence in both the methods, we are away from the true value.

This method is based on the separation of armature leakage reactance and armature reaction effects into emf and mmf quantities respectively. The armature leakage reactance X_L *, is called* ***Potier reactance*** *in this method, hence this method is also called* ***Potier reactance method.***

To determine armature leakage reactance and armature reaction m.m.f. separately, the following two tests are to be performed on the given alternator.

1. Open circuit test

2. Zero power factor test

The single experimental setup to perform both these tests is shown in the figure below.

The open circuit characteristic giving the relationship between induced emf **E** and the field current I_f on no-load at rated speed is obtained from the open circuit test exactly in the same steps as in EMF and MMF tests *and is given below for quick reference.*

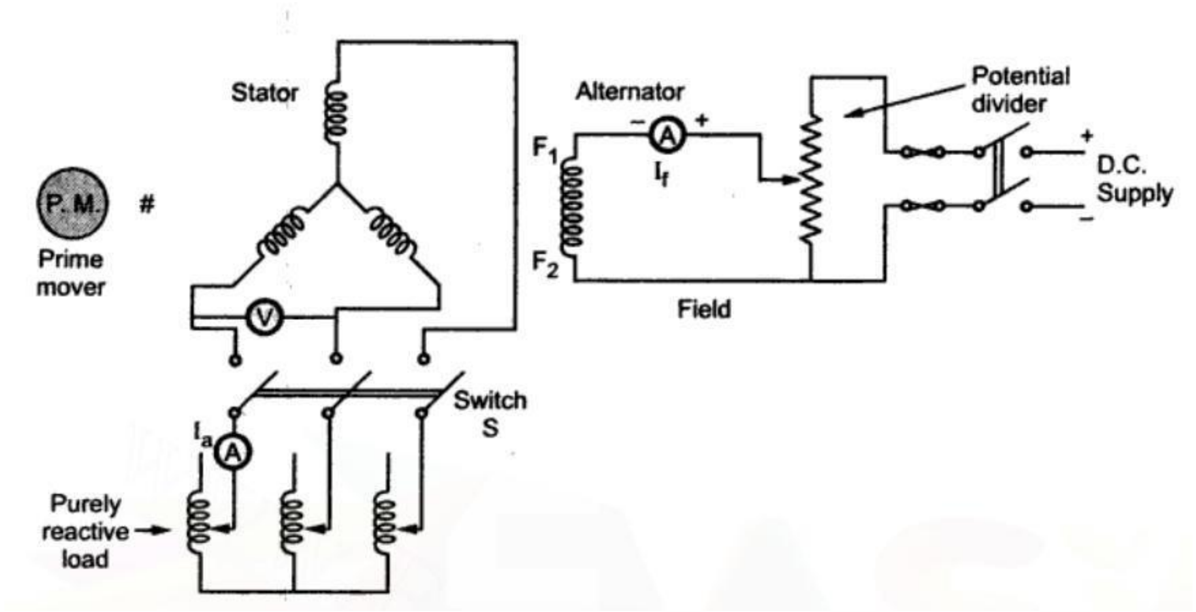


Figure: Experimental setup for ZPF method

*The switch **S** is kept open.*

1. *The alternator is driven by its prime mover at its synchronous speed and maintained constant throughout the test*
2. *The excitation is varied in definite number of steps with the help of the potential divider, from zero until rated terminal voltage is exceeded. The open circuit e.m.f. is measured with the help of voltmeter. The readings are tabulated.*
3. *From this data the OCC of the alternator i.e plot of induced EMF **E** versus I_f is plotted*

Zero Power Factor Test

ZPF test gives data to get a graph of terminal voltage against excitation when delivering full load zero power factor current.

By closing the switch S a purely inductive load (with a power factor of Cos 90^0 i.e., zero PF lagging) gets connected to the alternator through an ammeter. The machine speed is maintained constant at its synchronous value. The load current delivered by the alternator to such a purely inductive load is maintained constant at its rated full load value by varying excitation and by adjusting variable inductance of the inductive load.

In this test, there is no need to obtain number of points to obtain the ZPF curve. Only two points are enough to construct the zero power factor saturation curve as explained below.

One point for this curve is zero terminal voltage (short circuit condition) and the field current required delivering full load short circuit armature current. This point is obtained from the SCC (Short Circuit Characteristic which is also required to be plotted along with OCC). The other point is the field current required to obtain rated terminal voltage while delivering the rated full load armature current to the Inductive load. With the help of these two points the ZPF saturation curve can be obtained and plotted along with OCC and SCC as shown in the figure below.

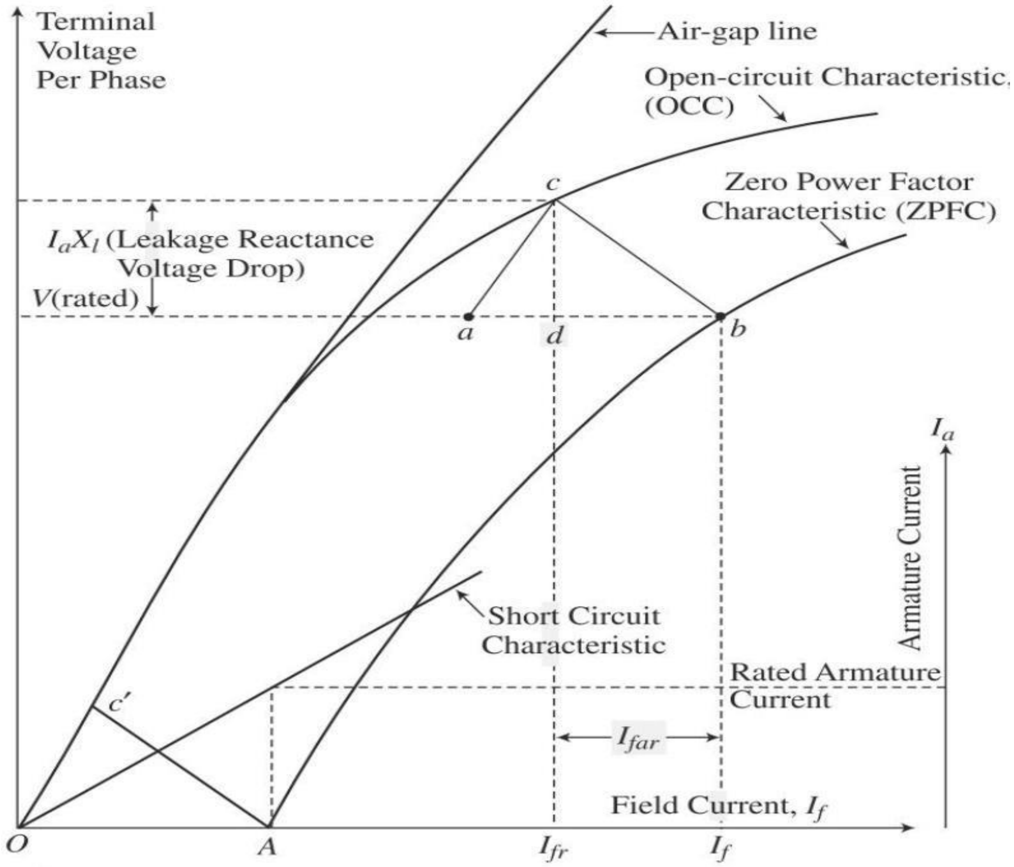


Figure: Open circuit and Zero Power Factor load characteristics

Figure above shows the **OCC, SCC** and **ZPF** characteristics. Important properties and the data that can be obtained from the above characteristics are given below.

1. Distance **OA** represents the field current required for flow of rated armature current when the terminal voltage is zero (obtained from Short circuit test)
2. Point **b** on **ZPFC** corresponds to the terminal voltage at a field current of I_f when the alternator is supplying rated current at zero power factor inductive load.
3. The distance **ab** is equal to distance **OA**(and both are parallel). Line **ac** is drawn from point **a** parallel to the air gap line to touch the **OCC** at point **c**. Then point **c** and **b** are joined. Triangle ***abc*** is called the Potier triangle.
4. Drop a perpendicular from point **c** to **ab** meeting at point **d**. The vertical distance **cd** of the Potier triangle represents the leakage reactance drop I_aX_L. Distance **db** represents the field current required to oppose the armature reaction mmf. Distance **ad** represents the field current required to overcome leakage reactance voltage drop I_aX_s.
5. From the Potier triangle, therefore leakage reactance of the armature is calculated as: X_L= **[Voltage drop per phase** (distance ***cd***)**]/[Rated armature current per phase]**

*It is not necessary to draw the complete **ZPFC** by taking several readings. If we slide the Potier triangle **abc** downwards such that the point **c** always rests on the OCC, then the locus of point **b** becomes the **ZPF C**haracteristic.*

A step by step procedure for drawing the OCC, SCC & ZPF characteristics while simultaneously drawing the phasor diagram and then calculation of voltage regulation using Potier triangle method (ZPF Method) is given below.

1. Draw the open circuit characteristic by choosing a suitable scale for rated terminal voltage **V** and the field current I_f. The voltage should be the per phase value.
2. Choosing an appropriate scale factor for armature current I_a draw the **SCC** also on the same plot such that both plots can be seen as in the figure above.
3. **OA** is marked on I_f axis representing the field current required on short circuit to drive the rated armature current.

4. Another point **b** is located by taking the length of field current **I_f** and length of rated terminal voltage required to drive the rated armature current into full-load zero power factor lagging load (found from **ZPF** test).

5. Mark **ab** equal and parallel to **OA.** From point **a** draw a line parallel to the air-gap line touching the **OCC** at point **c**.
6. Join **c** and **b**. Triangle **abc** is the ***Potier*** triangle. Drop a perpendicular from **c** to **d** onto the line **ab**.Measure the distance **cd** and calculate the leakage reactance $\mathbf{X_L}$ by considering the voltage scale. Determine the value of Ra.
7. Calculate $\mathbf{E' = V + I_aR_a + j\ I_a\ X_L}$ (By phasor addition as shown in the Phasor diagram below)
8. Corresponding to voltage **E'** find the field current from the **OCC**, (which is $\mathbf{I_{fr}}$ in the figure containing **ZPF** characteristics.Next draw the phasor $\mathbf{I_{fr}}$ leading **E'** by 90°. Next draw $\mathbf{I_a}$ lagging voltage **V** by the power factor angle **ϕ**. Then draw $\mathbf{I_{far}}$ in phase opposition to $\mathbf{I_a}$. Draw the resultant field current $\mathbf{I_f}$, by adding $\mathbf{I_{fr}}$ and $\mathbf{I_{far}}$ vectorially**.**
9. From **OCC** find the value of **E** corresponding to $\mathbf{I_f}$
10. Calculate percentage voltage regulation as:

    % Voltage regulation = [(E-V)/V]x100

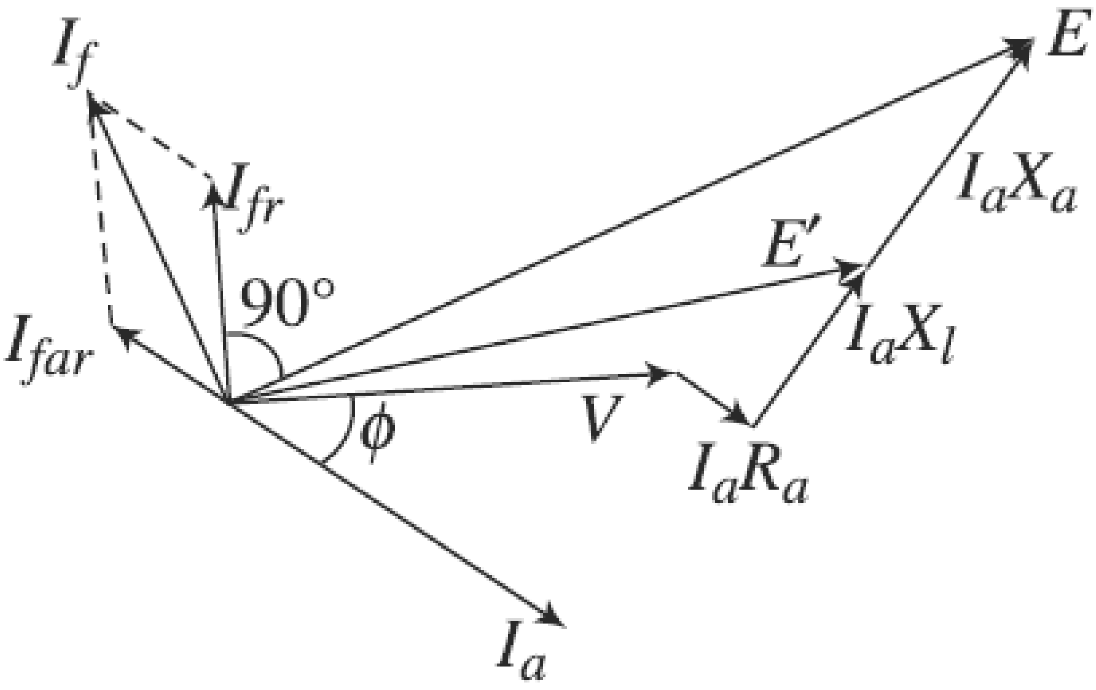


Figure 5-37: Phasor diagram of a Synchronous Generator – Determining Voltage Regulatio

Illustrative Examples:

Example 1: *An armature of a three phase alternator has 120 slots The alternator has8 poles. Calculate its distribution factor.*

Solution: n$=\frac{slots}{Pole}=\frac{120}{8}=15$

m = Slots/Pole/Phase = $\frac{n}{3}=\frac{15}{3}=5$

β = $\frac{180^0}{n}=\frac{180^0}{15}=12^0$

∴ K$_d$ = $\frac{\sin(\frac{mQ}{2})}{m\sin(\frac{Q}{2})}=\frac{\sin(\frac{5\times12}{2})}{5\times\sin(\frac{12}{2})}=\mathbf{0.957}$

Example 2:*In a 4 pole, 3 phase alternator, armature has 36 slots. It is using an armature winding which is short pitched by one slot. Calculate its coil span factor.*

Solution: n = $\frac{Slots}{Pole}=\frac{36}{4}=9$

β = $\frac{180^0}{n}=20^0$

Now coil is shorted by 1 slot i.e. by 20^0 to full pitch distance.

∴ α = Angle of short pitch = 20^0

∴ **K$_c$ = Cos (α/2)**= Cos (20^0/2) = $\mathbf{0.9848}$

Example 3:*An Armature runs at 250 r.p.m. and generates an e.m.f. at 50 Hz. There are 216 slots each containing 5 conductors. The winding is distributed and full pitch. All the conductors of each phase are in series and flux per pole is 30 mWb which is sinusoidal distributed. If the winding is star connected, determine the value of induced e.m.f. available across the terminals.*

Solution: N$_s$ =250 r.p.m., f = 50 Hz

N$_s$ = $\frac{120f}{P}$ i.e. 250 = $\frac{120\times50}{P}$

∴ Number of poles **P = 24**

∴ $$\mathbf{n} = \frac{Slots}{Pole} = \frac{216}{24} = 9$$

∴ $$\mathbf{m} = \frac{n}{3} = 3$$

∴ $$\boldsymbol{\beta} = \frac{\mathbf{180^0}}{\boldsymbol{n}} = \frac{180^0}{9} = 20^0$$

We know that the distribution factor **K_d** is given by:

$$\mathbf{K_d} = \frac{\sin\left(\frac{m\beta}{2}\right)}{m\sin\left(\frac{\beta}{2}\right)} = \frac{\sin\left(\frac{3\times 20}{2}\right)}{3\times\sin\left(\frac{20}{2}\right)} = 0.9597$$

K_c = 1 as winding is full pitch.

Total number of conductors **Z** = 216 × 5 = 1080

∴ $$\mathbf{Z_{ph}} = \frac{\boldsymbol{Z}}{\mathbf{3}} = \frac{1080}{3} = 360$$

$\mathbf{T_{ph}} = \frac{Z_{ph}}{2} = \frac{360}{2} = \mathbf{180}$ ..... (2 conductors → turn)

We know that **E_{ph}**= 4.44 K_cK_d f Ø T_{ph}

= 4.44 ×1 × 0.9597 × 50 ×30 × 10^{-3}x 180

= 1150.48 V

E_{line} = $\sqrt{3}$ E_{ph}

= $\sqrt{3}$ × 1150.48 = 1992.70 V.

Example 4: *A 3 phase, 16 Pole, star connected alternator has 144 slots on the armature periphery. Each slot contains 10 conductors. It is driven at 375 r.p.m. The line value of e.m.f. available across the terminals is observed to be 2.657 KV. Find the frequency of the induced e.m.f and flux per pole.*

Solution: Number of Poles **P** = 16, **N_s** = 375 r.p.m.,

Slots = 144, Conductor/Slots = 10, **E_{line}**= 2.657 Kv

$N_s = \frac{120f}{P}$ i.e. $375 = \frac{120\times f}{16}$

∴ **f** = 50 Hz

Assuming full pitch winding, **K_c** = 1

∴ $\mathbf{n} = \frac{\boldsymbol{Slots}}{\boldsymbol{Pole}} = \frac{144}{16} = 9$

∴ $\mathbf{m} = \frac{n}{3} = 3$

∴ $\beta = \frac{180^0}{n} = \frac{180^0}{9} = 20^0$

We know that the distribution factor **K_d** is given by: $\mathbf{K_d} = \frac{\sin\left(\frac{m\beta}{2}\right)}{m\sin\left(\frac{\beta}{2}\right)} = \frac{\sin\left(\frac{3\times 20}{2}\right)}{3\times\sin\left(\frac{20}{2}\right)}$

$$= 0.9597$$

Total conductors = Slots × Conductors / Slot

i.e. **Z** = 144 × 10 = 1440

$$\therefore \quad Z_{ph} = \frac{Z}{3} = \frac{1440}{3} = 480$$

$$T_{ph} = \frac{Z_{ph}}{2} = \frac{480}{2} = 240$$

$$E_{ph} = \frac{E_{line}}{\sqrt{3}} = \frac{2.657}{\sqrt{3}} = 1.534\ kV$$

Using the above values in the equation for EMF we get : **E_{ph} = 4.44 $K_C K_d$ f Ø T_{ph}**

$1.534 \times 10^3 = 4.44 \times 1 \times 0.9597 \times 50 \times Ø \times 240$

From which we get: $Ø = (1.534 \times 10^3)/(4.44 \times 1 \times 0.9597 \times 50 \times 240)$

$Ø = 0.03$ Wb = 30 mWb

Important questions:

1. Compare and contrast the technical features of Synchronous Generators with (i) Induction Generators and (ii) DC Generators.
2. (a) Explain the basic principle of operation and construction details of 3 ϕ Synchronous Generators.
   (b) What are the advantages of Stationary Armature and Rotating Field system as compared to Stationary field and Rotating Armature System in a Synchronous Generator?
3. With the help of neat sketches explain the two types of Rotor Construction, their advantages vs. disadvantages and applications.
4. (a)Explain with the help of a neat sketch how a Brushless exciter system works.
   (b) What is a pilot exciter and how it works along with a brush less exciter.
5. With the help of simple sketches explain the following terms pertaining to Armature windings in a Synchronous Generator :
   (a) Pole pitch &Slot angle (β): (b)Single Layer and Double Layer Winding
   (c)Full Pitch and Short Pitch Winding (d) Concentrated and Distributed Winding
   (e) Integral & Fractional Slot Winding.

6. Derive an expression for the EMF generated in a Synchronous generator assuming full pitch and concentrated winding.
7. Define the terms (a) Pitch or Coil Span factor &(b) Distribution factor in Synchronous Generators and derive their expressions with relevant figures.

Then give the generalized EMF equation including the effects of short pitch and distributed winding.

8. Explain in detail the terms Armature reaction, leakage reactance, synchronous reactance and Synchronous Impedance in a Synchronous Generator.
9. Draw the equivalent circuit of a Synchronous Generator and also the phasor diagrams with (i) Lagging Pf Load (ii) Unity Pf Load (iii) Leading Pf Load
10. Explain what are Load Characteristics & Voltage regulation of a Synchronous Generator.
11. Explain in detail the determination of Voltage regulation by the following three important Methods:
    (i) Synchronous Impedance or EMF method
    (ii) MMF method
    (iii) Zero Power Factor Method
12. All the above worked out illustrative problems.

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UNIT-IV

PARALLEL OPERATION OF SYNCHRONOUS MACHINES

- **Synchronizing Alternators with Infinite Bus bars**
- **Synchronizing Power / Torque**
- **Parallel operation and Load sharing**
- **Effect of change of Excitation and Mechanical power input.**

SYNCHRONOUS MOTORS

- **Theory of operation- phasor diagrams**
- **Variation of current and power factor with excitation**
- **Synchronous condenser**
- **Hunting and its suppression**
- **Methods of starting**

  - **Important Questions**

Introduction:

For a clear understanding of the parallel operation of Generators the concept of Power Angle &Torque Angle and operation of Synchronous Generators alone is to be understood first. Hence these topics are covered first before dealing with Parallel operation of Synchronous Generators.

Power Angle and Torque Angle in Synchronous Generators:

A synchronous generator is a synchronous machine used as a generator. It converts mechanical power to three-phase electrical power. The source of mechanical power, the *prime mover,* may be a diesel engine, a steam turbine, a water turbine, or any similar device. ***Whatever the source, it must have the basic property that its speed is almost constant regardless of the power demand. If that were not so, then the resulting power system's frequency would vary..***
All the mechanical power going into a synchronous generator does not become electrical power out of the machine. The difference between input power and output power represents the losses of the machine. The power-flow diagram of a synchronous generator is shown in the figure below.

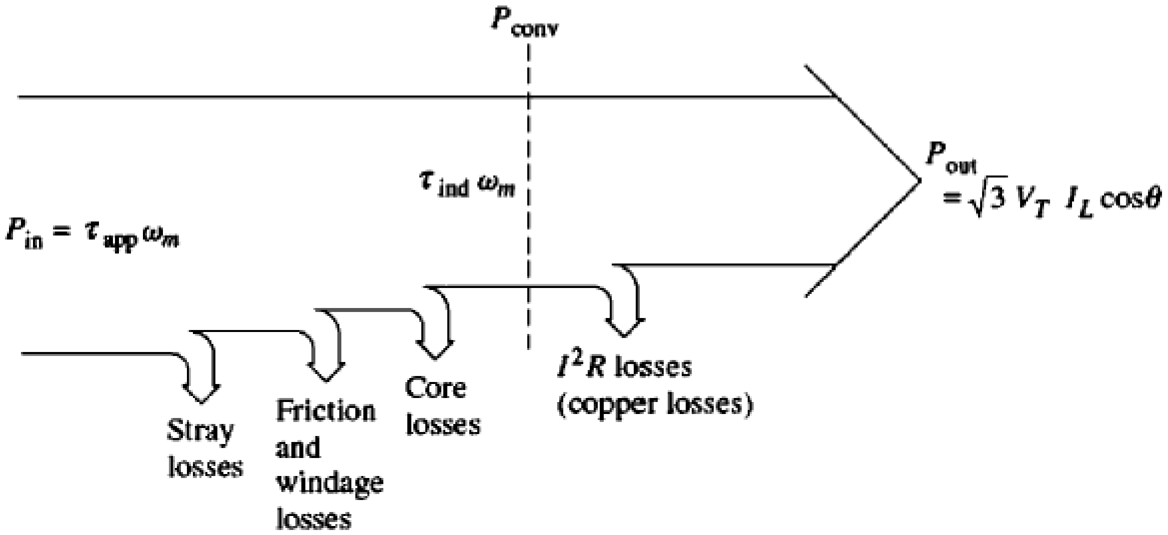


Figure: The power-flow diagram of a Synchronous Generator.

The input mechanical power which is the shaft power in the generator given by:

$$P_{in} = \tau_{app}.\omega_m$$

while the power converted from mechanical to electrical form internally is given by: $\mathbf{P_{con} = \tau_{ind} . \omega_m = 3E_aI_a\cos\gamma}$

where '**γ**' is the phase angle between $\mathbf{E_a}$ and $\mathbf{I_a}$. The difference between the input power to the generator and the power converted in the generator represents the mechanical, core, and stray losses of the machine.

The *Real* ($\mathbf{P_{out}}$) *and Reactive (Q) electrical output* power of the synchronous generator can be expressed in phase quantities as:

$$\mathbf{P_{out} = 3V_\phi I_a \cos\theta} \qquad .... (1)$$

$$\mathbf{Q_{out} = 3V_\phi I_a \sin\theta} \qquad .... (2)$$

where **θ** is the phase angle between the phase voltage $\mathbf{V_\phi}$ and the armature current $\mathbf{I_a}$.

If the armature resistance $\mathbf{R_a}$ is ignored (since $\mathbf{X_s >> R_a}$*),* then a very useful relation can be derived to approximate the output power of the generator. To derive this relation, refer the phasor diagram shown in the figure below which shows a simplified phasor diagram of a generator with the stator resistance ignored.

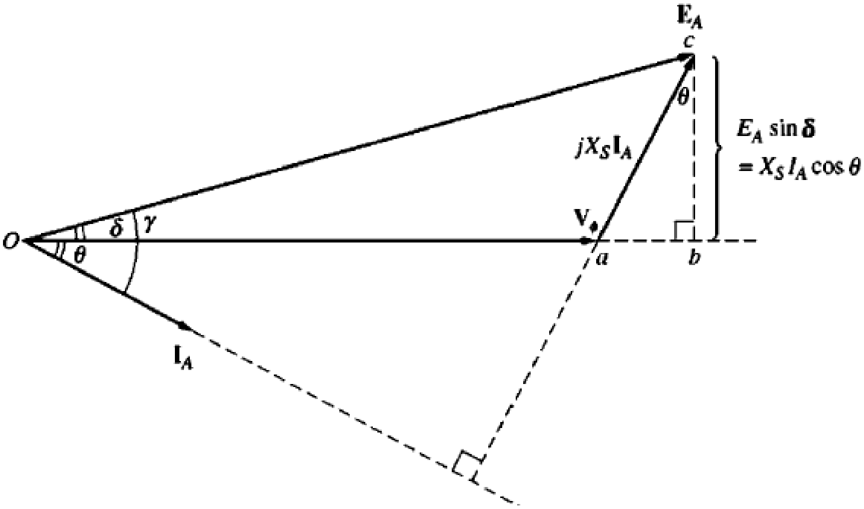


Figure: Simplified Phasor diagram with armature resistance ignored.

Notice that the vertical segment ***bc*** can be expressed as $\mathbf{E_A \sin\delta}$ or $\mathbf{X_S I_A \cos\theta}$**.** Therefore:

$$\mathbf{I_A \cos\theta = E_A \sin\delta / X_S}$$

And substituting this in the above equation for power output $\mathbf{P_{out} = 3V_\phi I_a \cos\theta}$ we get :

$$\mathbf{P = (3V_\phi E_A \sin\delta) / X_S} \qquad ...... \quad (3)$$

Since we have assumed the resistances to be negligible there are no electrical losses in the generator and the above equation for **P** stands good for both **P_{con}** and **P_{out}**.

The above equation **(3)** shows that the power produced by a synchronous generator depends on the angle **δ** between **V_ϕ** and **E_A**. The angle **δ** is known as the ***Power angle*** of the machine. The variation of Power and Torque as a function of **δ** is shown in the figure below . Notice also that the maximum power that the generator can supply occurs when **$\delta = 90^0$.** At **$\delta = 90°$,** sin **δ** = I, and

$$P_{max} = (3V_\phi E_A) / X_S$$

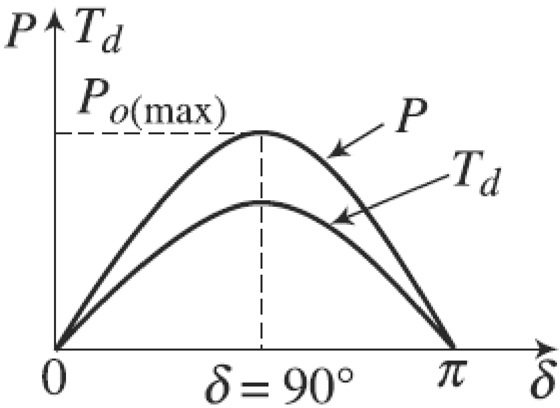


Figure: Power/torque-angle characteristic of a cylindrical rotor type Synchronous Generator

The maximum power indicated by this equation is called the ***static stability limit*** of the generator. Normally, real generators never even come close to this limit. Full-load torque angles of 15 to 20° are more typical of real machines.

Now take another look at Equations **(1), (2)** and **(3)** we find that if **V_ϕ** is assumed to be constant, then the ***real power output is directly proportional*** *to* **$I_a \cos \Theta$** and the ***reactive power output is directly proportional*** *to* **$I_a \sin \Theta$**. These facts are useful in plotting phasor diagrams of synchronous generators as loads change.

An alternative expression for the induced torque in a synchronous generator can be derived from the above equation for power converted **(3).**

Because **$P_{conv} = \tau_{ind} \cdot \omega_m$** the induced torque can be expressed as:

$$\tau_{ind} = (3V_\phi E_A \sin \delta) / (\omega_m X_S) \qquad \text{--} \quad (4)$$

This expression describes the ***induced torque*** in terms of electrical quantities where as the equation: $\tau_{ind} = k.B_R.B_{net} \sin \delta$ gives the same information in terms of magnetic flux densities. In this context we should know that the same **δ** which is now the phase angle between the Rotor flux density B_R and the net flux density B_{net} in the stator is called ***Torque angle***. As can be seen in the same above figure Torque also becomes maximum when $\delta = 90^0$

The synchronous generator operating alone:

The power input to an alternator is applied by a prime mover, which in most cases is a steam turbine. This input is directly proportional to the electrical output. If output is increased, more power must be developed by the prime mover, otherwise, speed will drop. If speed drops, there will be a drop in output voltage and frequency. On the other hand, if by increasing the prime mover steam supply, input power is increased without increasing the electrical output, the speed of the set will increase. Increase in speed will cause increase in terminal voltage and frequency.

It is rare to find a synchronous generator supplying its own load independently. For emergency power supply requirement, small synchronous generators driven by diesel engines are used.

The performance of a synchronous generator under load varies greatly depending on the power factor of the load and on whether the generator is operating alone or in parallel with other synchronous generators. In this section, we will study the behavior of synchronous generators operating alone. Here the concepts are illustrated with simplified phasor diagrams ignoring the effect of R_A. Unless otherwise stated, the speed of the generators is assumed to be constant, and all terminal characteristics are drawn assuming constant speed. Also, the rotor flux in the generators is assumed constant unless their field current is explicitly changed.

The Effect of Load Changes on a Synchronous Generator Operating Alone:

To understand the operating characteristics of a synchronous generator operating alone, examine a generator supplying a load. A diagram of a single generator supplying a load is shown in the figure below.

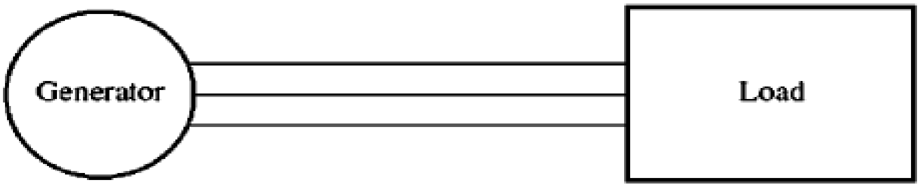


Figure: A Single Generator supplying a load.

An increase in the load is an increase in the real and/or reactive power drawn from the generator. Such a load increase increases the load current drawn from the generator. Because the field resistor has not been changed, the field current is constant, and therefore the flux $\boldsymbol{\varphi}$ is constant. Since the prime mover also keeps a constant speed $\boldsymbol{\omega}$, the *magnitude of the internal generated voltage* $\mathbf{E}_a = K \varphi \omega$ *is constant.*

If $\mathbf{E}_a$ is constant, then, what does vary with a changing load? The way to find out is to construct phasor diagrams showing an increase in the load, keeping the constraints on the generator in mind.

First, let us examine a generator operating at a lagging power factor. If more load is added at the *same power factor,* then $|\mathbf{I}_a|$ increases but remains at the same angle $\boldsymbol{\theta}$ with respect to $\mathbf{V}_\phi$ as before. Therefore, the armature reaction voltage $\mathbf{jX_sI_a}$ is larger than before but at the same angle. Now since

$$\mathbf{E}_a = \mathbf{V}_\phi + \mathbf{jX_sI_a}$$

$\mathbf{jX_sI_a}$ must stretch between $\mathbf{V}_\phi$ at an angle of $\mathbf{0°}$ and $\mathbf{E}_a$, which is constrained to be of the same magnitude as before the load increase. If these constraints are plotted on a phasor diagram, there is one and only one point at which the armature reaction voltage can be parallel to its original position while increasing in size. The resulting plot is shown in the figure **a** below.

If the constraints are observed, then it is seen that as the load increases, the voltage $\mathbf{V}_\phi$ decreases rather sharply.

Now suppose the generator is loaded with unity-power-factor loads. With the same constraints as before, it can be seen that this time $\mathbf{V}_\phi$ decreases only slightly (see figure-b).

Finally, let the generator be loaded with leading-power-factor load. If new loads are added at the same power factor this time, the armature reaction voltage lies outside its previous value, and $\mathbf{V}_\phi$ actually *rises* (see figure **c**). In this last case, an increase in the load in the generator produced an increase in the terminal voltage.

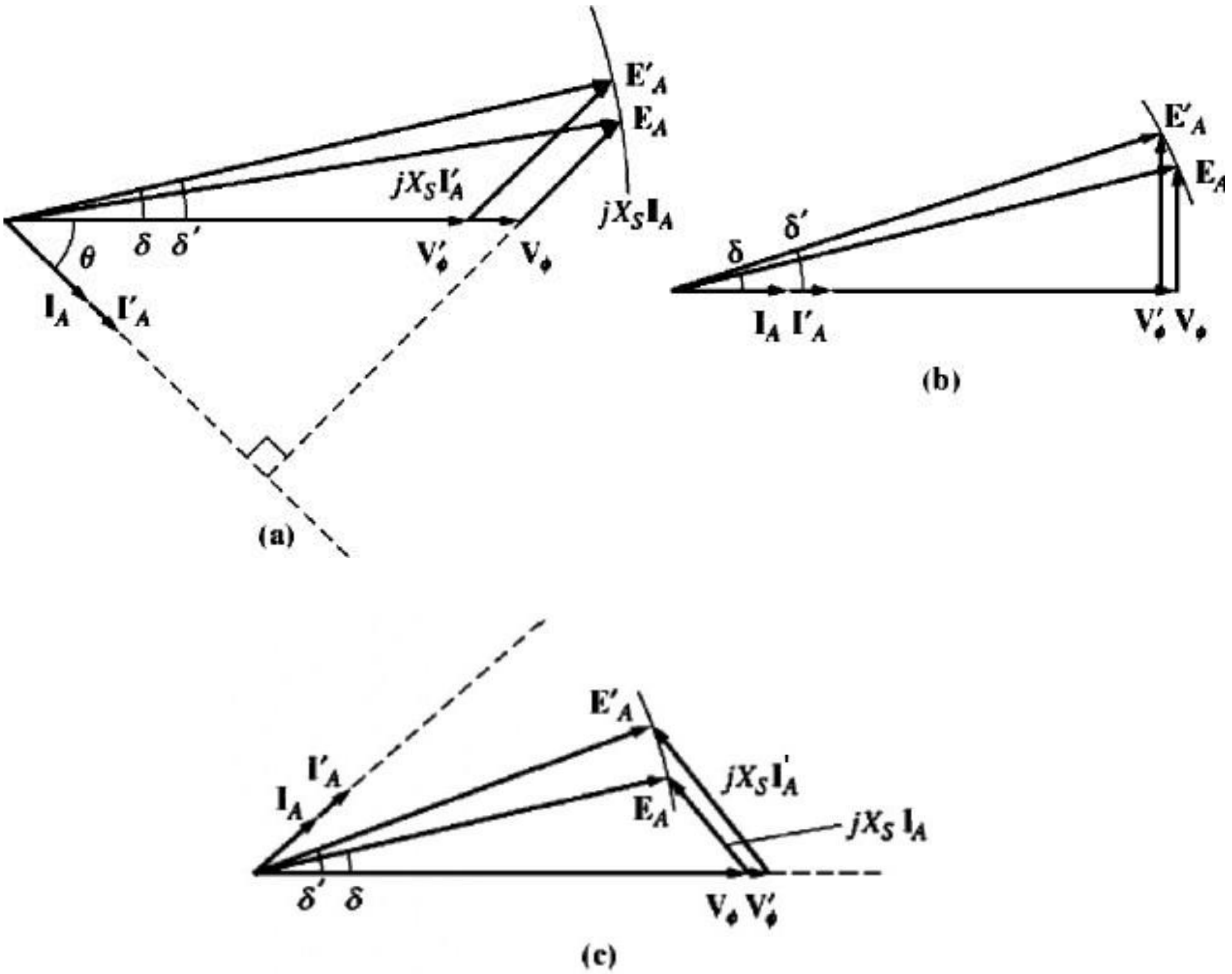


Figure: The effect of an increase in generator loads at constant power factor upon its terminal voltage (a) Lagging power factor (b) unity power factor (c) leading power factor

General conclusions from this discussion of synchronous generator behavior are:

I. If lagging loads (**+Q** or inductive reactive power loads) are added to a generator, $\mathbf{V}_\phi$ and the terminal voltage $\mathbf{V}_T$ decrease significantly.

2. If unity-power-factor loads (no reactive power) are added to a generator, there is a slight decrease in $\mathbf{V_\phi}$ and the terminal voltage.

3. If leading loads (**- Q** or capacitive reactive power loads) are added to a generator, $\mathbf{V_\phi}$ and the terminal voltage will rise.

Normally, it is desirable to keep the voltage supplied to a load constant, even though the load itself varies. To maintain the terminal voltage constant the obvious approach is to vary the magnitude of $\mathbf{E_A}$, to compensate for changes in the load. Recall that $\mathbf{E_a = K\,\phi\,\omega}$. Since the frequency should not be changed in a normal system, $\mathbf{E_A}$ can be controlled by varying the flux in the machine.
For example, suppose that a lagging load is added to a generator. Then the terminal voltage will fall, as was previously shown. To restore it to its previous level the field current is to be increased. An increase in $\mathbf{I_f}$ increases the flux, which in turn increases $\mathbf{E_A}$ and an increase in $\mathbf{E_A}$ increases the phase and terminal voltage.

The process can be reversed to decrease the terminal voltage. It is possible to regulate the terminal voltage of a generator throughout a series of load changes simply by adjusting the field current.

Synchronous Generators connected in parallel to an Infinite Bus:

It is an established practice these days to connect a number of synchronous generators in parallel to supply a common load. In power stations, instead of having one large capacity generator, a number of smaller units are installed and their output terminals connected in parallel. Moreover, for a variety of reasons, large number of stations in a country are interconnected through transmission and distribution lines and such a system is known as a Power Grid. All the synchronous generators of the system, therefore, work in parallel which is equivalent to a very large synchronous machine. Similarly all the electrical loads of the consumers are connected in parallel and form a very large variable load.

A supply system bus-bar with a large number of synchronous generators connected in parallel is referred to as an ***infinite bus-bar***. Any additional machine, whether to work as a generator or as a motor is connected in parallel with the system. The characteristics of an infinite bus-bar system are constant terminal voltage, constant bus-bar frequency and very small synchronous impedance (since a large number of generators are in parallel).There are a number of advantages of connecting alternators in parallel to such an *infinite bus-bar* system.

Synchronizing Power & Torque:

A Synchronous Generator when synchronized to an infinite bus will tend to remain in synchronism for limited electrical and mechanical disturbances. The power angle characteristic of a cylindrical rotor synchronous generator is governed by the expression:

$$P = \left(\frac{E\,V}{X_s} \right) \sin \delta$$

Assume that the generator is supplying a load of $\mathbf{P_0}$ with a load angle **δ**. Any sudden change of load on the generator will cause a momentary retardation of the rotor thereby increasing the load angle by **Δδ**. This increase in **δ** will cause an increase in power output by **ΔP** which in turn will cause the rotor to oppose the increase in **δ**. The reverse will happen when **δ** will tend to decrease. The rotor will settle at its original load angle **δ** in an oscillatory manner. Therefore, **ΔP** caused by **Δδ** is the power that brings the machine back to its stable mode of operation.

The ratio **dP/dδ** is called the synchronising power coefficient or stiffness of the electromagnetic coupling and is an indicator of the capability of the synchronous machine to stay in synchronism i.e. the power required to correct a unit phase change is called synchronizing power and is given by:

Synchronising Power:

$$P_{\text{syn}} = \frac{dP}{d\delta} = \left(\frac{EV}{X_S} \right) \cos \delta \quad \text{Watt/elec. radian}$$

Synchronising power gives rise to a ***synchronising torque*** which is the Torque required to correct a unit phase change and given by:

Synchronising Torque:

$$T_{\text{syn}} = \frac{1}{\omega_S}\frac{dP}{d\delta} \text{ Nm/elec. radian}$$

where $$\omega_s = \frac{2\pi N_s}{60}$$

From the expression for synchronising power, it is observed that **P_{syn}** is directly proportional to **E** and inversely proportional to synchronous reactance **X_S**. Machines with over excitation and small value of **X_S** will have high value of synchronizing power. Further, when value of **δ** is zero, **P_{syn}** is maximum and when **δ** is nearly 90° there is hardly any synchronising power or restoring action to counter the disturbances.

Machine Floats on a Bus-Bar: When synchronised, the generated emf of the incoming machine is just equal to the bus-bar voltage. The synchronous machine will be just floating on the bus-bar, i.e., it will neither deliver nor receive any power. The prime mover driving the machine will be supplying the no-load losses only.

Once a synchronous machine is synchronised, it will tend to remain in step with the other alternators. Any tendency to depart from the above condition is opposed by a ***synchronising torque*** (as explained above) developed due to a circulating current flowing through the alternators. The alternator, which due to some disturbances tends to speed up will develop a circulating current and power will flow from this alternator to the others, thereby having a loading effect on this advancing alternator. This will bring retarding action on its rotor and thus put it back in step with the other alternators. On the other hand, if any alternator tends to retard, power will flow from the other alternators to this alternator and the synchronising torque will tend to keep this machine in synchronism with the others.

Parallel Connection & Synchronizing of Alternators:

Before a synchronous generator is connected to a common ***infinite bus bar*** or a ***Power Grid*** or a ***Set of already running Generators*** to share the load it should be ensured that the following conditions are satisfied. Achieving the compliance of these conditions and then only adding an incoming Generator to the existing set of Generators/Power Grid is called Synchronization of the new Generator with the already running Generators.

Advantages of Parallel Operation of Synchronous Generators:

The following are the advantages of connecting a large number of synchronous generators in parallel to supply a common load:
(a) Repair and maintenance of individual generators can be carried out effectively maintaining the continuity of supply by properly scheduling maintenance of generators one after the other. If only one large generator is installed, supply is to be cut off for maintenance work.
(b) For operating an alternator at maximum efficiency it is to be run near to its full-load capacity. It is uneconomical to operate large alternators on low loads. If several small units are used, units can be added or put off depending upon the load requirement and thus the units can be operated at or near to their rated capacity.
(c) Additional sets can be connected in parallel to meet the increasing demand, thereby reducing the initial capital cost of buying larger units in anticipation of increasing demands.
(d) There is physical and economic limit to the possible capacity of alternators that can be built. The demand of a single power station may be as high as 1200 MVA. It may not be feasible to build a single alternator of such a high rating due to physical and economic considerations.
(e) Having many generators increases the reliability of the power system, since the failure of anyone of them does not cause a total power loss to the load.

Conditions for Parallel Connection or Synchronization:

For satisfactory parallel connection of alternators, the following three conditions must be fulfilled:
(a) The generated voltage of the incoming alternator to be connected in parallel with a bus-bar should be equal to the bus-bar voltage.
Generated voltage of the incoming alternator can be adjusted by adjusting the field excitation.

(b) Frequency of the generated voltage of the incoming alternator should be equal to the bus-bar frequency.

Frequency of the incoming alternator can be controlled and made equal to bus-bar frequency by controlling the speed of the prime mover driving the incoming alternator.

(c) Phase sequence of the voltage of the incoming alternator should be the same as that of the bus-bar.

Phase sequence of the alternator and the bus-bar can be checked by a phase sequence indicator. Alternatively, a three lamps setup as shown in the figure below can be used for checking the phase sequence.

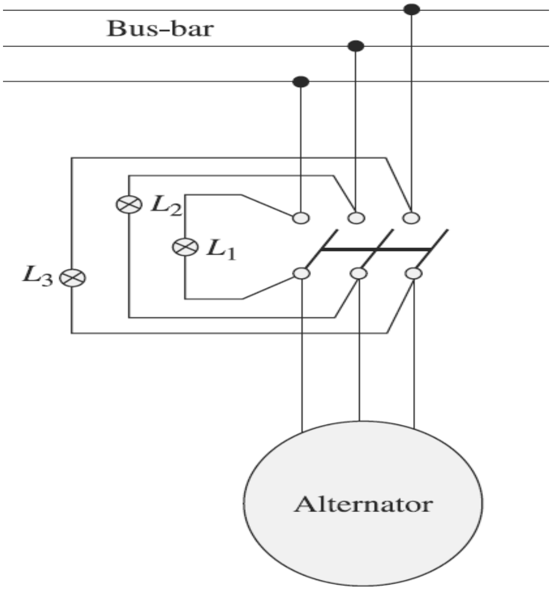


Figure: Three lamp method of checking the phase sequence of an alternator

Three lamps **L1, L2** and **L3** are connected as shown in the figure. When the synchronous generator is run at rated speed if all the lamps glow together and become dark together then the phase sequence of the incoming alternator is same as that of the bus-bar. Once the three conditions mentioned earlier are satisfied, the incoming alternator can be switched on to the bus bar ***at the instant when the voltages of the incoming generator and the bus-bar are in exact phase.*** For this purpose the two commonly used methods are described as follows.

1. A simple way is to observe the same three light bulb setup described above for checking the phase sequence. When all the three light bulbs become dark , the voltage difference across them is zero and the systems are in phase. This simple scheme works, but it is not very accurate. A better approach is to employ a synchroscope.

2. A *synchroscope* is a meter that measures the difference in phase angle between the ***two sides of the same Phase (R_1R_2, Y_1Y_2 or B_1B_2) of the two systems***. The face of a synchroscope is shown in the above figure. The dial shows the phase difference between any of the phase pairs mentioned above with 0^0 (meaning in phase at the top and 180^0 at the bottom). Since the frequencies of the two systems are slightly different, the phase angle on the meter changes slowly.

If the incoming generator frequency is higher than the running system (the desired situation), then the phase angle advances and the synchroscope needle rotates clockwise. If the incoming machine frequency is lower, the needle rotates counterclockwise. When the synchroscope needle is in the vertical position, the voltages are in phase, and the switch can be closed to connect the systems.

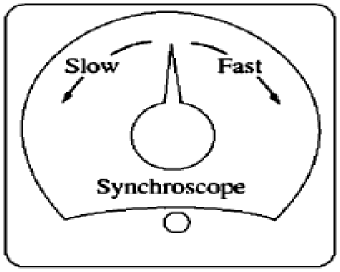


Figure: Front Panel of a Synchroscope

Notice that a *synchroscope checks the relationship of phase angle on both sides of only one phase.* It gives no information about phase sequence.

Active and Reactive Load Sharing:

A Synchronous Generator after synchronisation just floats on the bus-bar as explained above. It neither delivers power nor receives power. When a generator is connected in parallel, it just shares a portion of the total load depending upon its kVA rating. We shall examine how load sharing of alternators running in parallel can be achieved. We will study the effect of change of excitation and that of prime-mover input.

Effect of Change of Excitation:

For DC generators, load sharing between a number of machines running in parallel can be achieved by adjusting their excitations. For synchronous generators, change of excitation, i.e., change of field current does not change the active power shared by them. Change of excitation only changes the reactive power supplied by each machine. This is explained with the help of a phasor diagram shown below. In this figure, $\mathbf{V_B}$ represents the bus-bar voltage and $\mathbf{E_{in}}$ is the voltage induced in the incoming machine. Since the incoming machine is connected in parallel, these two voltages are opposing each other as shown. When excitation of the incoming machine is changed to $\mathbf{E'_{in}}$ it will cause a resultant voltage, $\mathbf{E_R}$ to appear which will cause a current $\mathbf{I_s}$ to flow from the machine to the bus-bar, i.e., to the load. Current $\mathbf{I_s}$ will lag $\mathbf{E_R}$ by about 90°, because the synchronous reactance of the machine is much higher than its resistance. $\mathbf{I_L}$ is the current supplied to the load from the bus-bar and the total per phase power supplied is $\mathbf{V_B I_L \cos \phi_L}$.

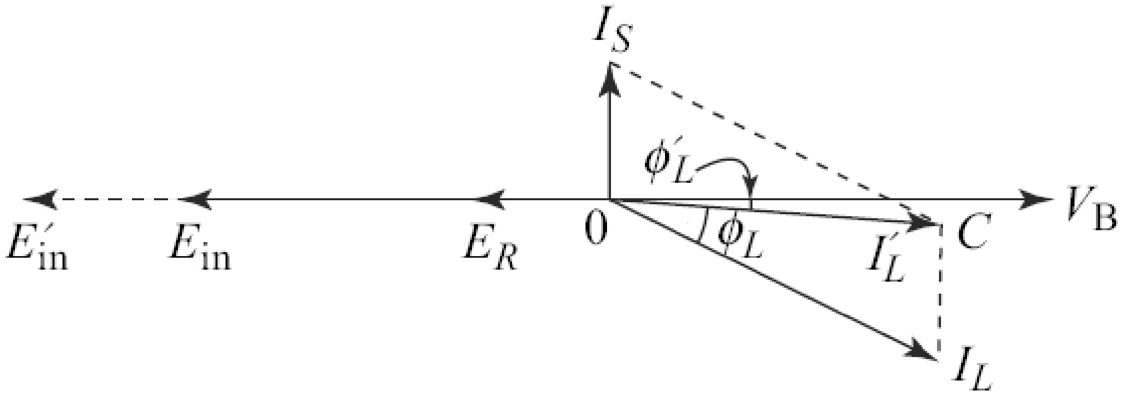


Figure: Effect of change of excitation of a synchronous machine connected in parallel with the bus-bar

Now the current supplied from the bus-bar is changed to $\mathbf{I_L'}$ since the incoming machine is supplying a reactive current, $\mathbf{I_S}$. Since $\mathbf{V_B}$ is constant, active load power is proportional to the length **OC**. The active power supplied by the existing machines connected to the bus-bar has not changed, i.e., the **I_L cos ϕ_L** has remained equal to **I_L' cos ϕ_L'.** Change of excitation of the incoming machine has only changed the reactive power delivered by the existing machines.

Effect of Change of Prime mover Input:

If the input to the prime mover of the incoming generator is increased, it will start sharing the load while remaining in synchronism with the existing alternators connected to the bus-bar. Control of active power shared between the alternators is achieved by changing the input to their prime movers. Change in the input to prime movers in a thermal power station is achieved by a change of throttle opening and thus allowing more or less steam into the turbine, whereas in a hydel power station prime mover input is controlled by controlling the water inlet into the water turbine.

Let the prime mover input to the incoming alternator be increased. This will move the generated EMF phasor **E_{in}** forward as shown in the figure below.

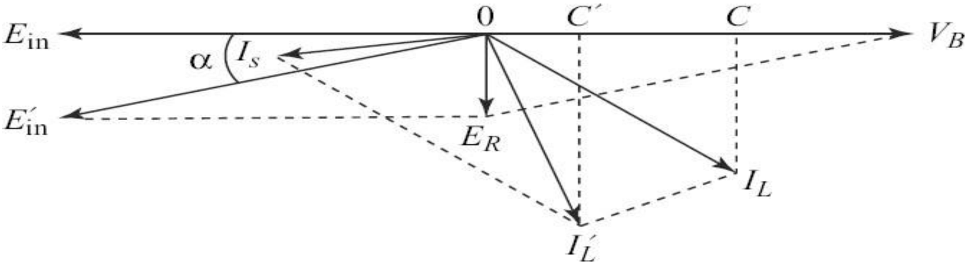


Figure: Effect of change of prime mover input to Synchronous Generator connected in parallel with the bus-bar

Let **E’** in be the new position of the generated **EMF** of the incoming alternator. The resultant voltage **E_R** will now cause a current **I_S** which has a strong in-phase component with the voltage. Thus the incoming machine will supply active power to the load. The **I_L'** will be the new load current supplied by the existing alternators, which has an active component represented by **OC’**. Thus, there is a reduction of active power load on the existing generators due to the sharing of active load by the incoming generator achieved by changing of prime mover input.

SYNCHRONOUS MOTORS

Theory of operation:

The basic concept of a synchronous motor is explained with the help of the figure below which shows a two-pole Synchronous Motor. The field current **I_F** of the motor produces a steady-state magnetic field **B_R**. A three-phase set of voltages is applied to the stator, which produces a three-phase current flow in the armature windings. This current flow produces a uniform rotating magnetic field **B_S**.

So there are now two magnetic fields present in the machine, and the *rotor field will tend to line up with the stator field.* Since the stator magnetic field is rotating, the rotor magnetic field (and the rotor itself) will constantly try to catch up with the rotating stator magnetic field. The larger the angle between the two magnetic fields (up to a certain maximum value), the greater the torque on the rotor of the machine. The basic principle of ***synchronous motor*** operation is that the rotor "chases" the rotating stator magnetic field around in a circle, never quite catching up with it but with the same speed.

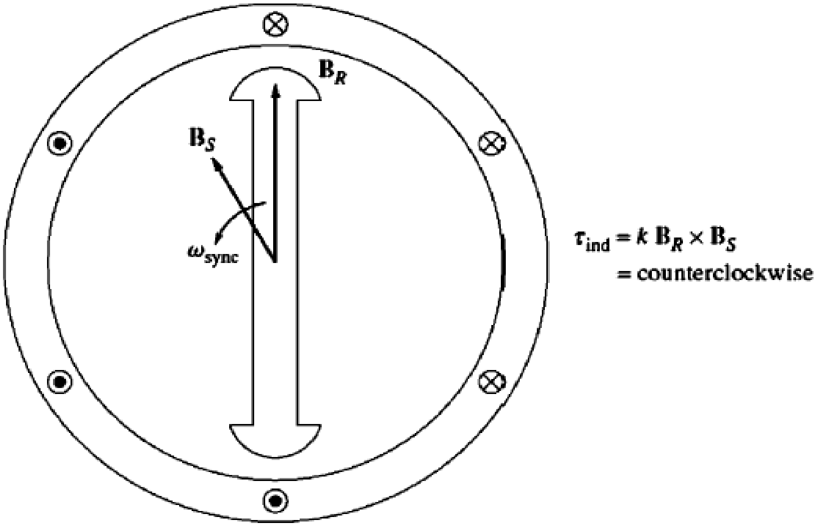


Figure: A two pole Synchronous Motor

Since a Synchronous Motor is the same physical machine as a Synchronous Generator, all the basic speed, power, and torque equations of synchronous Generators apply to Synchronous Motors also.

Equivalent Circuit of a Synchronous Motor

A synchronous motor is the same in all respects as a synchronous generator, except that the direction of power flow is reversed. Since the direction of power flow in the machine is reversed, the direction of current flow in the stator of the motor also is expected to reverse. Therefore, the equivalent circuit of a Synchronous Motor is exactly the same as the equivalent circuit of a Synchronous Generator, *except* that the reference direction of $\mathbf{I}_A$ is *reversed.* The resulting per phase equivalent circuit of a Synchronous Motor is shown in the figure below. Like in Generator, the three phases of the equivalent circuit may be either Y- or Δ connected.

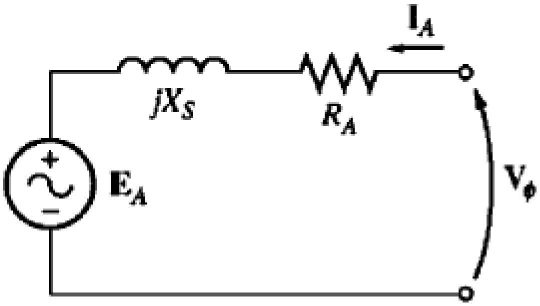


Figure: Equivalent circuit

Because of the change in direction of $\mathbf{I}_A$, the Kirchhoff's voltage law equation for the equivalent circuit changes as below with just a reversal of sign on the current term.

$$\boxed{\mathbf{V}_\phi = \mathbf{E}_A + jX_S\mathbf{I}_A + R_A\mathbf{I}_A} \quad \ldots\ldots\ldots\ldots (1)$$

Or

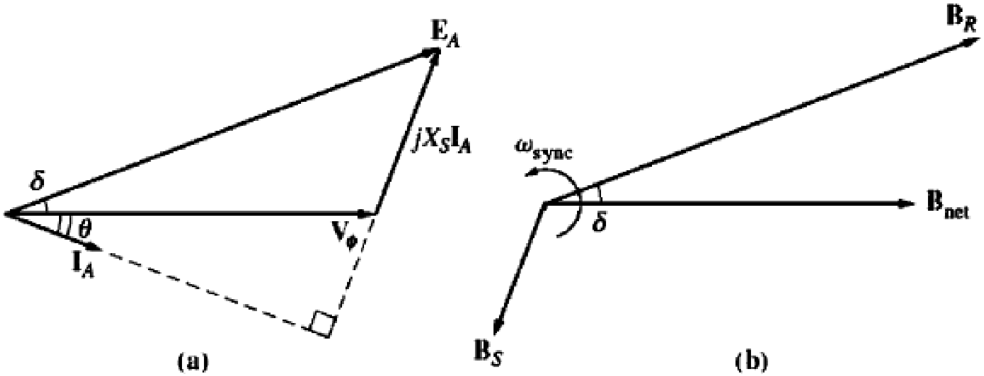
$$\boxed{\mathbf{E}_A = \mathbf{V}_\phi - jX_S\mathbf{I}_A - R_A\mathbf{I}_A} \quad \ldots\ldots\ldots\ldots (2)$$

The Synchronous Motor Phasor Diagrams:

To better understand synchronous motor operation let us once again look at a synchronous generator connected to an infinite bus. The generator has a prime mover turning its shaft, causing it to rotate. The direction of the applied torque

$\mathbf{T_{app}}$ from the prime mover is in the direction of motion, because the prime mover makes the generator rotate in the first place.

The phasor diagram of the generator operating with a large field current is shown in the figure (a) below along with the corresponding magnetic field diagram is shown in the figure(b) . As described before, $\mathbf{B_R}$ corresponds to (produces) $\mathbf{E_A}$, $\mathbf{B_{net}}$ corresponds to (produces) $\mathbf{V_\Phi}$, and $\mathbf{B_S}$ corresponds to $\mathbf{E_{Stat}}$ $\mathbf{(= -jX_SI_A)}$. The direction of rotation of both the phasor diagram and magnetic field diagram is counterclockwise in the figure, following the standard mathematical convention of increasing angle.



(a) Phasor diagram of a Synchronous Generator operating at a lagging power factor (b) Corresponding magnetic field diagram.

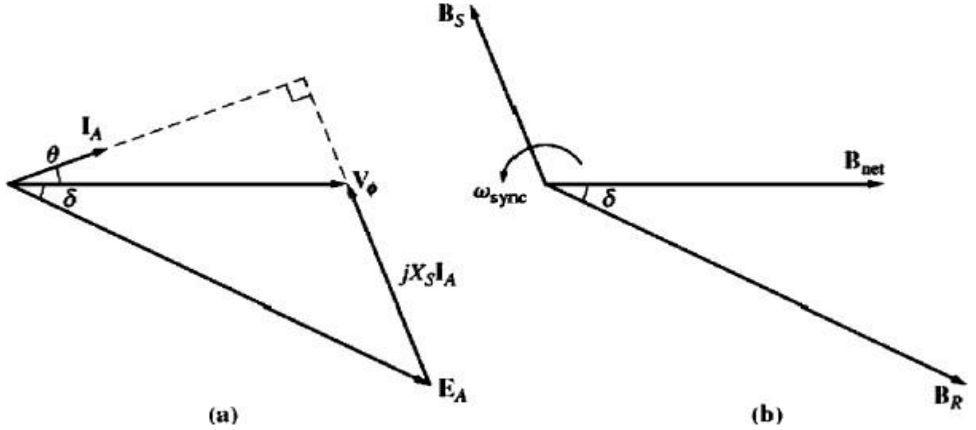
The induced torque in the generator can be found from the magnetic field diagram. From the fundamentals of AC Machines we know that the induced torque is given by:

$$\mathbf{T_{ind}} = k\, \mathbf{B_R} \times \mathbf{B_{net}} \qquad \text{..... (3)}$$

$$\mathbf{T_{ind}} = k\, \mathbf{B_R} \times \mathbf{B_{net}} \sin \delta \qquad \text{..... (4)}$$

Notice from the magnetic field diagram that *the induced torque in this machine is clockwise,* opposing the direction of rotation. In other words, the induced torque in the generator is a ***counter torque***, opposing the rotation caused by the external applied torque $\mathbf{T_{app}}$.

Now, suppose that, instead of turning the shaft in the direction of motion, the prime mover suddenly loses power and starts to drag on (follow on) the machine's shaft. Now the rotor slows down because of the drag on its shaft and falls behind the net magnetic field in the machine as shown in the figure below. As the rotor, and therefore $\mathbf{B}_R$, slows down and falls behind $\mathbf{B}_{net}$, the operation of the machine suddenly changes. By Equation **(3)** above when $\mathbf{B}_R$ is behind $\mathbf{B}_{net}$ the induced torque's direction reverses and becomes counter clockwise. In other words, the machine's torque is now in the direction of motion, and the machine is acting as a motor.



(a) Phasor diagram of a Synchronous Motor. (b) Corresponding magnetic field diagram.

The increasing torque angle **δ** results in a larger and larger torque in the direction of rotation, until eventually the motor's induced torque equals the load torque on its shaft. At that point, the machine will be operating at steady state and synchronous speed again, ***but now as a motor***.

If we look closely at the phasor diagrams corresponding to generator operation and motor operation shown in the above figures we find that the quantity $\mathbf{jX_sI_A}$ *points* from $\mathbf{V}_\phi$, to $\mathbf{E}_A$, in the generator and from $\mathbf{E}_A$ to $\mathbf{V}_\phi$ in the motor. The reason is that the reference direction of $\mathbf{I}_A$, was reversed in the definition of the motor equivalent circuit. The basic difference between motor and generator operation in synchronous machines can be seen both in the magnetic field diagram and in the phasor diagram. *In a generator,* $\mathbf{E}_A$ lies ahead of $\mathbf{V}_\phi$ and $\mathbf{B}_R$ lies ahead of $\mathbf{B}_{net}$. *In a motor,* $\mathbf{E}_A$ lies behind $\mathbf{V}_\phi$ and $\mathbf{B}_R$ lies behind $\mathbf{B}_{net}$. In a motor the induced torque is in the direction of motion and in a generator the induced torque is a counter torque opposing the direction of motion.

Steady-State Synchronous Motor operation:

This section explores the behavior of synchronous motors under varying conditions of load and field current as well as power-factor correction with synchronous motors. In the following studies, armature resistance of the motors is ignored for simplicity.

The Synchronous Motor Torque-Speed Characteristic Curve:

Synchronous motors supply power to loads that are basically constant-speed devices. They are usually connected to power systems *very* much larger than the individual motors, so the power systems appear as infinite buses to the motors. This means that the terminal voltage and the system frequency will be constant regardless of the amount of power drawn by the motor. The speed of rotation of the motor is locked to the applied electrical frequency, so the speed of the motor will be constant regardless of the load. The resulting torque-speed characteristic curve is shown in the figure below.

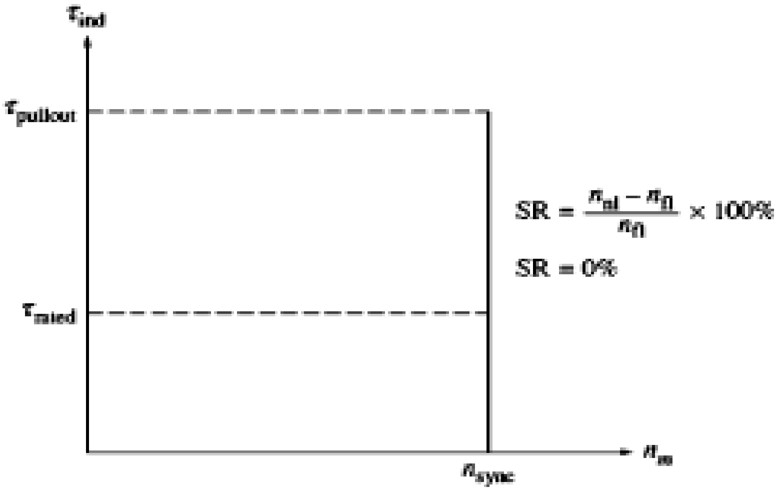


Figure: The Torque-Speed Characteristic of a Synchronous Motor. Since the speed of the Motor is constant, its speed regulation is '0' percent

The steady-state speed of the motor is constant from no load up to the maximum torque that the motor can supply (called the *pullout torque).* Hence the speed regulation of this motor is **0** percent. The torque equation is given by:

$$\tau_{max} = kB_RB_{net}$$

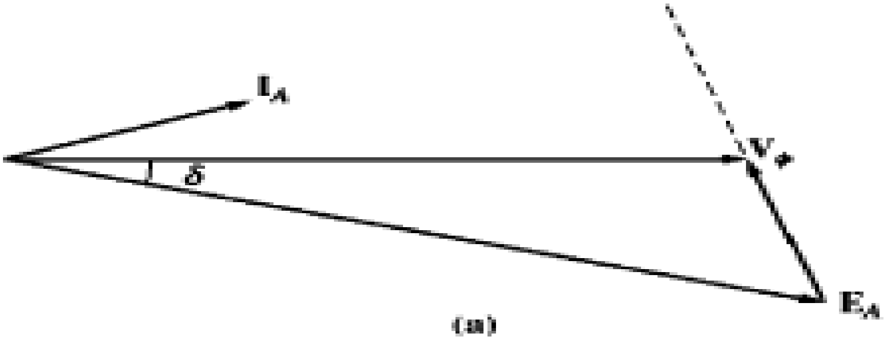
$$\tau_{max} = (3V_\phi E_A)/\omega_m X_S$$

These equations indicate that the larger the field current (and hence) the greater will be the maximum torque of the motor. There is therefore a stability advantage in operating the motor with a large field current or large **E_A.**

The Effect of Load Changes on a Synchronous Motor:

If a load is attached to the shaft of a synchronous motor, the motor will develop enough torque to keep the motor and its load turning at a synchronous speed. But now let us see what happens when the load is changed on a synchronous motor.

To find out, let us examine a synchronous motor operating initially with a leading power factor, as shown in the figure (a) below.



(a) Phasor diagram of a motor operating at a leading power factor

If the load on the shaft of the motor is increased, the rotor will initially slow down. As it does, the torque angle **δ** becomes larger, and the induced torque increases. The increase in induced torque speeds up the rotor back and the motor again turns at synchronous speed but with a larger torque angle **δ**.

Let us now see how the phasor diagram looks like during this process. To find out, let us examine the constraints on the machine during a load change. Figure (a) above shows the motor's phasor diagram before the load is increased. The internal generated voltage **E_A** is equal to **$K\phi\omega$** and so depends *only on* the field current in the machine and the speed of the machine. The speed is constrained to be constant by the input power supply, and since no one has touched the field circuit, the field current is constant as well. Therefore, **$|E_A|$** *must be constant as the load changes.* The distances proportional to power (**E_A Sin δ** and **I_A Cos ϕ**) will increase, but the magnitude of **E_A** must remain constant. As the load increases, **E_A** swings down in the manner shown in the figure (b) below.

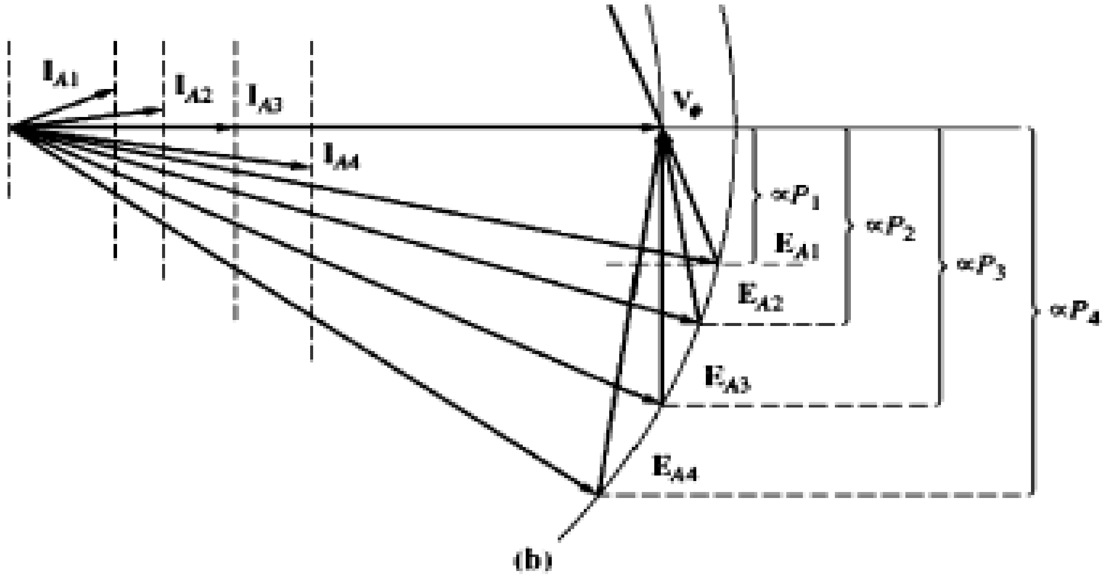


Figure (b): The effect of an increase in load on the operation of a synchronous motor.

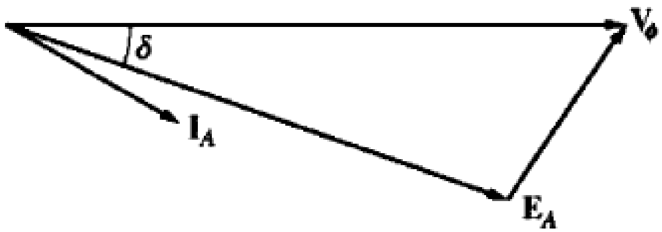
As **E_A** swings down further and further, the quantity **jX_SI_A** has to increase to reach from the tip of **E_A** to **V_ϕ** , and therefore the armature current **I_A** also increases. Notice that the power factor angle **ϕ** also changes, becoming lesser and lesser ***leading*** initially until it becomes **0^0** and then more and more ***lagging***.

Effect of change of excitation on current and power factor of a Synchronous Motor driving a constant load:

When the load on a synchronous motor is constant, the input power **$V_\phi I_A \cos\phi$** drawn from the bus-bar will remain constant. As the bus-bar voltage **V_ϕ** (**E_A Sin δ**)

is constant, $\mathbf{I_A \cos \phi}$ will remain constant. Under this condition the effect of change of field excitation on the armature current $\mathbf{I_A}$ drawn by the motor and the power factor will be as follows:

Figure (a) below shows the phasor relationships between all the parameters viz. $\mathbf{V_\phi, E_A, I_A, \phi}$ and $\boldsymbol{\delta}$ initially with a lagging power factor.

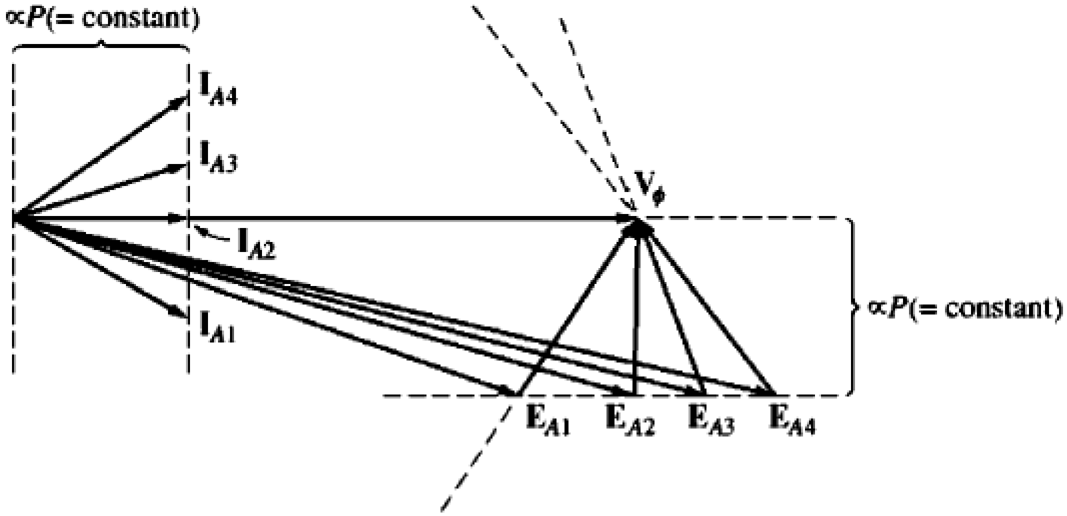


(a)

(a) A synchronous motor operating at a lagging power factor

We know that an *increase in field current increases the magnitude of* $\mathbf{E_A}$ *but does not affect the real power supplied by the motor.* The power supplied by the motor changes only when the shaft load torque changes. Let us understand this point with the help of the following phasor diagram/explanation.
Since a change in $\mathbf{I_F}$ does not affect the shaft speed n_m and since the load attached to the shaft is unchanged, the real power supplied is unchanged. But $\mathbf{V_\phi}$ is also constant, since it is kept constant by the power source supplying the motor.

The distances proportional to power on the phasor diagram $\mathbf{[E_A \sin \delta (V_\phi)}$ and $\mathbf{I_A \cos \phi}$ must therefore be constant. When the field current is increased, $\mathbf{E_A}$ increases, but it can only do so by sliding out along the line of constant power. This effect is shown in the figure **(b)** below.



(b)

(b) The effect of an increase in field current of this motor

Notice that as the value of $\mathbf{I}_F$ increases, $\mathbf{E}_{A1}$ increases to $\mathbf{E}_{A2}$ and $\mathbf{I}_{A1}$ changes to $\mathbf{I}_{A2}$**.** The magnitude of the armature current $\mathbf{I}_A$ first decreases and then increases again. At low $\mathbf{E}_A$, the armature current is lagging and it is consuming reactive power **Q**. As the field current is increased, the armature current eventually lines up with $\mathbf{V}_{\phi}$ corresponding to unity power factor and then as the field current is increased further, the armature current becomes leading, and the motor becomes a capacitive load. Effectively the motor is supplying reactive power **Q** to the system.

Figure below shows the effect of increase and decrease of excitation ***on the magnitude and power factor of the current drawn by the motor in the form of a characteristic at a particular load.*** It is seen that when the excitation is increased the motor draws a leading current.

In the figure below,at normal excitation, power factor is unity. The magnitude of armature current at this excitation is the minimum and is equal to **OD**. For excitation higher than the normal excitation, the magnitude of armature current will increase and the power factor will be leading. At excitation lower than the normal excitation, the magnitude of armature current will again increase but the power factor will be lagging as has been shown in the figure.

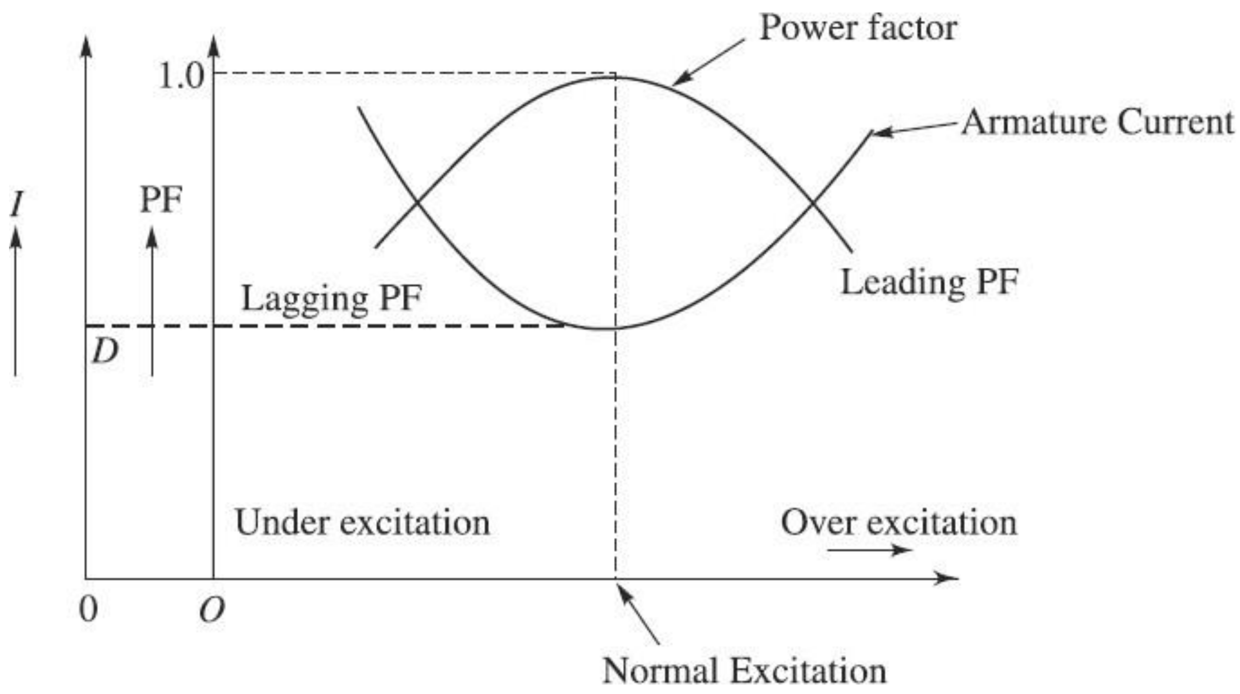


Figure: Effect of change of excitation on armature current and power factor of a synchronous Motor

The shape of the **I**$_A$ versus **I**$_f$ characteristic is similar to the letter **V** of the english alphabet and that is why this characteristic of synchronous motor is often referred to as synchronous motor ***V-curve***. A series of **V-**curves can be obtained at various loads on the motor keeping each load constant at a particular value and changing the excitation from from under excitation to over excitation as shown in the figure below.

Since an overexcited synchronous motor, also called a synchronous condenser, draws leading power factor current, it can be used for power factor improvement in a power system (Power Grid).

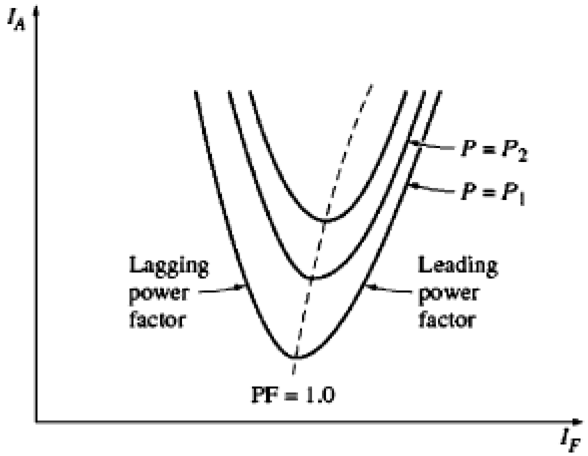


Figure: Synchronous Motor 'V' curves

Synchronous condenser:

- An over excited synchronous motor without a shaft extension, i.e., without any load on its shaft, used exclusively for power factor improvement in a power system, is called a ***Synchronous Condenser***.
- Since an overexcited synchronous motor, draws leading power factor current, it can be used for power factor improvement in a power system (Power Grid).
- Installation of overexcited synchronous motors in parallel with the other loads will improve the power factor of the power system.
- Since it drives no load, it develops little torque and hence has a very light frame (very small size).
- Sometimes, an over excited Synchronous motor can be run with a small load also so that it can provide power factor improvement to the power system and drive some essential mechanical loads as well .

Let us refer to the **'V'** curves of a Synchronous Motor i.e. a plot of $\mathbf{I_A}$ versus $\mathbf{I_F}$ shown in the figure below to and explain how it works.

There are several '**V**' curves drawn, corresponding to different real power levels. For each curve, the minimum armature current occurs at unity power factor, when only real power is supplied to the motor. For field currents *less* than the value giving minimum $\mathbf{I_A}$, the armature current is lagging, consuming reactive power **Q**. For field currents *greater* than the value giving the minimum $\mathbf{I_A}$, the armature current is leading, supplying **Q** to the power system just like a capacitor.

Therefore, by controlling the field current of a synchronous motor, the *reactive power* supplied to or consumed by the power system can be controlled.

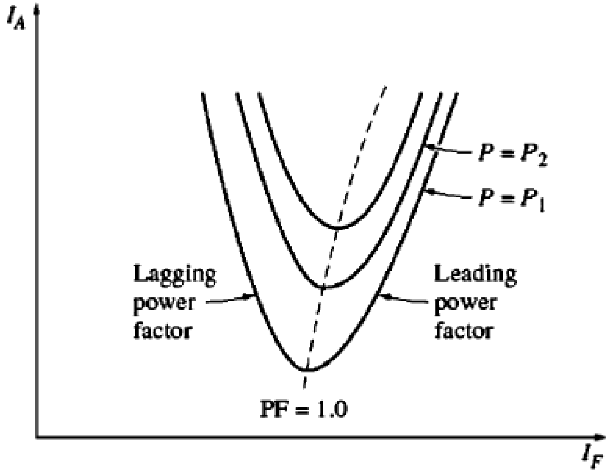
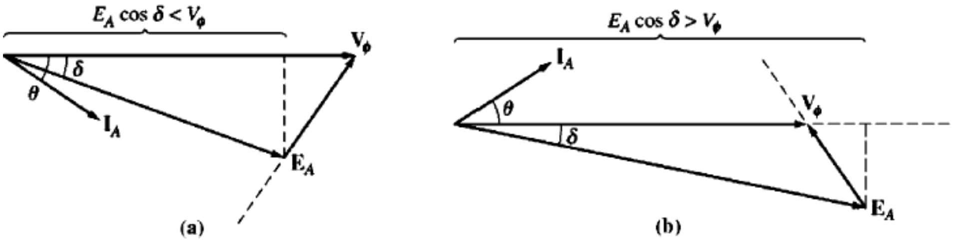


Figure: Synchronous Motor V curves

This can be better understood with reference to the phasor diagrams of a Synchronous motor shown below with lagging and leading power factors.



(a) The phasor diagram of an *under excited* synchronous motor. (b) The phasor diagram of an *over excited* synchronous motor.

- When the projection of the phasor **E_A** onto **V_ϕ** **($E_A \cos\delta$)** is *shorter* than **V_ϕ** itself, a synchronous motor has a lagging current and consumes reactive power **Q**. Since the field current is small in this situation, the motor is said to be ***under excited***.
- On the other hand, when the projection of **E_A** onto **V_ϕ** is *longer* than **V_ϕ** itself, a synchronous motor has a leading current and supplies reactive power **Q** to the power system. Since the field current is large in this condition, the motor is said to be ***overexcited.***

Since now it is supplying reactive power to the Power system, it is working like a capacitor and improving the power factor of the system.

Hunting and its suppression:

A synchronous motor will be subjected to oscillations in speed when it is suddenly loaded or unloaded. The rotor speed changes momentarily until the torque angle **δ** adjusts itself to the new output requirement. If the load increases, the rotor slips backwards to an increased torque angle **δ**, while a load reduction causes the rotor to advance to a smaller torque angle position. But because of the moment of inertia, the rotor overshoots the final position, slowing down or speeding up more than the required value. Thus the rotor is subjected to periodic but momentary speed changes while the rotor is attempting to adjust to a correct torque angle, the average speed of the motor remaining constant. This quick forward and back ward motion of the rotor as it rotates at the average constant speed is called *"hunting".* The rotor is said to be hunting (i.e. in search of) for the correct torque angle in response to the changing load conditions.

Such an oscillation in speed produces undesirable current and torque pulsation. However, the squirrel cage winding made on the pole faces that provides the motor with its starting torque also dampens the oscillation in speed. Since, the damper winding is short-circuited in itself, there results a rotating mmf which in conjunction with the rotating field develops a damping torque, thus minimising oscillation.

The damper winding remains ineffective as long as the speed is constant at the synchronous speed.

Methods of Starting Synchronous Motors:

- In the earlier sections, the motor was always assumed to be initially rotating at *synchronous speed.* What has not yet been considered is the question: How did the motor go to synchronous speed in the first place?
- If three-phase supply is given to the stator phases of a stationary synchronous machine with the rotor excited, no steady starting torque will be developed. It would be instead a sinusoidally time-varying torque at the same frequency as

that of the supply frequency, the average value of which is zero. It is because the Rotor movement would be very small as compared to the movement of the rotating stator magnetic field and with the result, in the first half cycle if the torque developed is say CCW, then in the second half cycle torque developed would be in the CW direction. Hence, the rotor vibrates violently and gets overheated. That is the reason why a synchronous motor as such is not self-starting and needs additional means of starting to bring the rotor speed close to that of the stator rotating magnetic field. Once the speed of the rotor is close to that of the stator magnetic field, then the Rotor would catch up and move at the same speed as that of the stator RMF.

A Synchronous Motor can be started from its stationary condition by any the following methods:

1. ***Reduce the speed of the stator mngnetic field*** to a low enough value that the rotor can accelerate and lock in with it during one half-cycle of the magnetic field's rotation. This can be done by reducing the frequency of the applied electric power.

2. ***Use an external prime mover*** to accelerate the synchronous motor up to synchronous speed, carry out the paralleling operation , and bring the machine on the line as a generator. Then, turning off or disconnecting the prime mover will make the synchronous machine run as a Synchronous machine.

3. ***Use damper windings or amortisseur windings****:* The function of damper windings and their use in motor starting will be explained below.

Motor Starting by Reducing Electrical Frequency:

If the stator magnetic field in a synchronous motor rotates at a low enough speed, there will be no problem for the rotor to accelerate and to lock in with the stator magnetic field. The speed of the stator magnetic field can then be increased to the operating speed by gradually increasing frequency up to its normal 50 Hz value.

Though this method works well, in the earlier days before the development of Solid state electronics, getting a variable frequency source with rated voltages and power levels was very difficult. But now a days Solid state frequency converters are readily available meeting any of the technical requirements. With the development of such modern solid-state variable frequency drive packages, it is possible to continuously control the electrical frequency applied to the motor all from a fraction of a hertz up to and above the full rated frequency. If such a variable-frequency drive unit is included in a motor-control circuit to achieve speed control, then starting the synchronous motor is very easy- simply adjust the frequency to a very low value for starting, and then raise it up to the desired operating frequency for normal running.

When a synchronous motor is operated at a speed lower than the rated speed, its internal generated voltage $E_A = K\varphi\omega$ will be smaller than normal. If E_A is reduced in magnitude, then the terminal voltage applied to the motor must also be reduced to keep the stator current at a safe level. The voltage in any variable-frequency drive or variable-frequency starter circuit must vary roughly linearly with the applied frequency thus maintaining a constant v/f ratio.

Motor Starting with an External Prime Mover:

The second approach to starting a synchronous motor is to attach an external starting motor to it and bring the synchronous machine up to full speed with the external motor. Then the synchronous machine can be paralleled with its power system as a generator, and the starting motor can be detached from the shaft of the machine. Once the starting motor is turned off, the shaft of the machine slows down, the rotor magnetic field $\mathbf{B}_R$ falls behind $\mathbf{B}_{net}$ and the synchronous machine starts to act as a motor. Once paralleling is completed and motor starts running at synchronous frequency , the synchronous motor can be loaded as required.

Since most large synchronous motors have brushless excitation systems mounted on their shafts, it is often possible to use these exciters as starting motors.

For many medium-size to large synchronous motors, an external starting motor or starting by using the exciter may be the only possible solution, because the power systems they are tied to may not be able to handle the starting currents needed to use the amortisseur winding approach described next.

Motor Starting by Damper windings:

By far the most popular way to start a synchronous motor is to employ *damper* windings. They are special bars laid into slots carved in the face of a synchronous motor's rotor and then shorted out on each end by a large *shorting ring as shown in the figure below.*

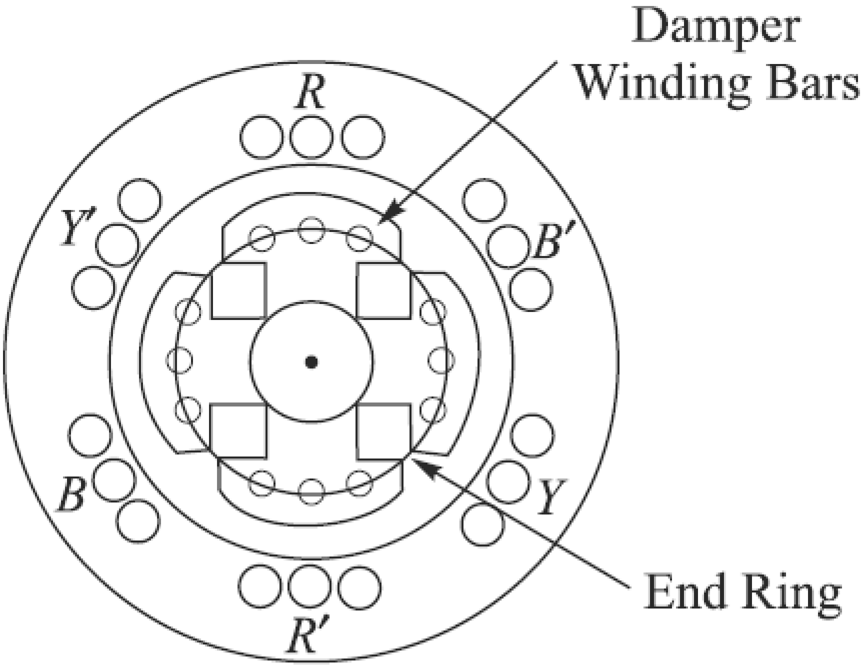


Figure: Damper windings provided on pole faces of a synchronous machine

As we know with such an arrangement, sometimes the torque is counter clockwise and sometimes it is essentially zero, but it is *always unidirectional.* Since there is a net torque in a single direction, the motor's rotor speeds up. (This is entirely different from starting a synchronous motor with its normal field current, since in that case torque is first clockwise and then counterclockwise, averaging out to zero. In this case, torque is *always* in the same direction, so there is a nonzero average torque.) On application of three-phase supply to the stator, a synchronous motor with damper winding will start as a three-phase induction motor and rotate at a speed near to synchronous speed. Now with the application of dc excitation to the field windings, the rotor will be pulled into synchronous speed since the rotor poles are now rotating at only slip-speed with respect to the stator rotating magnetic field.

In a real machine, the field windings are not open-circuited during the starting Procedure. If the field windings were open-circuited, then very high voltages would be produced in them during starting. If the field winding is short-circuited during starting, no dangerous voltages are produced, and the induced field current actually contributes extra starting torque to the motor.

To summarize, if a machine has *damper windings*, it can be started by the following procedure:

I. Disconnect the ***field windings*** from their DC power source and short them.
2. Apply a three-phase voltage to the stator of the motor, and let the rotor accelerate up to near-synchronous speed. The motor should have no load on its shaft, so that its speed can approach $\mathbf{n_{sync}}$ as closely as possible.
3. Connect the DC field circuit to its power source. After this is done, the motor will lock into step at synchronous speed, and loads may then be added to its shaft.

Important Questions:

1. Explain with the help of a Phasor diagram what is Power Angle and Torque Angle in a Synchronous Generator. Explain with the help of a plot how it varies with Power /Torque.
2. Explain the Effect of Load Changes on a Synchronous Generator Operating Alone.
3. Explain the concepts of an '*Infinite Bus*' and '*A Synchronous Generator Floats on the Bus*'.
4. What are the Advantages of Parallel Operation of Synchronous Generators?
5. (a)What are the conditions required to be fulfilled before paralleling a Generator to a Power Grid.
   (b) Explain briefly how they are checked and confirmed.
6. Explain the terms Synchronizing Power and Synchronizing Torque
7. With the help of Phasor diagrams explain clearly the effect of change of excitation and change of Mechanical Input Power on the active and reactive load sharing of Generators running in parallel with a Power Bus.
8. Explain the principle of operation of a Synchronous motor and draw its simple equivalent circuit.
9. Draw and explain the phasor diagram of a Synchronous Motor comparing it with that of a Synchronous generator.
10. Draw and explain the Torque - Speed characteristic of a Synchronous Motor.
11. Explain the operation of a Synchronous motor with the help of a Phasor diagram for a varying load.

12. Explain the effect of change of excitation of a Synchronous Motor driving a constant load on the Armature current and power factor.
13. Explain what is a Synchronous Condenser with the help of relevant plots and background theory.
14. Explain what is hunting in a Synchronous Motor and the methods of it’s suppression.
15. Why Synchronous Motors are not self starting? List out and explain the methods of starting Synchronous Motors.

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