DEPARTMENT OF ELECTRICAL ENGINEERING

COURSE: **Energy Conversion -II**
BRANCH: Electrical Engineering Semester
Semester-5th

LECTURE NOTES

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UNIT-I SINGLE PHASE MOTORS

1.1 INTRODUCTION

The characteristics of single phase induction motors are identical to 3-phase induction motors except that single phase induction motor has no inherent starting torque and some special ar-rangements have to be made for making it self starting. It follows that during starting period the single phase induction motor must be converted to a type which is not a single phase induction motor in the sense in which the term is ordinarily used and it becomes a true single phase induction motor when it is running and after the speed and torque have been raised to a point beyond which the additional device may be dispensed with. For these reasons, it is necessary to distinguish clearly between the starting period when the motor is not a single phase induction motor and the normal running condition when it is a single phase induction motor. The starting device adds to the cost of the motor and also requires more space. For the same output a 1-phase motor is about 30% larger than a corresponding 3-phase motor.

The single phase induction motor in its simplest form is structurally the same as a poly-phase induction motor having a squirrel cage rotor, the only difference is that the single phase induction motor has single winding on the stator which produces mmf stationary in space but alternating in time, a polyphase stator winding carrying balanced currents produces mmf rotat-ing in space around the air gap and constant in time with respect to an observer moving with the mmf. The stator winding of the single phase motor is disposed in slots around the inner periphery of a laminated ring similar to the 3-phase motor.

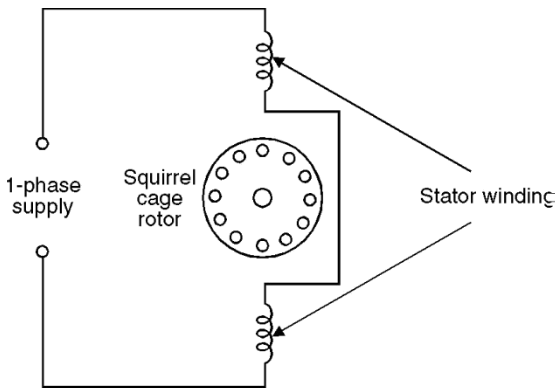

Fig .1 Elementary single phase induction motor.

An induction motor with a cage rotor and single phase stator winding is shown schematically in Fig. 1. The actual stator winding as mentioned earlier is distributed in slots so as to produce an approximately sinusoidal space distribution of mmf.

1.2 PRINCIPLE OF OPERATION

Suppose the rotor is at rest and 1-phase supply is given to stator winding. The current flowing in the stator winding gives rise to an mmf whose axis is along the winding and it is a pulsating mmf, stationary in space and varying in magnitude, as a function of time, varying from positive maxi-mum to zero to negative maximum and this pulsating mmf induces currents in the short-circuited rotor of the motor which gives rise to an mmf. The currents in the rotor are induced due to transformer action and the direction of the currents is such that the mmf so developed opposes the stator mmf. The axis of the rotor mmf is same as that of the stator mmf. Since the torque developed is proportional to sine of the angle between the two mmf and since the angle is zero, the net torque acting on the rotor is zero and hence the rotor remains stationary.

For analytical purposes a pulsating field can be resolved into two revolving fields of con-stant magnitude and rotating in opposite directions as shown in Fig. 1.1 and each field has a magnitude equal to half the maximum length of the original pulsating phasor.

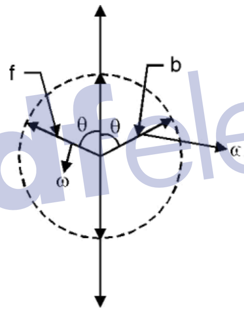

Fig.1.1. Representation of the pulsating field by space phasors.

These component waves rotate in opposite direction at synchronous speed. The forward (anticlockwise) and backward-rotating (clockwise) mmf waves f and b are shown in Fig. 1.1. In case of 3-phase induction motor there is only one forward rotating magnetic field and hence torque is developed and the motor is self-starting. However, in single phase induction motor each of these component mmf waves produces induction motor action but the corresponding torques are in opposite direction. With the rotor at rest the forward and backward field produce equal torques but opposite in direction and hence no net torque is developed on the motor and the motor remains stationary. If the forward and backward air gap fields remained equal when the rotor is revolving, each of the component fields would produce a torque-speed characteristic similar to that of a polyphase induction motor with negligible leakage impedance as shown by the dashed curves f and b in Fig. 1.2.

The resultant torque-speed characteristic which is the algebraic sum of the two component curves shows that if the motor were started by auxiliary means it would produce torque in what-ever direction it was started.

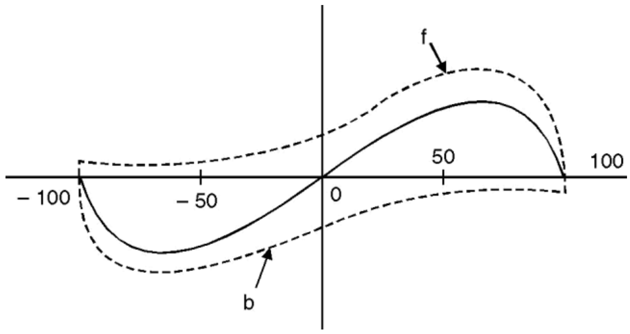

Fig. 1..2. Torque-speed characteristic of a 1-phase induction motor based on constant forward and backward flux waves

In reality the two fields, forward and backward do not remain constant in the air gap and also the effect of stator leakage impedance can't be ignored. In the above qualitative analysis the effects of induced rotor currents have not been properly accounted for.

When single phase supply is connected to the stator and the rotor is given a push along the forward rotating field, the relative speed between the rotor and the forward rotating magnetic field goes on decreasing and hence the magnitude of induced currents also decreases and hence the mmf due to the induced current in the rotor decreases and its opposing effect to the forward rotating field decreases which means the forward rotating field becomes stronger as the rotor speeds up. However for the backward rotating field the relative speed between the rotor and the backward field increases as the rotor rotates and hence the rotor emf increases and hence the mmf due to this component of current increases and its opposing effect to the backward rotating field increases and the net backward rotating field weakens as the rotor rotates along the forward rotating field. However, the sum of the two fields remains constant since it must induce the stator counter emf which is approximately constant if the stator leakage impedance drop is negligible. Hence, with the rotor in motion the torque of the forward field is greater and that of the backward field is less than what is shown in Fig. 9.3. The true situation being as is shown in Fig. 1.3.

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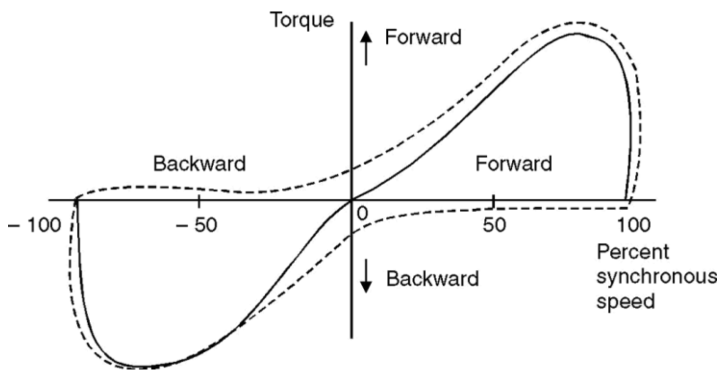


Fig. 1.3. Torque-speed characteristic of a 1-phase induction motor taking into account changes in the flux waves.

In the normal running region at a few per cent slip the forward field is several times stronger than the backward field and the flux wave does not differ materially from the constant
amplitude revolving field in the air gap of a balanced polyphase motor. Therefore, in the normal running range of the motor, the torque-speed characteristic of a single phase motor is not very much different from that of a polyphase motor having the same rotor and operating with the same maximum air gap flux density.

In addition to the torque shown in Fig. 1.4, double-stator frequency torque pulsation are produced by the interaction of the oppositely rotating flux and mmf waves which move past each other at twice synchronous speed. These double frequency torques produce no average torque as these pulsations are sinusoidal and over the complete cycle the average torque is zero. However, sometimes these are additive to the main torque and for another half a cycle these are subtractive and therefore a variable torque acts on the shaft of the motor which makes the motor noisier as compared to a polyphase induction motor where the total torque is constant. Such torque pulsa-
tions are unavoidable in single phase circuits. Mathematically

$$T \alpha I^2 \qquad \text{...(2.1)}$$

Let $I = I_m \sin\omega t$

$$T = K I^2 \sin^2 \omega t$$

$$= KI_m^2 \frac{(1 - \cos \omega t)}{2} \qquad \text{...(2.2)}$$

So the expression for torque contains a constant term superimposed over by a pulsating torque with pulsation frequency twice the supply frequency.

1.3 STARTING OF SINGLE PHASE INDUCTION MOTORS

The single phase induction motors are classified based on the method of starting method and in fact are known by the same name descriptive of the method. Appropriate selection of these motors depends upon the starting and running torque requirements of the load, the duty cycle and limitations on starting and running current drawn from the supply by these motors. The cost of single phase induction motor increases with the size of the motor and with the performance such as starting torque to current ratio (higher ratio is desirable), hence, the user will like to go in for a smaller size (hp) motor with minimum cost, of course, meeting all the operational requirements. However, if a very large no. of fractional horsepower motors are required, a specific design can always be worked out which might give minimum cost for a given performance requirements. Following are the starting methods.

(a) Split-phase induction motor. The stator of a split phase induction motor has two windings, the main winding and the auxiliary winding. These windings are displaced in space by 90 electrical degrees as shown in Fig. 9.5 (a). The auxiliary winding is made of thin wire (super enamel copper wire) so that it has a high R/X ratio as compared to the main winding which has thick super enamel copper wire. Since the two windings are connected across the supply the current I_m and I_a in the main winding and auxiliary winding lag behind the supply voltage V, I_a leading the current I_m Fig. 9.5(b). This means the current through auxiliary winding reaches maximum value first and the mmf or flux due to I_a lies along the axis of the auxiliary winding and after some time ($t = \theta/w$) the current I_m reaches maximum value and the mmf or flux due to I_m lies along the main winding axis. Thus the motor becomes a 2-phase unbalanced motor. It is unbalanced since the two currents are not exactly 90 degrees apart. Because of these two fields a starting torque is developed and the motor becomes a self-starting motor. After the motor starts, the auxiliary winding is disconnected usually by means of centrifugal switch that operates at about 75 per cent of synchronous speed. Finally the motor runs because of the main winding. Since this being single phase some level of humming noise is always associated with the motor during running. A typical torque speed characteristic is shown in Fig. 1.4 (c). It is to be noted that the direction of rotation of the motor can be reversed by reversing the connection to either the main winding or the auxiliary windings.

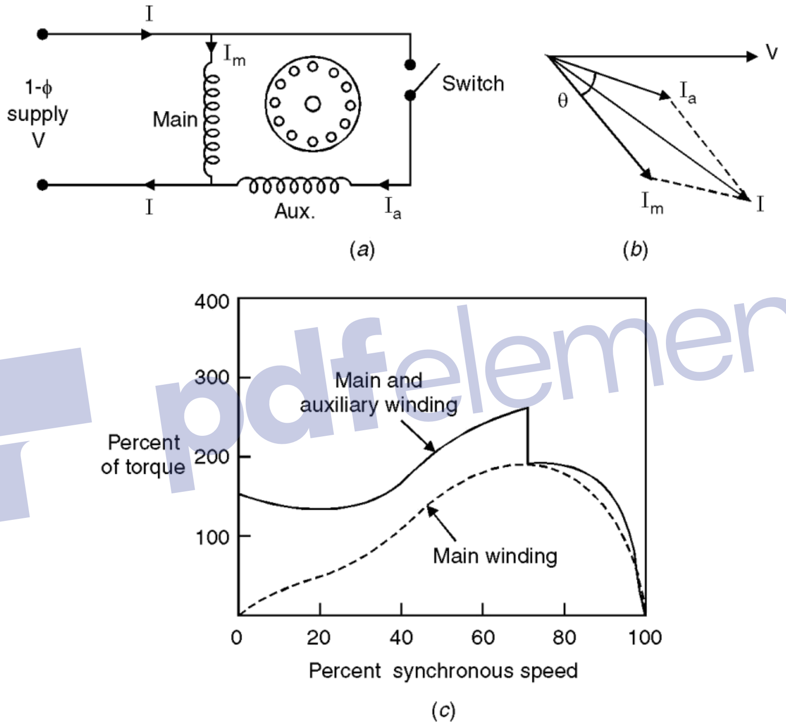


Fig. 1.4 Split phase induction motor (=) Connection
(>) Phasor diagram at starting (?) Typical torque-speed characteristic.

(b) Capacitor start induction motor. Capacitors are used to improve the starting and running performance of the single phase inductions motors.

The capacitor start induction motor is also a split phase motor. The capacitor of suitable value is connected in series with the auxiliary coil through a switch such that I_a the current in the auxiliary coil leads the current I_m in the main coil by 90 electrical degrees in time phase so that the starting torque is maximum for certain values of I_a and I_m. This becomes a balanced 2-phase motor if the magnitude of I_a and I_m are equal and are displaced in time phase by 90° electrical degrees. Since the two windings are displaced in space by 90 electrical degrees as shown in Fig. 1.5 maximum torque is developed at start. However, the auxiliary winding and capacitor are disconnected after the motor has picked up 75 per cent of the synchronous speed. The motor will start without any humming noise. However, after the auxiliary winding is disconnected, there will be some humming noise.

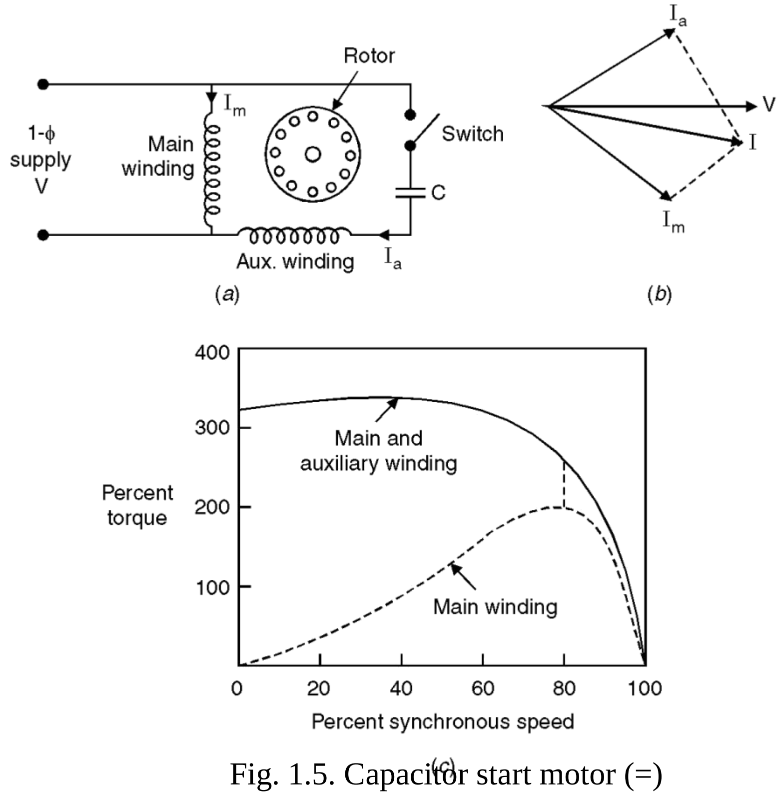


Fig. 1.5. Capacitor start motor (=)
Connection (>) Phasor diagram at start (?)
Speed torque curve.

Since the auxiliary winding and capacitor are to be used intermittently, these can be designed for minimum cost. However, it is found that the best compromise among the factors of starting torque, starting current and costs results with a phase angle somewhat less than 90° between I_m and I_a. A typical torque-speed characteristic is shown in Fig. 9.6 (c) high starting torque being an outstanding feature.

(c) Permanent-split capacitor motor. In this motor the auxiliary winding and capaci-tor are not disconnected from the motor after starting, thus the construction is simplified by the omission of the switch as shown in Fig.1.6 (a).

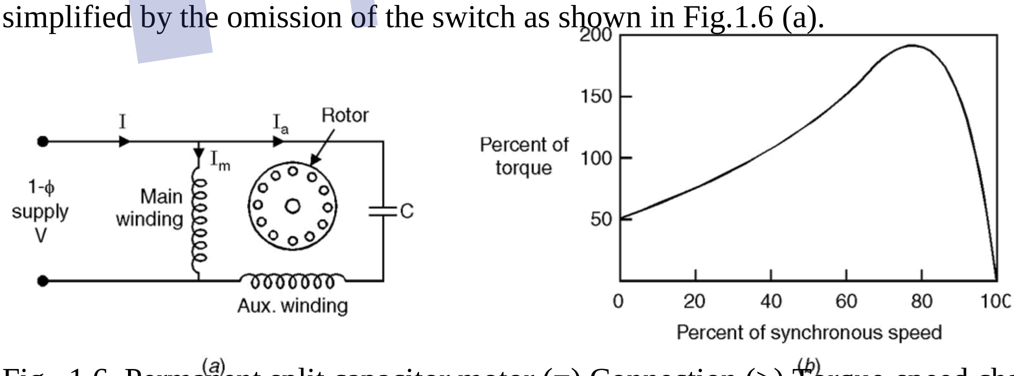


Fig. .1.6. Permanent split capacitor motor (=) Connection (>) Torque-speed characteristiS

Here the auxiliary winding and capacitor could be so designed that the motor works as a perfect 2-phase motor at anyone desired load. With this the backward rotating magnetic field would be completely eliminated. The double stator frequency torque pulsations would also be eliminated, thereby the motor starts and runs as a noise free motor. With this there is improve-ment in p.f. and efficiency of the motor. However, the starting torque must be sacrificed as the capacitance is necessarily a compromise between the best starting and running characteristics. The torque-speed characteristic of the motor is shown in Fig. 1.6 (b).

(d) Capacitor start capacitor run motor. If two capacitors are used with the auxiliary winding as shown in Fig. 9.8 (a), one for starting and other during the start and run, theoretically optimum starting and running performance can both be achieved.

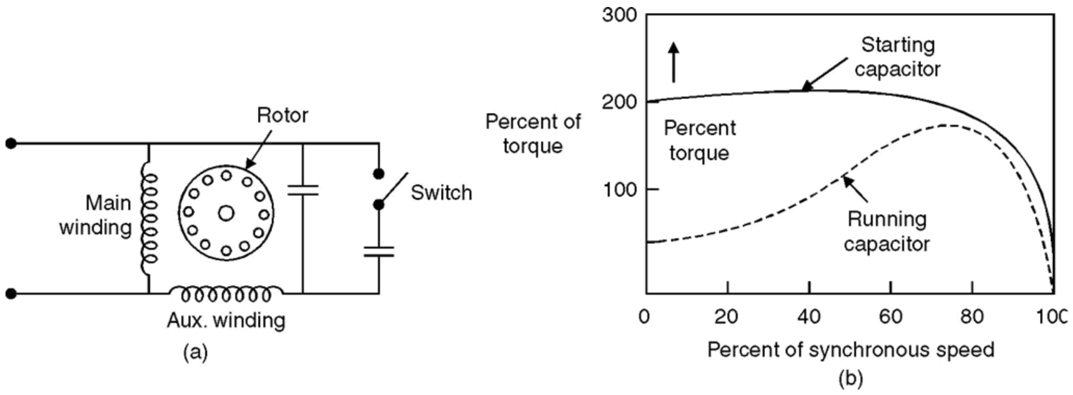


Fig. 1.7. (=) Capacitor start capacitor run motor (>) Torque-speed characteristic.

The small value capacitor required for optimum running conditions is permanently con-nected in series with the auxiliary winding and the much larger value required for starting is obtained by a capacitor connected in parallel with the running capacitor. The starting capacitor is disconnected after the motor starts.

The value of the capacitor for a capacitor start motor is about 300 □F for $\frac{1}{2}$ hp motor. Since this capacitor must carry current for a short starting period, the capacitor is a special compact ac electrolytic type made for motor starting duty. However, the capacitor permanently connected has a typical rating of 40 □F ; since it is connected permanently, the capacitor is an ac paper, foil and oil type. The cost of the motor is related to the performance ; the permanent capacitor motor is the lowest cost, the capacitor start motor next and the capacitor start capacitor run has the highest cost.

(e) Shaded pole induction motor. Fig. 9.9 (a) shows schematic diagram of shaded pole induction motor. The stator has salient poles with one portion of each pole surrounded by a short-circuited turn of copper called a shading coil. Induced currents in the shading coil (acts as an inductor) cause the flux in the shaded portion of the pole to lag the flux in the other portion. Hence the flux under the unshaded pole leads the flux under the shaded pole which results in a rotating field moving in the direction from unshaded to the shaded portion of the pole and a low starting torque is produced which rotates the rotor in the direction from unshaded to the shaded pole. A typical torque speed characteristic.. The efficiency is low. These motors are the least expensive type of fractional horse power motor and are built upto about $\frac{1}{20}$ hp. Sincethe rotation of the motor is in the direction from unshaded towards the shaded part of the pole, a shaded pole motor can be reversed only by providing two sets of shading coils which may be opened and closed or it may be reversed permanently by inverting the core.

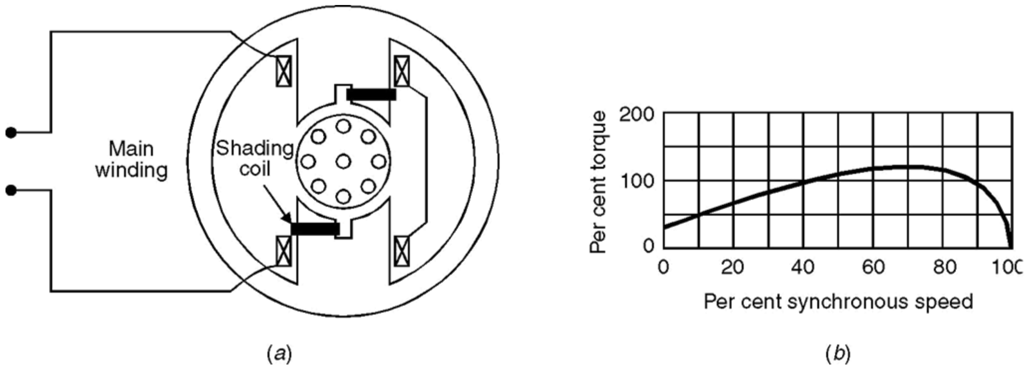


Fig. .1.8. Shaded-pole motor and typical torque-speed characteristic.

3.4 APPLICATION

The split phase induction motors are used for fans, blowers, centrifugal pumps and office equipments. Typical ratings are $\frac{1}{20}$ to $\frac{1}{2}$ hp; in this range they are the lowest cost motors available. The capacitor start motors are used for compressors, pumps, refrigeration and air-condition-ing equipments and other hard to start-loads.

The capacitor start capacitor run motors are manufactured in a number of sizes from $\frac{1}{8}$ to $\frac{3}{4}$ hp and are used in compressors, conveyors, pumps and other high torque loads. The permanent split capacitor motors are manufactured in the range of $\frac{1}{20}$ hp to $\frac{3}{4}$ hp and are used for direct connected fans, blowers, centrifugal pumps and loads requiring low starting torque. The shaded pole motors are used in toys, hair driers, desk fans etc.

UNIT-II Construction and Principle of operation of Synchronous Machines

2.1 ALTERNATOR - CONSRUCTION AND WORKING PRINCIPLE

Synchronous generator or AC generator is a device which converts mechanical power in the form of A.C.

It works on the principle of ELECTRO MAGNETIC INDUCTION and it is also called as **Alternator**.

An alternator consists of armature winding and field magnet, but the difference between the alternator and DC generator is that in the DC generator armature rotates and the field system is stationary. This arrangement is the alternator is just reverse of it there the armature is stationary called as stator and field system is rotating called as Rotor.

2.2 For generating EMF, three things are essential:

1) Magnetic field
2) System of conductors
3) Relative motion between those two.

The conductors are mounted on the stators and the field poles are mounted on the Rotor core Relative motion between the stator conductors and the field is brought about rotating the field system.

The rotor is coupled mechanically to a suitable print mover. When the prime mover runs, the rotor core also rotates and the field flux is cut by the stationary stator conductors and emf's are induced in them.

If a load is connected across the stator terminals electric power would be delivered to it.

2.3 ADVANTAGES OF STATIONARY ARMATURE

The generated power can be easily taken out from the stator.

There is no possibility of the armature conductors flying of, when the machine runs at high speed since they are housed in the stator slots.

There is no difficulty in insulating the armature (stationary) winding for very high voltages, i.e, as high as 30000v or more.

Two slip rings are required for the supply of DC energy required for rotor field excitation. Since exciting current is to be supplied at low voltage, there is no difficulty in insulating them.

Rotating field is competitively light and can run with high speeds.

2.4 DIFFERENCES:-

S.No.	STATIONARY FIELD SYSTEM	ROTATING FIELD SYSTEM
1	4 slip rings are required.	100 slip rings are required.
2	Heavy armature current passes through slip rings.	Very low field current passes through slip rings.
3	More sparking at slip rings.	No sparking at slip rings.
4	Armature supply is taken through slip rings.	Armature supply is taken through fixed connections.
5	Capacity is limited to 30KVA.	It can be designed to any capacity.
6	Voltage is limited to 440v.	Voltage is up to 33KV is generated.
7	Low efficiency.	High efficiency.
8	More maintenance.	Less maintenance.

2.5 CONSTRUCTION:-

An alternator consists of mainly two parts

1. Stator
2. Rotor

1. Stator:-

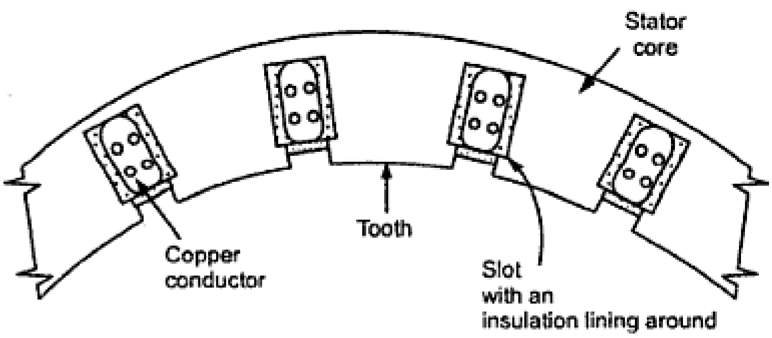


Fig 2.1

The armature core is supported by the stator frame and is built up of laminations of special magnetic iron or steel iron alloy the core is laminated to minimize the loss due to

Eddy currents.

The laminations are stamped out in complete rings or segments. The laminations are insulated from each other and have space between them for allowing the cooling air to pass through.

The inner periphery of the stator is slotted and copper conductors which are joined to one another constituting armature winding housed in these slots. The other ends of the winding are brought out are connected to fixed terminal from which the generator power can be taken out.

Different shapes of the armature slots are shown in the fig.

The wide open type slot also used in DC machines has the advantage of permitting easy installation of form-wound colis and there easy removal in case of repair but it has the disadvantage of distributing the air gaps flux into bunches that produce ripples in the wave of generated EMF.

The semi closed type slots are better in this respect but do not allow the use of form wound coils.

The fully closed slots donot disturb the air gap flux but they try to increase the inductance of the windings. The armature conductors have to be threaded through, there by increasing the initial labour and cost of the winding. Hence, these are rarely used.

2. <u>Rotor</u>:-

Depending upon the type of application, these are classified into two types

1) Salient-pole or projecting pole type
2) Non silent-pole or round rotor or cylindrical rotor

2.6 Salient-pole or projecting pole type

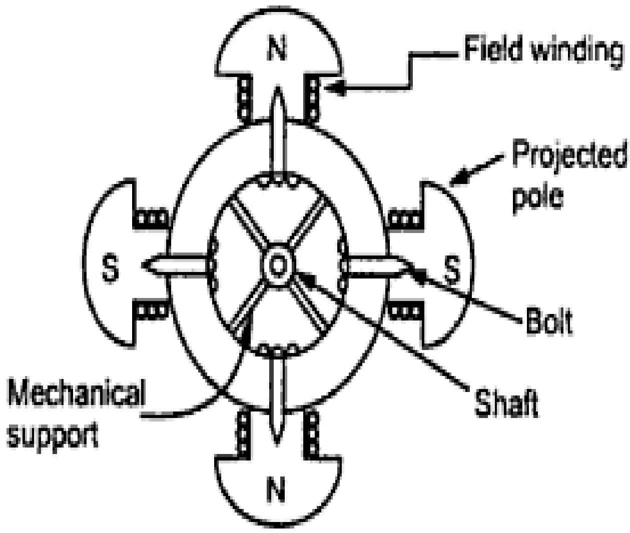


Fig 2.2

- It is used for and medium speed alternators used in hydro and diesel power generating station.
- The poles are made of laminated sheets and fixed to the rotor by dove tail joint.
- Short circuited damper bars are placed in the slots provided on the pole surfaces.
- These are used to prevent hunting and to provide starting torque in synchronous motors.
- The field coils are placed on the poles as shown in the figure

<u>Key features:-</u>

- It has non-uniform air gap.
- The diameter of the rotor is more than of the cylindrical rotor.
- The no. of holes is higher than that of the non salient-pole rotor
- Axial length is less.
- The prime mover speed is less and is driven in hydal turbines
- These generators are used in hydro electric stations so these are called as hydro generators.

2.7 Non-Salient pole type (or) Cylindrical type (or) Round rotor:

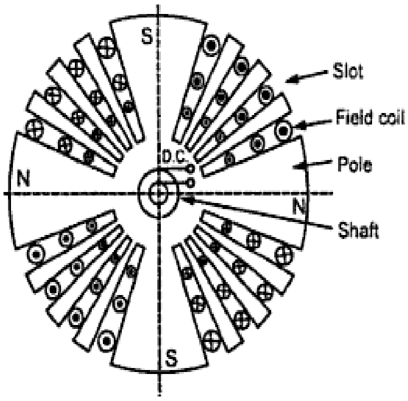


Fig 2.3

- Slots are provided in between the poles and these slots are placed with field winding Conductors.

Features :-

- No. of poles are less when compared to salient pole type.
- Diameter is less
- Axial length is more
- Air gap is uniform
- Prime mover speed is more and is driven in thermal turbines.
- These are used in thermal stations so, these are called as turbo Generators.

2.8 Frequency of the induced EMF:-

Consider an alternate whose rotor is driver at a constant speed N rpm.

Let "p" be no. of poles and f is the frequency of the generated voltage

No. of cycles of the induced EMF per sec

= No. of cycles per revolutions × no. of revolutions\sec

= $P/2 \times N/60 =$ $PN \times 120$.

Frequency $f = PN/120$ Hz.

For a given alternate, the no. of poles is fixed.

Hence in order to generate power at a specified frequency, the machine is to be run at a definite speed which is termed as synchronous speed.

NOTES:

Pole pitch:- distance between two adjacent opposite main poles by the no. of armature conductors.

Coil span:- distance b/w two coils starting and ending conductors

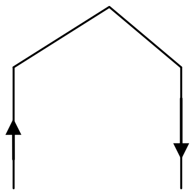


Fig 2.4

If the coil span = pole pitch, then full pitch winding (or) integral slot winding.

Integral slot (or) full pitch winding and short pitch (or) fractional chorded winding .

The distance between any two conductors is called slot angle (β)

Short pitch angle (α) = short chorded slots ×. B

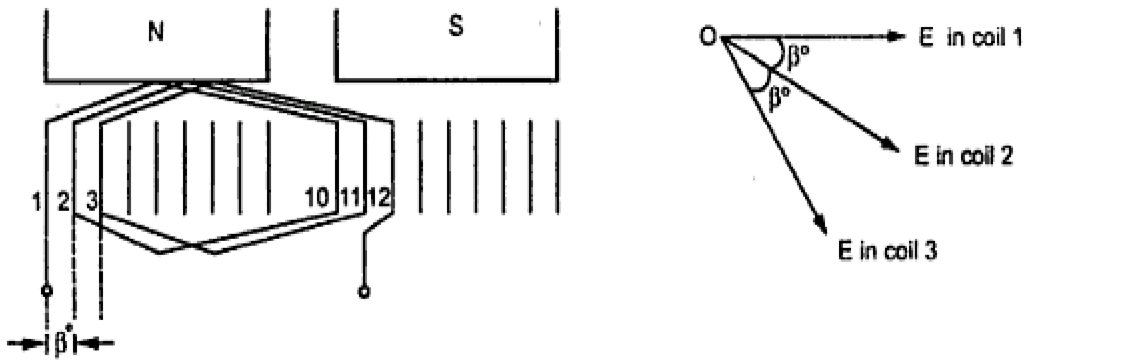


Fig 2.5

- If the distance b/w two coils sides of a coil, i.e. coil span is equal to one pole pitch, i.e. 180°E , it is called as full pitch winding.

- If the distance b/w two coils sides of a coil, i.e. coil span is less than one pole pitch i.e 180°E , it is called short pitch (or) fractional chorded winding.
- If the winding is short pitched by one slot then the short pitch angle α is equal to slot angle β.
- If it is short pitched by two slots, then $\alpha = 2\beta$ and so on.

2.9 EMF EQUATION:-

Consider a 3Ø alternator with "p" no. of poles driven at a constant speed N rpm.

Let Ep be the rms values of the induced emf per pole.

Ø is the average flux per pole in Webbers

Z is the no. of stator conductor per phase

T is the no. of stator turns per phase

And we know $T=Z/2$

F is the frequency of indused emf in hz

Therefore total flux cut per revolution by any one stator conductor is equal to PØ Webbers.

Time taken for one revolution is equal to 1/N min or 60/N sec

Therefore rate of cutting of flux is equal to = dØ/dt

= "PØ" / "60/N" (wb/sec)

= PØN/60 (wb/sec)

But we have $F=PN/120$

Therefore $2F=PN/60$

dØ/dt = 2ØF

According to faraday's second law of EMI

- The average value of the induced emf = 2FØ volts

- In any one phase Z conductors are joined in series, therefore average induced emf per phase = 2FØZ volts

  = 2FØ(2T) volts

  Avg. value of induced emf per phase = 4FØT volts

For a sine wave form factor = rms value/avg value = 1:11

RMS value of induced emf per phase = 1.11 × 4FØT

= 4.44FØT volts

In a practical alternator the space distribution of the filed flex is not purely senisoidal, it is having some distortion and moreover in a practical alternator short pitch winding is used, therefore by these two reasons , the actual EMF that is induced is somewhat less than the emf that is arrived at.

Therefore by inscrting pitch factor (or) chording factor (or) coil span factor (Kc or Kp) and Distribution or breadth factor (Kd or Kb) in the above emf equation , we with get the actual emf equations as E= 4,44fØTKcKd volts .

2.10 Pitch factor (or) chording factor (or) coil span factor :-

It is the ratio of vector sum of the emfs induced in the two coil sides of coil to their alrithmetic sum .

Kc= vector sum of induced emfs per coil / arithmetic sum of induced emf per coil

= voltage induced in short pitch winding / voltage induced in full pitch winding

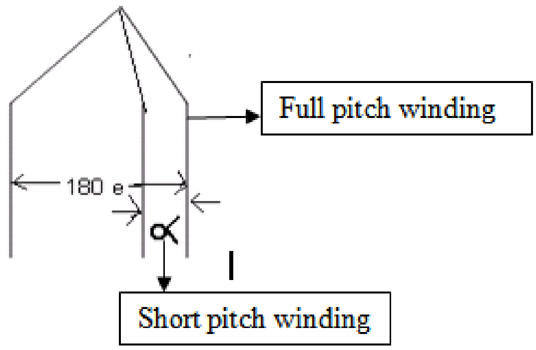


Fig 2.6

Let the coil span of the short pitch winding is less than one pole pitch (180°) by an angle α. Let the emf induced per coil side (conductor) is "E" volts

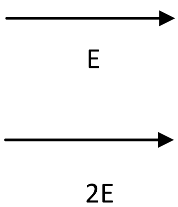
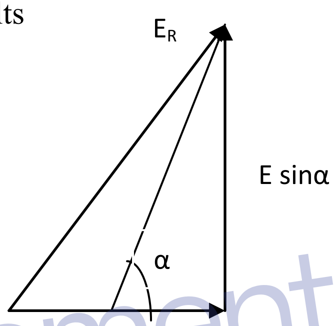


Fig 2.7



Er = (E(1+cosdα))2 + (ESmα)2

= E 1+1+2cosα

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

= 2E cosα/2

Arithmetic sum of the EMF's around, the coil is equal to E+E= 2E volts. Vector sum of the EMF's around the coil m shrt pitch winding is equal

OA+AB= OB

OA+AB=OB

2.OA.cos(α/2)

Kc = vector / arithmetic sum = 2Ecos (α/2) / 2E = cos (α/2)

Therefore K_c=cos (α/2) { Where α is the short pitch angle (or) λ}

2.11 Distributions Factor (or) breadth factor:- (K_d or K_b)

- When the coils comprising a phase of the windings are distributed in two or more slots per pole the e.m.fs in the adjacent coils will be out of phase with respect to one another and their resultant will be less than their algebraic sum.
- The ratio of the vector sum of the e.m.fs induced in all the coils distributed in a number of slots under one pole to the arithmetic sum of the e.m.fs induced (or to the resultant of the e.m.fs induced in all the coils concentrated in one slot under one pole) is known as distributed factor k_d.
- It is the ratio of voltage induced in a distribution winding to the voltage induced in the concentric winding.
- Let 'm' be the no. of stator slots per pole per phase.

B =180°/no.of slots/pole Which is known as slot angle.

E is the EMF induced per conductor. With radius 'R' and centre 'O' a circle is drawn to pass through the points ABCD

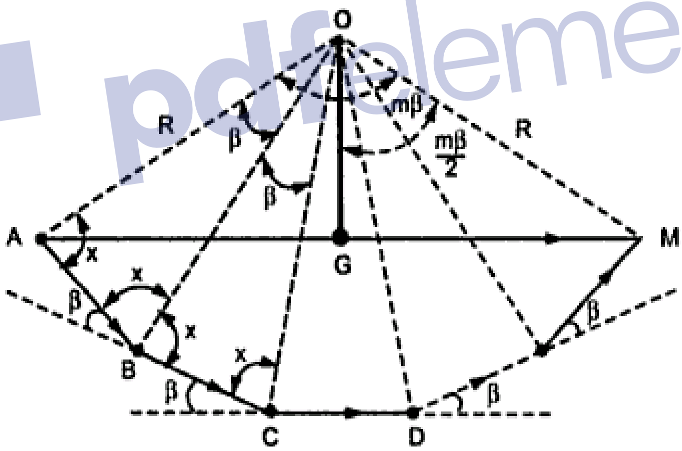


Fig 2.8

Arithmetic sum of EMF'S=AB+BC+CD++DF……………….

=E+E+E+E+E………………m times

= m E

From fig. vector sum of the EMF'S=AF

=2AS

From the ΔAOS, $\sin(m\beta/2) = AS/OA = AS/R$

$$AS = R\,S\,in(m\beta/2)$$

Vector sum = $AF = 2AS = 2R\sin(m\,\beta/2)$

From the Δ AOG $\sin(\beta/2) = AG/OA = AG/R = E/2R$

$$E = 2R\,\sin(\beta/2)$$

There Kd = vector sum / arthematic sum = $2R\,\sin(m\beta/2)\,/me$

$$= 2R\,\sin(m\beta/2)\,/\,m.2R.\sin/(\beta/2)$$

Therefore Kd or $Kb = \sin(m\,\beta/2)\,/\sin(\beta/2)$

Also Kd or $Kb = \sin(mn\,\beta/2)\,/\,m.\sin(n\,\beta/2)$ {where n = order of harmonic}

2.12 CONCENTRATION AND DISTRIBUTION WINDINGS:

- Each coil side contains a no. of conductors, if all the conductors of a coil side are placed in a single slot, it is called concentrated coil.
- It gives more voltage but the sine wave will not be smooth.
- When the conductors of the coil side are distributed in diff. slots, it is called as distributed slots.
- It gives less voltage but the wave form will be smooth.

2.13 SHORT-PITCH WINDING

Advantages:-

- Copper in end connection can be saved.
- Harmonics are reduced
- Iron losses will be reduced
- Efficiency will be increased
- Generated voltage waveform will be improved is more sinusoidal.

Disadvantages:-

- The magnitude of the induced voltage will be reduced

Advantages of distributed windings:-

- The generated voltage waveform will be improved, is more sinusoidal.

The magnitude of induced voltage will be reduced

UNIT-III SYNCHNROUS MACHINES CHARATERSTICS

3. Introdcution

Harmonics: When the uniformly sinusoidally distributed air gap flux is cut by either the stationary or rotating armature sinusoidal emf is induced in the alternator. Hence the nature of the waveform of induced emf and current is sinusoidal. But when the alternator is loaded waveform will not continue toSynchronous Machine Dr. Vishwanath Hegde16be sinusoidal or becomes nonsinusoidal. Such nonsinusoidal wave form is called complex wave form.

By using Fourier series representation it is possible to represent complex nonsinusoidal waveform in terms of series of sinusoidal components called harmonics, whose frequencies are integral multiples offundamental wave. The fundamental wave form is one which is having the frequency same as that of complex wave.

The waveform, which is of the frequency twice that of the fundamental is called second harmonic. The one which is having the frequency three times that of the fundamental is called third harmonic and so on. These harmonic components can be represented as follows.

Fundamental: $e1 = Em1 \sin(\omega t \pm \theta 1)$

2nd Hermonic $e2 = Em2 \sin(2\omega t \pm \theta 2)$

3rd Harmonic $e3 = Em3 \sin(3\omega t \pm \theta 3)$

5th Harmonic $e5 = Em5 \sin(5\omega t \pm \theta 5)$ etc.

In case of alternators as the field system and the stator coils are symmetrical the induced emf will also be symmetrical and hence the generated emf in an alternator will not contain any even harmonics.

Slot Harmonics: As the armature or stator of an alternator is slotted, some harmonics are induced into the emf which is called slot harmonics. The presence of slot in the stator makes the air gap reluctance at the surface of the stator non uniform. Since in case of alternators the poles are moving or there is a relative motion between the stator and rotor, the slots and the teeth alternately occupy any point in the air gap. Due to this the reluctance or the air gap will be continuously varying. Due to this variation of reluctance ripples will be formed in the air gap between the rotor and stator slots and teeth. This ripple formed in the air gap will induce ripple emf called slot harmonics. Minimization of Harmonics: To minimize the harmonics in the induced waveforms following methods are employed:

1. Distribution of stator winding.

2. Short Chording

3. Fractional slot winding

4. Skewing

5. Larger air gap length.

Effect of Harmonics on induced emf:

The harmonics will affect both pitch factor and distribution factor and hence the induced emf. In a well designed alternator the air gap flux density distribution will be symmetrical and hence can be represented in Fourier series as follows.

$B = B_{m1} \sin \omega t + B_{m3} \sin 3\omega t + B_{m5} \sin 5\omega t + \ldots$

The emf induced by the above flux density distribution is given by

$e = E_{m1} \sin \omega t + E_{m3} \sin 3\omega t + E_{m5} \sin 5\omega t + \ldots$

The RMS value of the resultant voltage induced can be given as

$E_{ph} = \sqrt{(E_1)^2 + (E_3)^2 + (E_5)^2 + \ldots (E_n)}$

Synchronous Machine Dr. Vishwanath Hegde

And line voltage $E_{Line} = \sqrt{3} \times E_{ph}$

3.1 Effect of Harmonics of pitch and distribution Factor:

The pitch factor is given by $K_p = \cos \alpha/2$, where α is the chording angle.

For any harmonic say nth harmonic the pitch factor is given by $K_{pn} = \cos n\alpha/2$

The distribution factor is given by $K_d = (\sin m\beta/2) / (m \sin \beta/2)$

For any harmonic say nth harmonic the distribution factor is given by $K_{dn} = (\sin m n\beta/2) / (m \sin n\beta/2)$

3.2 Operation of Alternators:

Similar to the case of DC generator, the behaviour of a Synchronous generator connected to an

external load is different than that at no-load. In order to understand the performance of the

Synchronous generator when it is loaded, consider the flux distributions in the machine when the

armature also carries a current. Unlike in the DC machine in alternators the emf peak and the current peak will not occur in the same coil due to the effect of the power factor of the load. The current and the induced emf will be at their peaks in the same coil only for upf loads. For zero power factor lagging loads, the current reaches its peak in a coil which falls behind that coil wherein the inducedemf is at its peak by 90 electrical degrees or half a pole-pitch. Likewise for zero power factor leading Synchronous Machine Dr. Vishwanath Hegde

loads, the current reaches its peak in a coil which is ahead of that coil wherein the induced emf is at its peak by 90 electrical degrees or half a pole-pitch. For simplicity, assume the resistance and leakage reactance of the stator windings to be negligible. Also assume the magnetic circuit to be linear i.e. the flux in the magnetic circuit is deemed to be proportional to the resultant ampere-turns - in other words the machine is operating in the linear portion of the magnetization characteristics. Thus the emf induced is the same as the terminal voltage, and the phase-angle between current and emf is determined only by the power factor (pf) of the external load connected to the synchronous generator.

3.3 Armature Reaction:

3.3.1 Magnetic fluxes in alternators

There are three main fluxes associated with an alternator:

(i) Main useful flux linked with both field & armature winding.

(ii) Leakage flux linked only with armature winding.

(iii) Leakage flux linked only with field winding.

The useful flux which links with both windings is due to combined mmf of the armature winding and field winding. When the armature winding of an alternator carries current then an mmf sets in

armature. This armature mmf reacts with field mmf producing the resultant flux, which differs from flux of field winding alone. The effect of armature reaction depends on nature of load (power factor of load). At no load condition, the armature has no reaction due to absence of armature flux. When armature delivers current at unity power factor load, then the resultant flux is displaced along the air gap towards the trailing pole tip. Under this condition, armature reaction has distorting effect on mmf wave as shown in Figure. At zero lagging power factor loads the armature current is lagging by 90° with armature voltage. Under this condition, the position of armature conductor when inducing maximum emf is the centre line of field mmf. Since there is no distortion but the two mmf are in opposition, the armature reaction is now purely demagnetizing as shown in Figure. Now at zero power factor leading, the armature current leads armature voltage by 90°. Under this condition, the mmf of armature as well as the field winding are in same phase and additive. The armature mmf has magnetizing effect due to leading armature current as shown

3.3.2 Armature reaction:

(a) Unity Power Factor

Distorting Effect of Armature Reaction

(b) Zero Power Factor Lagging

(c) Zero Power Factor Leading Synchronous Machine Dr. Vishwanath Hegde

Magnetizing Effect of Armature Reaction

The Equivalent Circuit of a Synchronous Generator

The voltage ‘E’ is the internal generated voltage produced in one phase of a synchronous generator. If the machine is not connected to a load (no armature current flowing), the terminal voltage ‘V’ will beequivalent to the voltage induced at the stator coils. This is due to the fact that there are no current flow in the stator coils hence no losses and voltage drop. When there is a load connected to the generator, there will be difference between E and V.

These differences are due to: a) Distortion of the air gap magnetic field by the current flowing in the stator called armature reaction.

b) Self inductance of the armature coil

c) Resistance of the armature coils

d) The effect of salient pole rotor shapes.

We will explore factors a, b, and c and derive a machine equivalent circuit from them. The effect of salient pole rotor shape will be ignored, and all machines in this chapter are assumed to have nonsalient or cylindrical rotors.

3.3.2 Armature Reaction

When the rotor is run, a voltage E is induced in the stator windings. If a load is connected to the

terminals of the generator, a current flows. The 3-phase stator current flow will produce a magnetic field of its own. This stator magnetic field will distort the original rotor magnetic field, changing the resulting phase voltage. This effect is called armature reaction because the armature (stator) current affects the magnetic field. From the phasor diagrams of the armature reaction it can be seen that E0 is the emf induced under no load condition and E can be considered as the emf under loaded condition. It can also be understood that the E0 is the emf induced due to the field winding acting alone and E is the emf induced when both field winding and stator winding are acting in combination. Hence emf E can be considered as sum of E0 and another fictitious emf Ea proportional to the stator current. From the figures it can be seen that the emf Ea is always in quadrature with current. This resembles the emf induced in an inductive reactance. Hence the effect of armature reaction is exactly same as if the stator has an additional reactance xa= Ea/I. This is called the armature reaction reactance. The leakage reactance is the true reactance and the armature reaction reactance is a fictitious reactance.

3.3 Synchronous Reactance and Synchronous Impedance

The synchronous reactance is an equivalent reactance the effects of which are supposed to reproduce the combined effects of both the armature leakage reactance and the armature reaction. The alternator is supposed to have no armature reaction at all, but is supposed to possess an armature reactance in excess of its true leakage reactance. When the synchronous reactance is combined vectorially with the armature resistance, a quantity called the synchronous impedance is obtained as shown. From the above discussion it is clear that the armature winding has one more reactance called armaturereaction reactance in addition to leakage reactance and resistance.

3.4 Considering all the three parameters

the equivalent circuit of a synchronous generator can be written as shown below. The sum of leakage reactance and armature reaction reactance is called synchronous reactance Xs. Under this condition impedance of the armature winding is called the synchronous impedance Zs. Hence synchronous reactance Xs = Xl + Xa Ω per phase and synchronous impedance Zs = Ra + j Xs Ω per phase As the armature reaction reactance is dependent on armature current so is synchronous reactance and hence synchronous impedance is dependent on armature current or load current

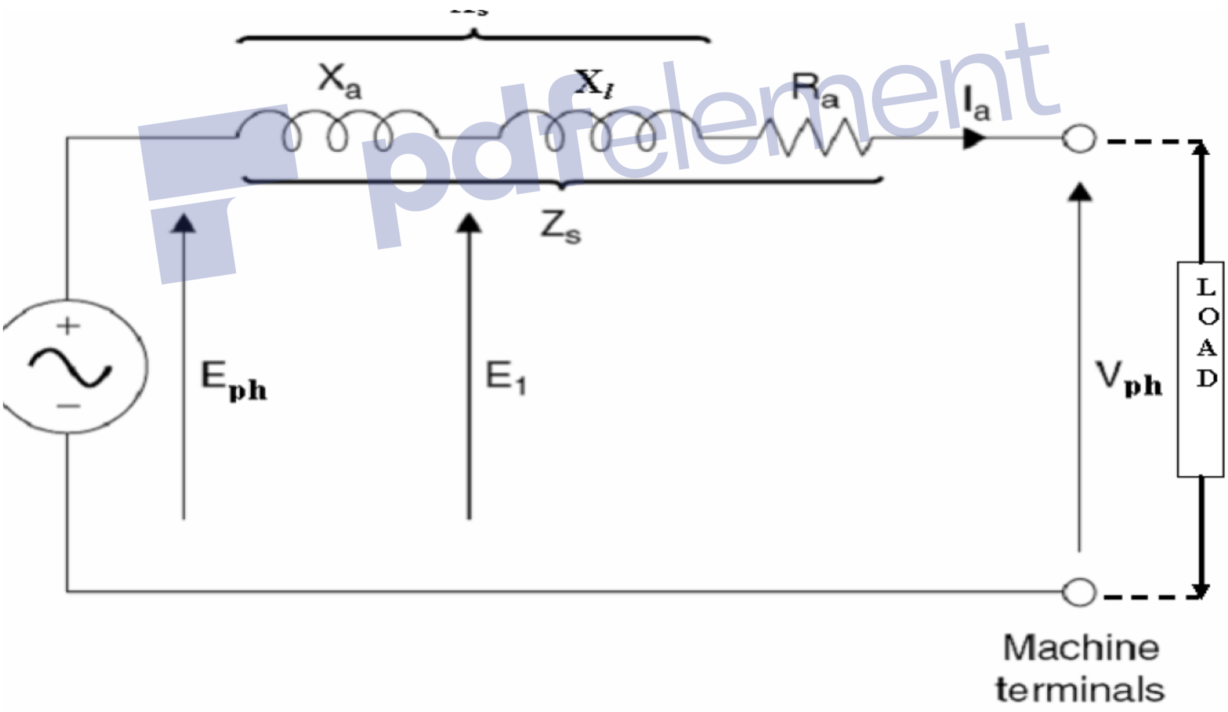


Fig 3.1

Considering the above equivalent circuit the phasor diagram of a non salient pole alternator for variousloading conditions considered above can be writtenas shown below.In the phasor diagrams E is the induced emf /phase = Eph and V is the terminal voltage /phase = Vph.From each of the phasor diagrams the expressionfor the induced emf Eph can be expressed in terms ofVph, armature current, resistance, reactances and impedance of the machine as follows.

(i) Unity power factor load

Under unity power factor load: Eph = (V + IRa) + j (IXS)
Eph = _[(V + IRa)2 + (IXS)2]

ii) Zero power factor lagging

Under zero power factor lagging: Eph = V + (IRa + j IXS) = V + I(Ra + j XS)
The above expression can also be written as Eph = _[(V cos_ + IRa)2 + (V sin_ + IXS)2]

iii) Zero power factor leading

Under zero power factor leading: Similarly for this case
Eph = _[(V cos_ + IRa)2 + (V sin_ - IXS)2]

Generator Load Characteristics

Consider a synchronous generator driven at constant speed and with constant excitation. On open circuit the terminal voltage V is the same as the open circuit e.m.f. Et .Suppose a unity-power-factor load be connected to the machine. The flow of loacurrentproduces a voltage drop IZs in the synchronous impedance, and terminal voltage V is reduced. Fig. 31 shows the complexor diagram for three types of load. It will be seen thatthe angle σ between Et and V increases with load, indicating a shift of the flux across thepole faces due to cross- magnetization. The terminal voltage is obtained from the complexsummation

V + Zs = Et
or V = Et – Izs

Algebraically this can be written
V =qE2t − I2X2s) − Ir

or non-reactive loads. Since normally r is small compared with Xs
V2 + I2X2s ≈ E2t = constant

so that the V/I curve, , is nearly an ellipse with semi-axes Et and Isc. The current Isc is that which flows when the load resistance is reduced to zero. The voltage V falls to zero also and the machine is on short-circuit with V = 0 and
I = Isc = Et/Zs ≈ Et/Xs

For a lagging load of zero power-factor, diagram is given in Fig. 31 The voltage is given as before and since the resistance in normal machines is small compared with the synchronous reactance, the voltage is given approximately by
V ≈ Et – Ixs

UNIT-IV Voltage Regulation of Alternators

4.1 Voltage Regulation:
When an alternator is subjected to a varying load, the voltage at the armature terminals varies to acertain extent, and the amount of this variation determines the regulationofthemachine. When thealternator is loaded the terminal voltage decreases as the drops in the machine stars increasing andhence it will always be different than theinduced emf.Voltage regulation of an alternator is defined as the change in terminalvoltage from no load to fulload expressed as a percentage of rated voltagewhen the load at a given power factor is removed without change in speed and excitation. Or The numerical value of the regulation is defined as thepercentage rise in voltage whenfull load at the specified power-factor is switched off with speed andfield current remaining unchanged expressed as a percentage of rated voltage.Hence regulation canbe expressed as

% Regulation = (Eph – Vph / Vph) x 100
where Eph = induced emf /phase, Vph = rated terminal voltage/phase
Methods of finding Voltage Regulation: The voltage regulation of an alternator can be determined bydifferent methods. In case of small generators it can be determined by direct loading whereas in caseof large generators it can not determined by direloadingbut will be usually predetermined bydifferent methods. Following are the different methods used for predetermination of regulation ofalternators.
1. Direct loading method
2. EMF method or Synchronous impedance method
3. MMF method or Ampere turns method
4. ASA modified MMF method
5. ZPF method or Potier triangle method
All the above methods other than direct loading are valid for nonsalient pole machines only. As thealternators are manufactured in large capacity direct loading of alternators is not employed
determination of regulation. Other methods can be employed for predetermination of regulation.
Hence the other methods of determination of regulations will be discussed in the following sections.

4.2 EMF method: This method is also known as synchronous impedance method. Here the magnetic
circuit is assumed to be unsaturated. In this method the MMFs (fluxes) produced by rotor and stator
are replaced by their equivalent emf, and hence called emf method.
To predetermine the regulation by this method the following informations are to be determined.
Armature resistance /phase of the alternator, open circuit and short circuit characteristics of the
alternator.

(Synchronous impedance method)

Tests:

Conduct tests to find

OCC (upto 125% of rated voltage) **SCC** (for rated current)

Armature resistance (per phase)

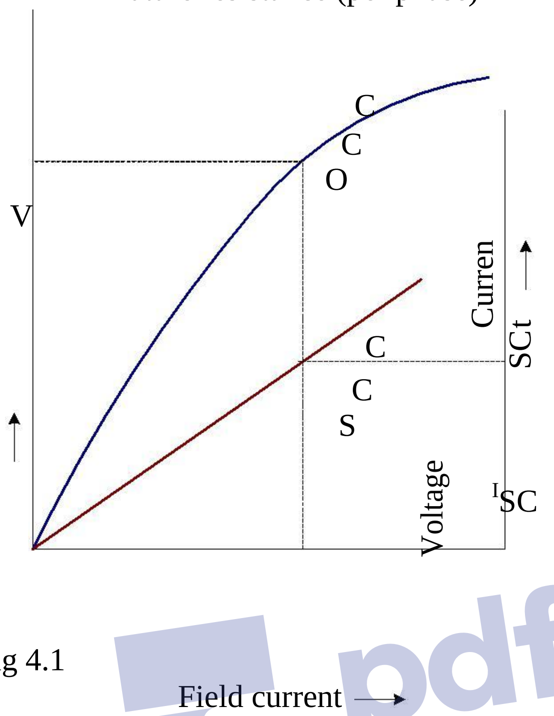


Fig 4.1

V = rated phase voltage

I_{sc} = short circuit current corresponding to the field current producing the rated voltage

Synchronous impedance per phase,

$$Z_s = V / I_{sc}$$

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

For any load current I and phase angle Φ, find E_0 as the vector sum of V, IR_a and IX_s

For lagging power factor

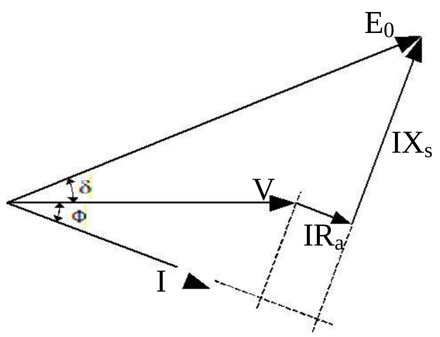


Fig 4.2

$$E_0 = \sqrt{(V\cos\Phi + IR_a)^2 + (V\sin\Phi + IX_s)^2}$$

For unity power factor

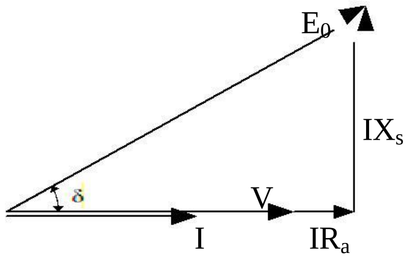


fig 4.3

$$E_0 = \sqrt{(V + IR_a)^2 + (IX_s)^2}$$

For leading power factor

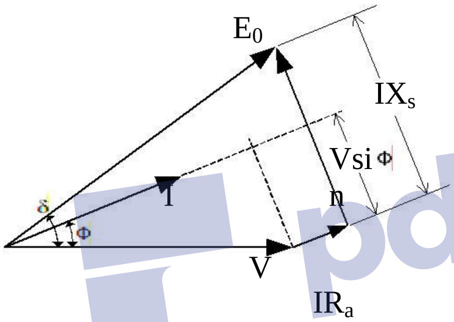


fig 4.4

$$E_0 = \sqrt{(V\cos\Phi + IR_a)^2 + (V\sin\Phi - IX_s)^2}$$

4.3 MMF method
(Ampere turns method)

Tests:

Conduct tests to find

OCC (upto 125% of rated voltage) SCC (for rated current)

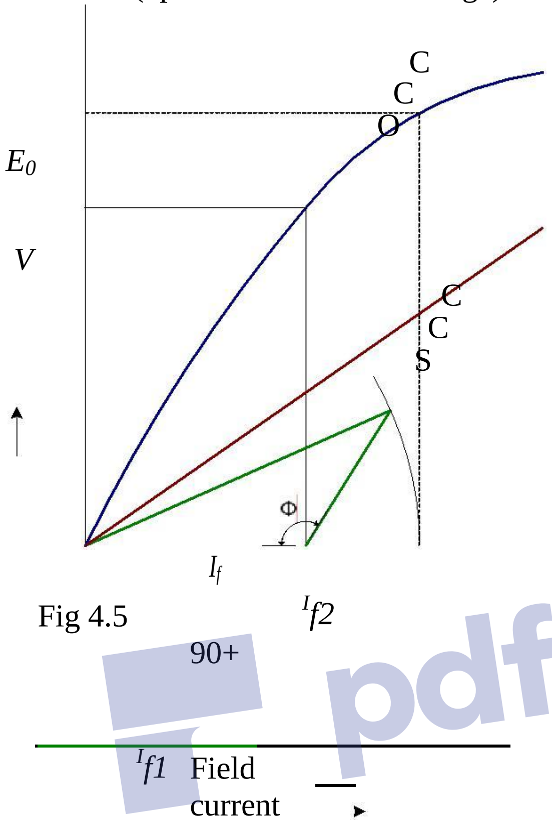


Fig 4.5

Steps:

By suitable tests plot OCC and SCC

rom the OCC find the field current I_{f1} to produce rated voltage, V.

From SCC find the magnitude of field current I_{f2} to produce the required armature current.

raw I_{f2} at angle (90+Φ) from I_{f1}, where Φ is the phase angle of current from voltage. If current is leading, take the angle of I_{f2} as (90-Φ).

Find the resultant field current, I_f and mark its magnitude on the field current axis.

From OCC. find the voltage corresponding to I_f, which will be E_0.

4.4 ZPF method
(Potier method)

Tests:

Conduct tests to find

OCC (upto 125% of rated voltage) SCC (for rated current)

ZPF (for rated current and rated voltage) Armature Resistance (if required)

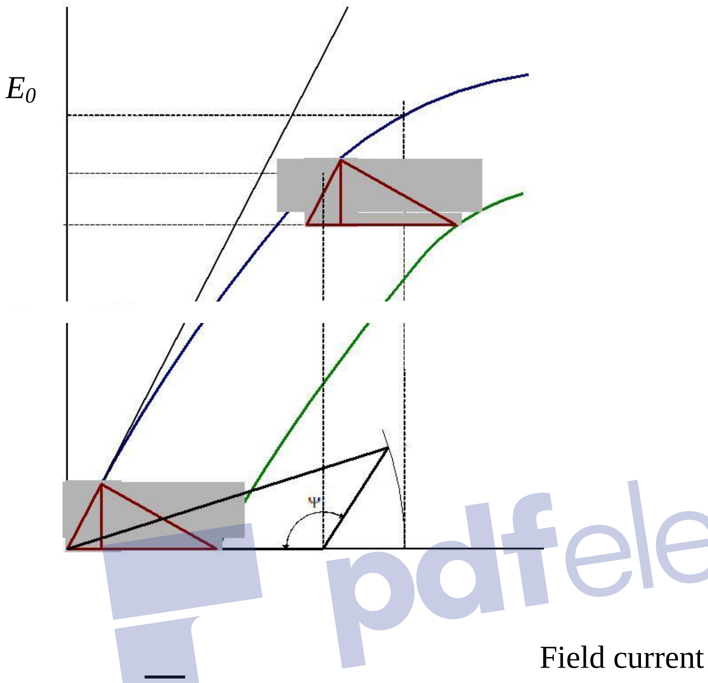


Fig 4.6

Steps:

1. By suitable tests plot OCC and SCC
2. Draw tangent to OCC (air gap line)
3. Conduct ZPF test at full load for rated voltage and fix the point B.
4. Draw the line BH with length equal to field current required to produce full load current at short circuit.
5. Draw HD parallel to the air gap line so as to touch the OCC.

6) Draw DE parallel to voltage axis. Now, DE represents voltage drop IX_L and BE represents the field current required to overcome the effect of armature reaction

Triangle BDE is called Potier triangle and X_L is the Potier reactance

7)Find E from V, IX_L and Φ. Consider R_a also if required. The expression to use is

$$E = \sqrt{(V\cos\Phi + IR_a)^2 + (V\sin\Phi + IX_L)^2}$$

8) Find field current corresponding to E.

9) Draw FG with magnitude equal to BE at angle (90+Ψ) from field current axis, where Ψ is the phase angle of current from voltage vector E (internal phase angle).

10) The resultant field current is given by OG. Mark this length on field current axis. From OCC find the corresponding E_0.

4.5 ASA method

Tests:

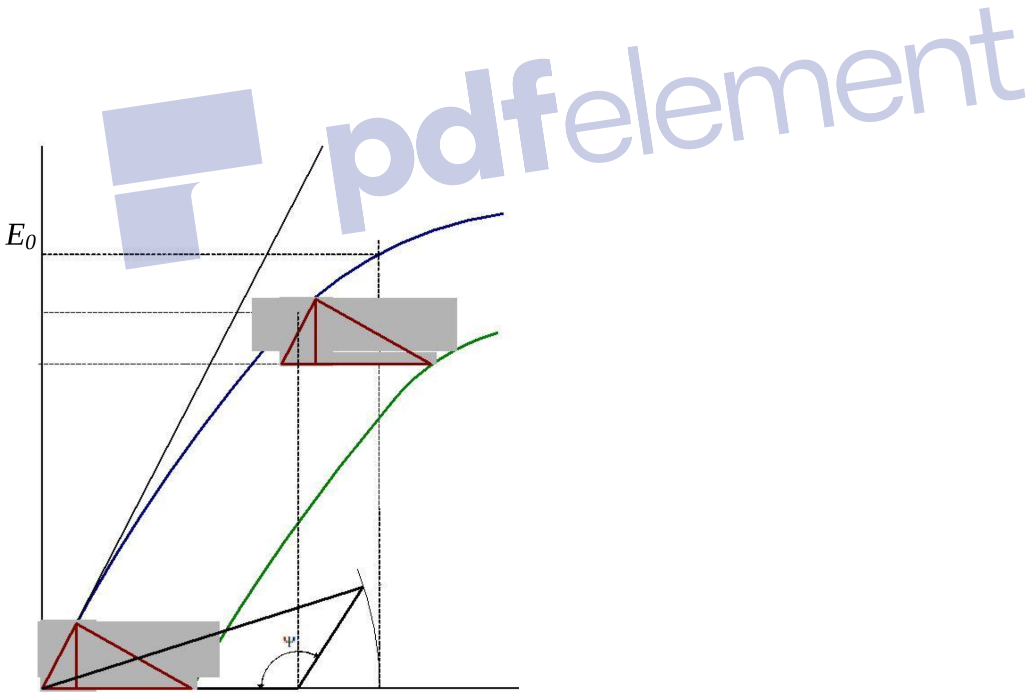
Conduct tests to find

OCC (upto 125% of rated voltage) SCC (for rated current)

ZPF (for rated current and rated voltage) Armature Resistance (if required)

Steps:

1. Follow steps 1 to 7 as in ZPF method.
2. Find I_{f1} corresponding to terminal voltage V using air gap line (OF_1 in figure).
3. xDraw I_{f2} with length equal to field current required to circulate rated current during short circuit condition at an angle (90+Φ) from I_{f1}. The resultant of I_{f1} and I_{f2} gives I_f (OF_2 in figure).
4. Extend OF_2 upto F so that F_2F accounts for the additional field current accounting for the effect of saturation. F_2F is found for voltage E as shown.
5. Project total field current OF to the field current axis and find corresponding voltage E_0 using OCC.



Field
__current

Fig 4.7

4.6 Slip Test

(for salient pole machines only)

Tests:

Conduct tests to find

X_d and X_q

Armature Resistance (if required)

1. Energise the alternator with field unexcited and driven close to synchronous speed by a prime mover.
2. Measure the line voltage and line current of the alternator.
3. Find X_d and X_q by the following expressions

$$X_d = \frac{V_{max}}{\sqrt{3} I_{min}} \qquad X_q = \frac{V_{min}}{\sqrt{3} I_{max}}$$

4. Find I_d as follows

$$\Psi = \tan^{-1} \frac{V \sin\Phi + I X_q}{V \cos\Phi + I R_a} \; ; \quad I_d = I \sin \Psi$$

5. Then expression for E_0 is

$$E_0 = [(V\cos\Phi + IR_a)^2 + (V\sin\Phi + IX_q)^2]^{1/2} + I_d(X_d - X_q)$$

4.7 Salient pole alternators and Blondel's Two reaction Theory:

The details of synchronous generators developed so far is applicable to only round rotor or nonsalientpole alternators. In such machines the air gap is uniform through out and hence the effect of mmf willbe same whether it acts along the pole axis or the inter polar axis. Hence reactance of the sator is samethroughout and hence it is called synchronous reactance. But in case salient pole machines the air gap
is non uniform and it is smaller along pole axis and is larger along the inter polar axis. These axes arecalled direct axis or d-axis and quadrature axis or q-axis. Hence the effect of mmf when acting along
direct axis will be different than that when it is acting along quadrature axis. Hence the reactance ofthe stator can not be same when the mmf is acting along d – axis and q- axis. As the length of the airgap is small along direct axis reluctance of the magnetic circuit is less and the air gap along the q –axis is larger and hence the along the quadrature axis will be comparatively higher. Hence along d-axismore flux is produced than q-axis. Therefore the reactance due to armature reaction willbe differentalong d-axis and q-axis. These reactances are

X_{ad} = direct axis reactance; X_{aq} = quadrature axis reactance

Hence the effect of armature reaction in the case of a salient pole synchronous machine can be takenas two components - one acting along the direct axis (coinciding with the main field

pole axis) and theother acting along the quadrature axis (inter-polar region or magnetic neutral axis) - and as such the
mmf components of armature-reaction in a salient-pole machine cannot be considered as acting on thesame magnetic circuit. Hence the effect of the armature reaction cannot be taken into account byconsidering only the synchronous reactance, in the case of a salient pole synchronous machine.In fact, the direct-axis component Fad acts over a magnetic circuit identical with that ofthe main fieldsystem and produces a comparable effect while the quadrature-axis component Faq acts along the
interpolar axis, resulting in an altogether smaller effect and, in addition, a flux distribution totallydifferent from that of Fad or the main field m.m.f. This explains why the application of cylindrical-rotor
theory to salient-pole machines for predicting the performance gives results not conforming to theperformance obtained from an actual test.
Blondel’s two-reaction theory considers the effects of the quadrature and direct-axis components ofthe armature reaction separately. Neglecting saturation, their different effects are considered byassigning to each an appropriate value of armature-reaction “reactance,” respectively *xad* and *xaq* . Theeffects of armature resistance and true leakage reactance (*XL*) may be treated separately, or may be
added to the armature reaction coefficients on the assumption that they are the same, for either thedirect-axis or quadrature-axis components of the armature current (which is almost true). Thus thecombined reactance values can be expressed as : *Xsd = xad + xl and Xsq = xaq + xl* for the direct- andcross-reaction axes respectively.
In a salient-pole machine, xaq, the quadrature-axis reactance is smaller than xad, the direct-axisreactance, since the flux produced by a given current component in that axis is smaller as thereluctance of the magnetic path consists mostly of the interpolar spaces. It is essential to clearly notethe difference between the quadrature and direct-axis components Iaq, and Iad of the armature current Ia,and the reactive and active components Iaa and Iar. Although both pairs are represented by phasors inphase quadrature, the former are related to the induced emf Et while the latter are referredtotheSynchronous terminal voltage V. These phasors are clearly indicated with reference to the phasor diagram of a(salient pole) synchronous generator supplying a lagging power factor (pf) load,

UNIT-V PARALLEL OPERATION OF SYNCHNOUS ALTERNATOR

5.1 Synchnours alternator connected to infinite bus:

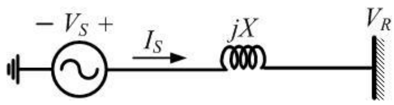


Fig 5.1

We have

$$I_S = \frac{V_1\angle\delta - V_2}{jX} = \frac{V_1\cos\delta - V_2 + jV_1\sin\delta}{jX}$$

The sending end real power and reactive power are then given by

$$P_S + jQ_S = V_S I_S^* = V_1(\cos\delta + j\sin\delta)\frac{V_1\cos\delta - V_2 - jV_1\sin\delta}{-jX}$$

This is simplified to

$$P_S + jQ_S = \frac{V_1V_2\sin\delta + j(V_1^2 - V_1V_2\cos\delta)}{X}$$

Since the line is loss less, the real power dispatched from the sending end is equal to the real power received at the receiving end. We can therefore write

$$P_e = P_S = P_R = \frac{V_1V_2}{X}\sin\delta = P_{\max}\sin\delta$$

where $P_{max} = V_1V_2/X$ is the maximum power that can be transmitted over the transmission line. The power-angle curve is shown in Fig. 9.2. From this figure we can see that for a given power P_0. There are two possible values of the angle $\delta - \delta_0$ and δ_{max}. The angles are given by

$$\delta_0 = \sin^{-1}\left(\frac{P_0}{P_{\max}}\right)$$

$$\delta_{\max} = 180° - \delta_0$$

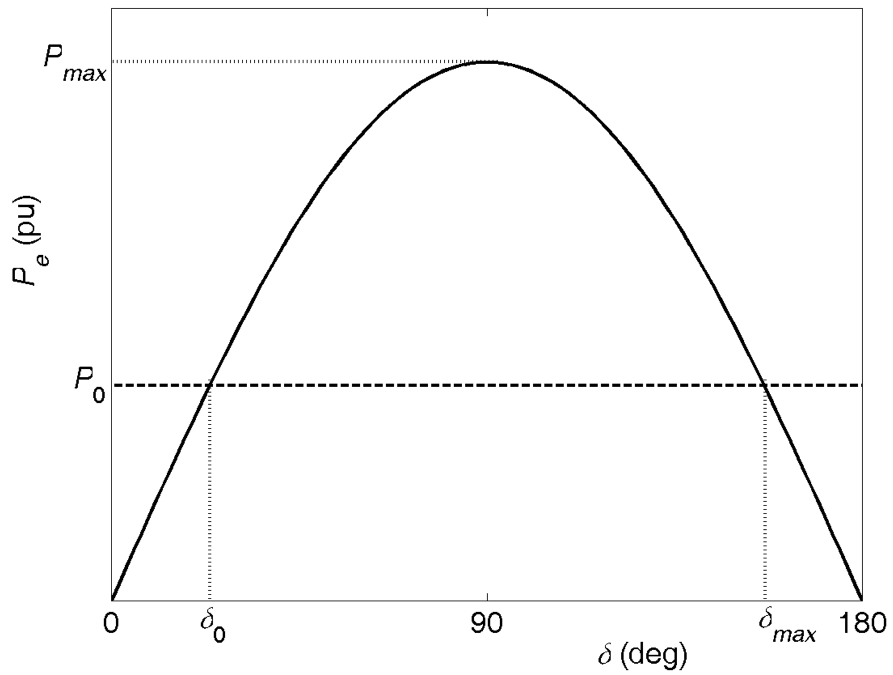


Fig 5.2 ***A typical power-angle curve***

5.2 Synchronising Power and Torque coefficients

A synchronous machine, whether a generator or a motor, when synchronized to infinite bus bar, has an inherent tendency to remain Synchronized. Consider a generator operation at a lagging power factor. At a steady load angle δo the steady power transfer is Po. Suppose that due to a transient disturbance, the rotor of the machine accelerates, so that the load angle increases by δσ. This alters the operating point of the machine to a new constant-power line and the load on the machine increases to Po + δP. Since the steady power input remains unchanged, this additional load retards the machine and brings it back to synchronism. Similarly, if owing to a transient disturbance, the rotor decelerates so that the load angle decreases, the load on the machine is thereby reduced to Po - δP. This reduction in load causes the rotor to accelerate and the machine is again brought back to synchronism. Clearly the effectiveness of this inherent correcting action depends on the extent of the change in power transfer for a given change in load angle. A measure of this effectiveness is given by the synchronizing power coefficient, which is denoted as

$$Ps = \frac{\partial P}{\partial \sigma}$$

$$P = \frac{3V}{Zs}\left[Ef \cos(\psi - \sigma) - V \cos\psi \right]$$

So that

$$Ps = \frac{\partial P}{\partial \sigma} = 3 \, V \, Ef \sin(\psi - \sigma)$$

Similarly the synchronizing torque coefficient is defined as

$$Ts = \frac{\partial T}{\partial \sigma} = \frac{1}{2 \pi \, no} \frac{\partial P}{\partial \sigma}$$

Therefore,

$$T_s = \frac{3}{2\pi n_o} \cdot \frac{V E_f}{Z_s} \sin(\psi - \sigma)$$

In many synchronous machines Xs > R, in which case equations (2.141) and (2.143) become

$$P_s = \frac{3 V E_f}{\quad} \cos\sigma$$

$$T_s = \frac{3}{2\pi n_o} \cdot \frac{V E_f}{X_s} \cos\sigma$$

The above equations show that the restoring action is greatest when σ = 0, i.e. on no-load. The restoring action is zero when σ=±90º At these values of load angle the machine would be at the steady state limit of stability and in a condition of unstable equilibrium. I It is impossible, therefore, to run a machine at the steady-state limit of stability since its ability to resist small changes is zero, unless the machine is provided with a special fast-acting excitation system.

5.3 Parallel operation of synch nous alternators

5.3.1 Synchronous generators parallel operation

Consider two machines A and B (as shown in Figure 2.8(a)), the voltages of which have been adjusted to equal values by means of the field regulators, and their speeds are slightly different. In Figure 2.8(b) the phase voltages are ERA etc., and the speed of machine A is ωA radians per second and of B, ωB radians per second. If the voltage phasors of A are considered stationary, those of B rotate at a relative velocity (ωB – ωA) and hence there are resultant voltages across the switch S of (ERA-ERB) , which reduce to zero during each relative revolution. If the switch is closed at an instant of zero voltage, the machines are connected (synchronized) without the flow of large currents due to the resultant voltages across the armatures. When the two machines are in synchronism they have a common terminal-voltage, speed and frequency.

In modern power systems isolated generators are very rare. Power systems are highly interconnected and many generators share the load. The first problem of an engineer is connecting a synchronous generator on an existing bus.

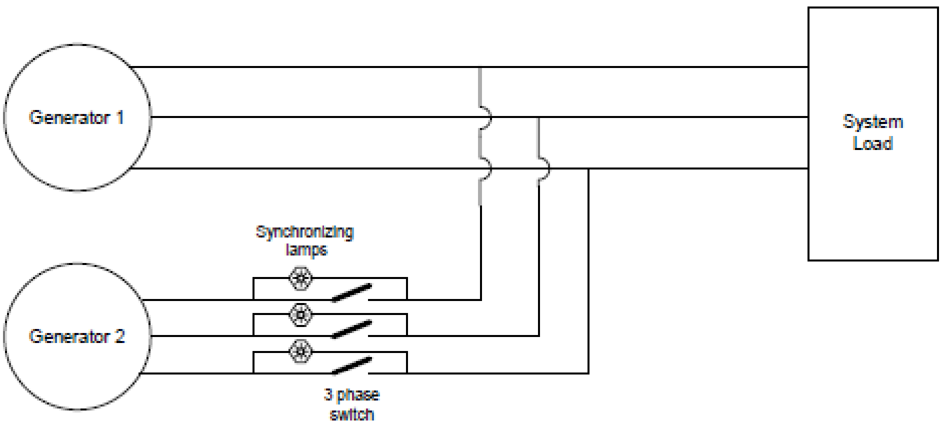


Fig 5.3

generator is set to deliver a certainpower on the shaft, and the voltageis set to deliver that powerto anelectrical load, a certain operating

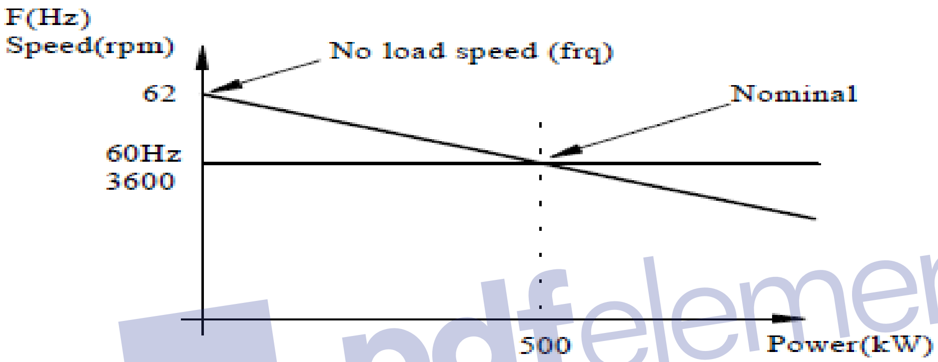


fig 5.4

point is reached [speed, Voltage,Power]. If the load increases, thegenerator speed (governor) willdecrease (not enough power tomove the shaft). Hence we can seethe typical prime mover/governorcharacteristic. The characteristic starts at the "no load speed", and droops. The droop rateis a parameter of the generator:

$$GD = \frac{\Delta f}{\Delta P} = \frac{f_{no\ load} - f_{full\ load}}{P_{rated}}$$

Since the power is related to the speed, a very useful formula is used as:

$$P_{output} = S_p \left(f_{nl} - f_{sys} \right)$$

Where: Sp is the slope of the curve in kW/Hzfnl is the no-load frequency of the generatorfsys is the operating frequency of the systemThis shows that the power generated by a generator is afunction of its frequency (orspeed).

5.4 Effect of Change of Excitation and Mechanical Input

Consider a star-connected alternator connected to an infinite busbars
Note that infinite busbars means that busbars voltage will remain constant and no frequency change will occur regardless of changes made in power input or field excitation of the alternator connected to it.

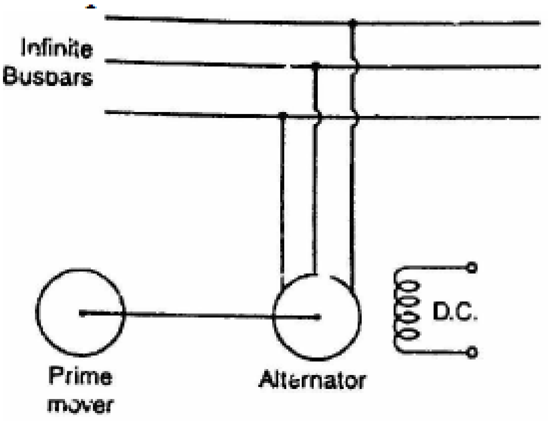


Fig 5.5

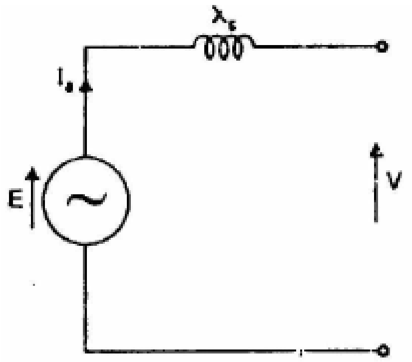


fig 5.6

Let V = busbars voltage/phase
E = e.m.f. of alternator/phase
Xs = synchronous reactance of alternator/phase
Armature current/phase,

$$I_s = \frac{E - V}{X_s}$$

5.5 **Effect of change of field excitation**

Suppose the alternator connected to infinite busbars is operating at unity p.f. It is then said to be normally excited. Suppose that excitation of the alternator is increased (overexcited) while the power input to the prime mover is unchanged. The active power output (W or kW) of the alternator will thus remain unchanged i.e., active component of current is unaltered. The overexcited alternator will supply lagging current (and hence lagging reactive power) to the infinite busbars. This action can be explained by the m.m.f. of armature reaction. When the alternator is overexcited, it must deliver lagging current since lagging current produces an opposing m.m.f. to reduce the over-excitation. Thus an overexcited alternator supplies lagging current in addition to the constant active component of current. Therefore, an overexcited alternator will operate at lagging power factor. Note that excitation does not control the active power but it controls power factor of the current supplied by the alternator to the infinite busbars. Fig. (5.7) shows the phasor diagram of an overexcited alternator connected to infinite busbars. The angle d between E and V is called power angle.

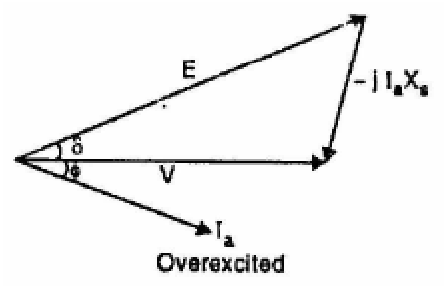


Fig 5.7

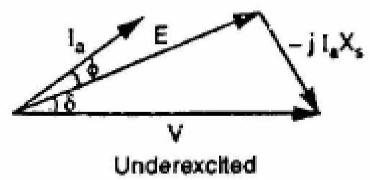


fig 5.8

Now suppose that excitation of the alternator is decreased below normal excitation (under-excitation) while the power input to the prime mover is unchanged. Therefore, the active power output (W or kW) of the alternator will remain unchanged L e., active component of current is unaltered. The underexcited alternator supplies leading current (and hence leading reactive power) to the infinite busbars. It is because when an alternator is underexcited, it must deliver leading current since leading current produces an aiding m.m.f. to increase the underexcitation. Thus an underexcited alternator supplies leading current in addition to the constant active component of current. Therefore, an underexcited alternator will operate at leading power factor. Fig. (5.8) shows the phasor diagram of an underexcited alternator connected to infinite busbars.

ii) Effect of change in mechanical input

Suppose the alternator is delivering power to infinite busbars under stable conditions so that a certain power angle d exists between V and E and E leads V. The phasor diagram for this situation is depicted in Fig. (5.6). Now, suppose that excitation of the alternator is kept constant and power input to its prime mover is increased. The increase in power input would tend to accelerate the rotor and £ would move further ahead of V i.e., angle d increases. Increasing d results in larger Ia (= E - V/Xs) and lower f as shown in Fig. (5.6). Therefore, the alternator will deliver more active power to the infinite busbars. The angle d assumes such a value that current Ia has an active power component corresponding to the input: Equilibrium will be reestablished at the speed corresponding to the frequency of the infinite busbars with a larger d. Fig. (5.7) is drawn for the same d.c. field excitation and, therefore, the same E as Fig. (5.8) but the active power output (= VIc cos f) is greater than for the condition of Fig. (5.8) and increase in 6 has caused the alternator to deliver additional active power to the busbars. Note that mechanical input to the prime mover cannot change the speed of the alternator because it is fixed by system frequency. Increasing mechanical input increases the speed of the alternator temporarily till such time the power angle d increases to a value required for stable operation. Once this condition is reached, the alternator continues to run at synchronous speed.

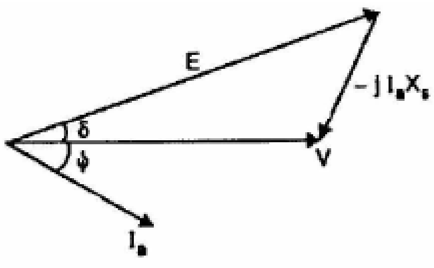


Fig 5.9

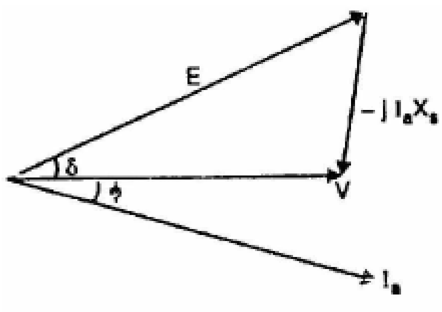


fig 5.10

Increasing the mechanical input power to the prime mover will notchange the speed ultimately but will increase the power angle d. As a result, thechange of driving torque controls the output kW and not the kVAR. When thischange takes place,thepowerfactorofthemachineispracticallynot affected

UNIT –VI Synchronous motor operation and starting

6.1 Introduction

It may be recalled that a d.c. generator can be run as a d.c. motor. In like manner, an alternator may operate as a motor by connecting its armature winding to a 3-phase supply. It is then called a synchronous motor. As the name implies, a synchronous motor runs at synchronous speed (Ns = 120f/P) i.e., in synchronism with the revolving field produced by the 3-phase supply. The speed of rotation is, therefore, tied to the frequency of the source. Since the frequency is fixed, the motor speed stays constant irrespective of the load or voltage of 3-phase supply. However, synchronous motors are not used so much because they run at constant speed (i.e., synchronous speed) but because they possess other unique electrical properties. In this chapter, we shall discuss the working and characteristics of synchronous motors.

6.2 Construction

A synchronous motor is a machine that operates at synchronous speed and converts electrical energy into mechanical energy. It is fundamentally an alternator operated as a motor. Like an alternator, a synchronous motor has the following two parts:

(i) a stator which houses 3-phase armaturewinding in the slots of the stator core and receives power from a 3-phase supply [See(Fig. (6.1)].

(ii) a rotor that has a set of salient poles excitedby direct current to form alternate N and S

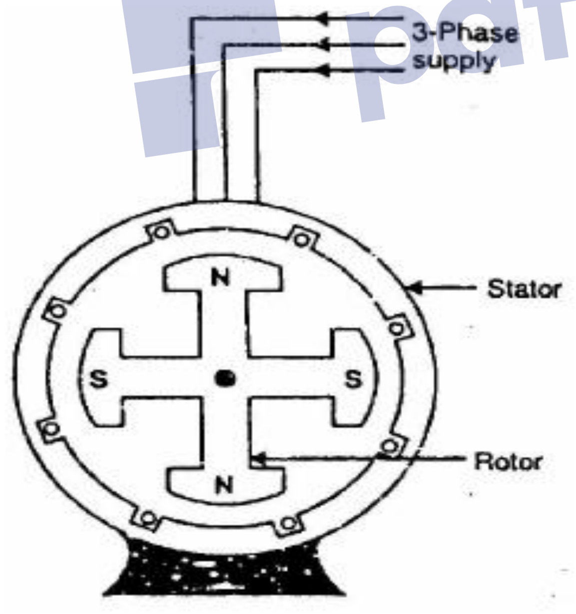


Fig 6.1

poles. The exciting coils are connected inseries to two slip rings and direct current isfed into the winding from an external excitermounted on the rotor shaft.The stator is wound for the same number of polesas the rotor poles. As in the case of an induction motor, the number of poles determines the synchronous speed of the motor:

Synchronous speed,

Ns = 120f/P
where f = frequency of supply in Hz
P = number of poles
An important drawback of a synchronous motor is that it is not self-starting and auxiliary means have to be used for starting it.

6.3 Some Facts about Synchronous Motor
Some salient features of a synchronous motor are:
(i) A synchronous motor runs at synchronous speed or not at all. Its speed is constant (synchronous speed) at all loads. The only way to change its speed is to alter the supply frequency (Ns = 120 f/P).
(ii) The outstanding characteristic of a synchronous motor is that it can be made to operate over a wide range of power factors (lagging, unity or leading) by adjustment of its field excitation. Therefore, a synchronous motor can be made to carry the mechanical load at constant speed and at the same time improve the power factor of the system.
(iii) Synchronous motors are generally of the salient pole type.
(iv) A synchronous motor is not self-starting and an auxiliary means has to be used for starting it. We use either induction motor principle or a separate starting motor for this purpose. If the latter method is used, the machine must be run up to synchronous speed and synchronized as an alternator.
6.4 Operating Principle
The fact that a synchronous motor has no starting torque can be easily explained.
(i) Consider a 3-phase synchronous motor having two rotor poles NR and SR. Then the stator will also be wound for two poles NS and SS. The motor has direct voltage applied to the rotor winding and a 3-phase voltage applied to the stator winding. The stator winding produces a rotating field which revolves round the stator at synchronous speed Ns(= 120 f/P). The direct (or zero frequency) current sets up a two-pole field which is stationary so long as the rotor is not turning. Thus, we have a situation in which there exists a pair of revolving armature poles (i.e., NS - SS) and a pair of stationary rotor poles (i.e., NR - SR).
(ii) Suppose at any instant, the stator poles are at positions A and B as shown in Fig. (6.1 (i)). It is clear that poles NS and NR repel each other and so do the poles SS and SR. Therefore, the rotor tends to move in the anticlockwise direction. After a period of half-cycle (or ½ f = 1/100 second), the polarities of the stator poles are reversed but the polarities of the rotor poles remain the same as shown in Fig. (6.1 (ii)). Now SS and NR attract
295
each other and so do NS and SR. Therefore, the rotor tends to move in the clockwise direction. Since the stator poles change their polarities rapidly, they tend to pull the rotor first in one direction and then after a period of half-cycle in the other. Due to high inertia of the rotor, the motor fails to start.

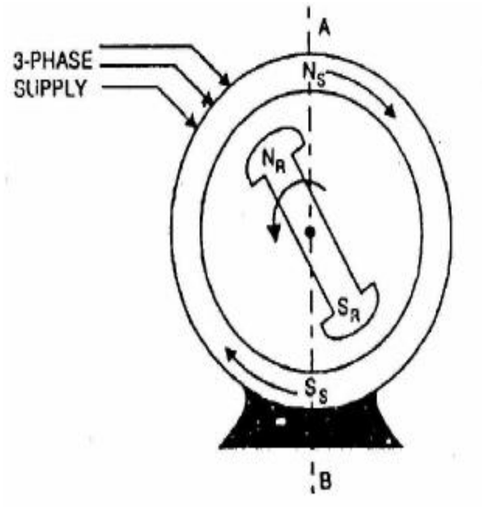


Fig 6.2

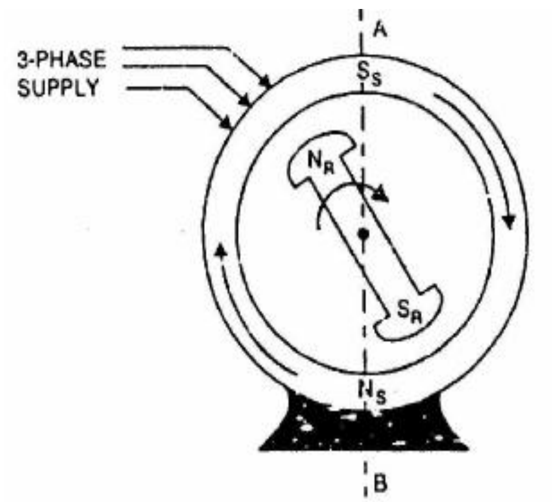
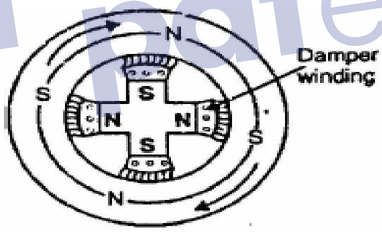


fig 6.3

Hence, a synchronous motor has no self-starting torque i.e., a synchronous motor cannot start by itself.

6.4 Making Synchronous Motor Self-Starting

A synchronous motor cannot start by itself. In orderto make the motor self-starting, a squirrel cagewinding (also called damper winding) is providedon the rotor. The damper winding consists



of copper bars fig 6.4

embedded in the pole faces of the salient polesof the rotor as shown in Fig. (6.4) The bars are short-circuited at the ends to form in effect a partialsquirrel cage winding. The damper windingservesto start the motor.

(i) To start with, 3-phase supply is given to the stator winding while the rotor field winding is left unenergized. The rotating stator field induces currents in the damper or squirrel cage winding and the motor starts as an induction motor.

(ii) As the motor approaches the synchronous speed, the rotor is excited with direct current. Now the resulting poles on the rotor face poles of opposite polarity on the stator and a strong magnetic attraction is set up between them. The rotor poles lock in with the poles of rotating flux. Consequently, the rotor revolves at the same speed as the stator field i.e., at synchronous speed.

(iii) Because the bars of squirrel cage portion of the rotor now rotate at the same speed as the rotating stator field, these bars do not cut any flux and, therefore, have no induced currents in them. Hence squirrel cage portion of the rotor is, in effect, removed from the operation of the motor.

It may be emphasized here that due to magnetic interlocking between the stator and rotor poles, a synchronous motor can only run at synchronous speed. At any other speed, this magnetic interlocking (i.e., rotor poles facing opposite polarity stator poles) ceases and the average torque becomes zero. Consequently, the motor comes to a halt with a severe disturbance on the line.

Note: It is important to excite the rotor with direct current at the right moment. For example, if the d.c. excitation is applied when N-pole of the stator faces Npole of the rotor, the resulting magnetic repulsion will produce a violent mechanical shock. The motor will immediately slow down and the circuit breakers will trip. In practice, starters for synchronous motors arc designed to detect the precise moment when excitation should be applied.

6.5 Equivalent Circuit

Unlike the induction motor, the synchronous motor is connected to two electrical systems; a d.c. source at the rotor terminals and an a.c. system at the stator terminals.

1. Under normal conditions of synchronous motor operation, no voltage is induced in the rotor by the stator field because the rotor winding is rotating at the same speed as the stator field. Only the impressed direct current is present in the rotor winding and ohmic resistance of this winding is the only opposition to it as shown in Fig. (6.4 (i)).

2. In the stator winding, two effects are to be considered, the effect of stator field on the stator winding and the effect of the rotor field cutting the stator conductors at synchronous speed.

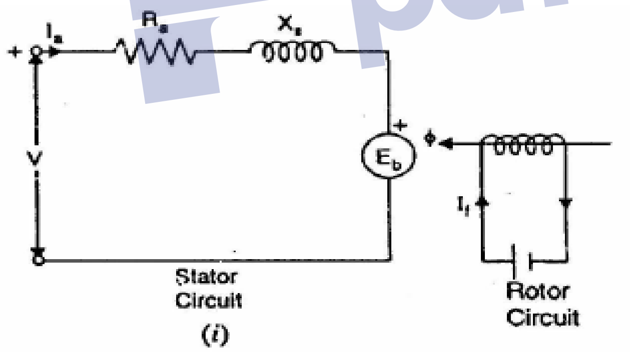


Fig 6.5

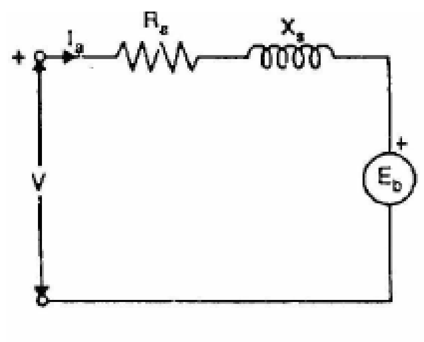


fig 6.6

(i) The effect of stator field on the stator (or armature) conductors is accounted for by including an inductive reactance in the armature winding. This is called synchronous reactance Xs. A resistance Ra must be considered to be in series with this reactance to account for the copper losses in the stator or armature winding as shown in Fig. (6.5 (i)). This resistance combines with synchronous reactance and gives the synchronous impedance of the machine.

(ii) The second effect is that a voltage is generated in the stator winding by the synchronously-revolving field of the rotor as shown in Fig. (6.5 (i)). This generated e.m.f. EB is known as back e.m.f. and opposes the stator voltage V. The magnitude of Eb depends upon rotor speed and rotor flux f per pole. Since rotor speed is constant; the value of Eb depends upon the rotor flux per pole i.e. exciting rotor current If.

Fig. (6.5 (i)) shows the schematic diagram for one phase of a star-connected synchronous motor while Fig. 6.5 (ii)) shows its equivalent circuit. Referring to the equivalent circuit in Fig. (6.5 (ii)).
Net voltage/phase in stator winding is
Er = V - Eb phasor difference
Armature current/phase,
where

$$I_a = \frac{E_r}{Z_s}$$

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

This equivalent circuit helps considerably in understanding the operation of a synchronous motor

A synchronous motor is said to be normally excited if the field excitation is such that Eb = V. If the field excitation is such that Eb < V, the motor is said to be under-excited. The motor is said to be over-excited if the field excitation is such that Eb > V. As we shall see, for both normal and under excitation, the motor has lagging power factor. However, for over-excitation, the motor has leading power factor.
Note: In a synchronous motor, the value of Xs is 10 to 100 times greater than Ra. Consequently, we can neglect Ra unless we are interested in efficiency or heating effects.

6.6 Motor on Load
In d.c. motors and induction motors, an addition of load causes the motor speed to decrease. The decrease in speed reduces the counter e.m.f. enough so that additional current is drawn from the source to carry the increased load at a reduced speed. This action cannot take place in a synchronous motor because it runs at a constant speed (i.e., synchronous speed) at all loads.
What happens when we apply mechanical load to a synchronous motor? The rotor poles fall slightly behind the stator poles while continuing to run at 299 r.p.m synchronous speed. The angular displacement between stator and rotor poles (called torque angle a) causes the phase of back e.m.f. Eb to change w.r.t. supply voltage V. This increases the net e.m.f. Er in the stator winding. Consequently, stator current Ia (= Er/Zs) increases to carry the load.

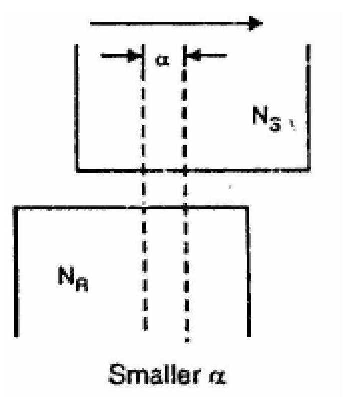


Fig 6.7

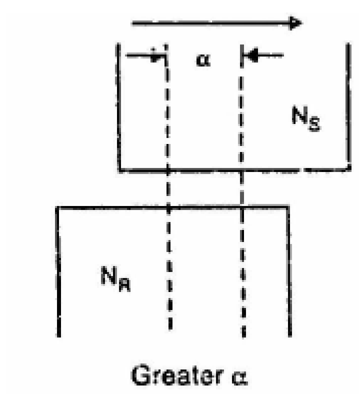


fig 6.8

The following points may be noted in synchronous motor operation:
(i) A synchronous motor runs at synchronous speed at all loads. It meets the increased load not by a decrease in speed but by the relative shift between stator and rotor poles i.e., by the adjustment of torque angle a.
(ii) If the load on the motor increases, the torque angle a also increases (i.e., rotor poles lag behind the stator poles by a greater angle) but the motor continues to run at synchronous speed. The increase in torque angle a causes a greater phase shift of back e.m.f. Eb w.r.t. supply voltage V. This increases the net voltage Er in the stator winding. Consequently, armature current Ia (= Er/Zs) increases to meet the load demand.
(iii) If the load on the motor decreases, the torque angle a also decreases. This causes a smaller phase shift of Eb w.r.t. V. Consequently, the net voltage Er in the stator winding decreases and so does the armature current
Ia (=Er/Zs).

6.7 Pull-Out Torque

There is a limit to the mechanical load that can be applied to a synchronous motor. As the load increases, the torque angle a also increases so that a stage is reached when the rotor is pulled out of synchronism and the motor comes to a standstill. This load torque at which the motor pulls out of synchronism is called pull—out or breakdown torque. Its value varies from 1.5 to 3.5 times the full—load torque.
When a synchronous motor pulls out of synchronism, there is a major disturbance on the line and the circuit breakers immediately trip. This protects the motor because both squirrel cage and stator winding heat up rapidly when the machine ceases to run at synchronous speed.

6.8 Motor Phasor Diagram

Consider an under-excited ^tar-connected synchronous motor (Eb < V) supplied with fixed excitation i.e., back e.m.f. Eb is constant-
Let V = supply voltage/phase
Eb = back e.m.f./phase
Zs = synchronous impedance/phase

(i) Motor on no load

When the motor is on no load, the torque angle a is small as shown in Fig. (11.7 (i)). Consequently, back e.m.f. Eb lags behind the supply voltage V by a small angle d as shown in the phasor diagram in Fig. (11.7 (iii)). The net voltage/phase in the stator winding, is Er.
Armature current/phase, Ia = Er/Zs
The armature current Ia lags behind Er by q = tan-1 Xs/Ra. Since Xs >> Ra, Ia lags Er by nearly 90°. The phase angle between V and Ia is f so that motor power factor is cos f
Input power/phase = V Ia cos f

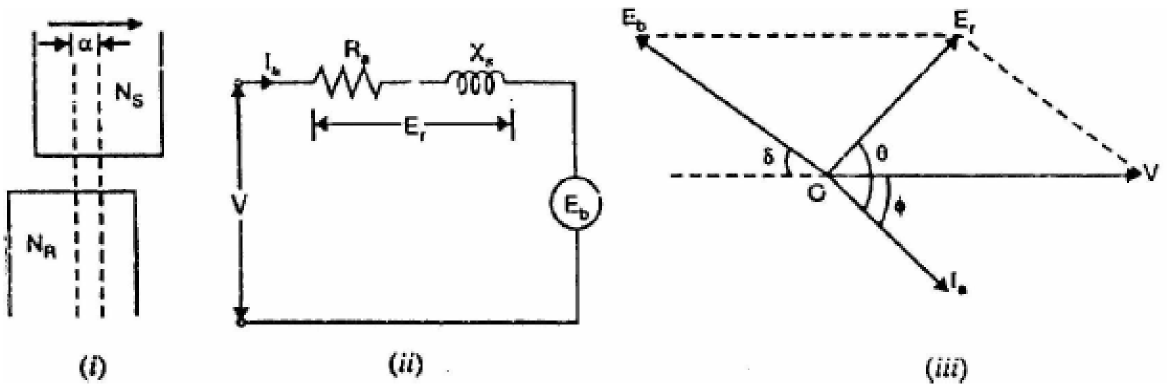


Fig 6.9

Thus at no load, the motor takes a small power VIa cos f/phase from the supply to meet the no-load losses while it continues to run at synchronous speed.

(ii) Motor on load

When load is applied to the motor, the torque angle a increases as shown in Fig. (6.9 (i)). This causes Eb (its magnitude is constant as excitation is fixed) to lag behind V by a greater angle as shown in the phasor diagram in Fig. (6.9 (ii)). The net voltage/phase Er in the stator winding increases. Consequently, the motor draws more armature current Ia (=Er/Zs) to meet the applied load. Again Ia lags Er by about 90° since Xs >> Ra. The power factor of the motor is cos f

Input power/phase, Pi = V Ia cos f

Mechanical power developed by motor/phase

Pm = Eb ´ ´ Ia ´ ´ cosine of angle between Eb and Ia

= Eb Ia cos(d - f)

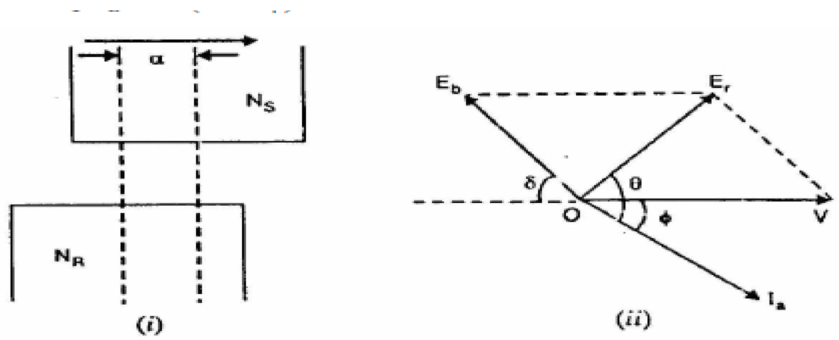


Fig 6.10

6.9 Effect of Changing Field Excitation at Constant Load

In a d.c. motor, the armature current Ia is determined by dividing the difference between V and Eb by the armature resistance Ra. Similarly, in a synchronous motor, the stator current (Ia) is determined by dividing voltage-phasor resultant (Er) between V and Eb by the synchronous impedance Zs.

One of the most important features of a synchronous motor is that by changing the field excitation, it can be made to operate from lagging to leading power factor. Consider a synchronous motor having a fixed supply voltage and driving a constant mechanical load. Since the mechanical load as well as the speed is constant, the power input to the motor (=3 VIa cos f) is also constant. This means that the in-phase component Ia cos f drawn from the supply will remain constant. If the field excitation is changed, back e.m.f Eb also changes. This results in the change of phase position of Ia w.r.t. V and hence the power factor cos f of the motor changes. Fig. (6.11) shows the phasor diagram of the synchronous motor for different values of field excitation. Note that extremities of current phasor Ia lie on the straight line AB.

(i) Under excitation

The motor is said to be under-excited if the field excitation is such that Eb < V. Under such conditions, the current Ia lags behind V so that motor power factor is lagging as shown in Fig. (6.11 (i)). This can be easily explained. Since Eb < V, the net voltage Er is decreased and turns clockwise. As angle q (= 90°) between Er and Ia is constant, therefore, phasor Ia also turns clockwise i.e., current Ia lags behind the supply voltage. Consequently, the motor has a lagging power factor.

(ii) Normal excitation

The motor is said to be normally excited if the field excitation is such that Eb = V. This is shown in Fig. (6.11 (ii)). Note that the effect of increasing excitation (i.e., increasing Eb) is to turn the phasor Er and hence Ia in the anti-clockwise direction i.e., Ia phasor has come closer to phasor V. Therefore, p.f. increases though still lagging. Since input power (=3 V Ia cos f) is unchanged, the stator current Ia must decrease with increase in p.f.

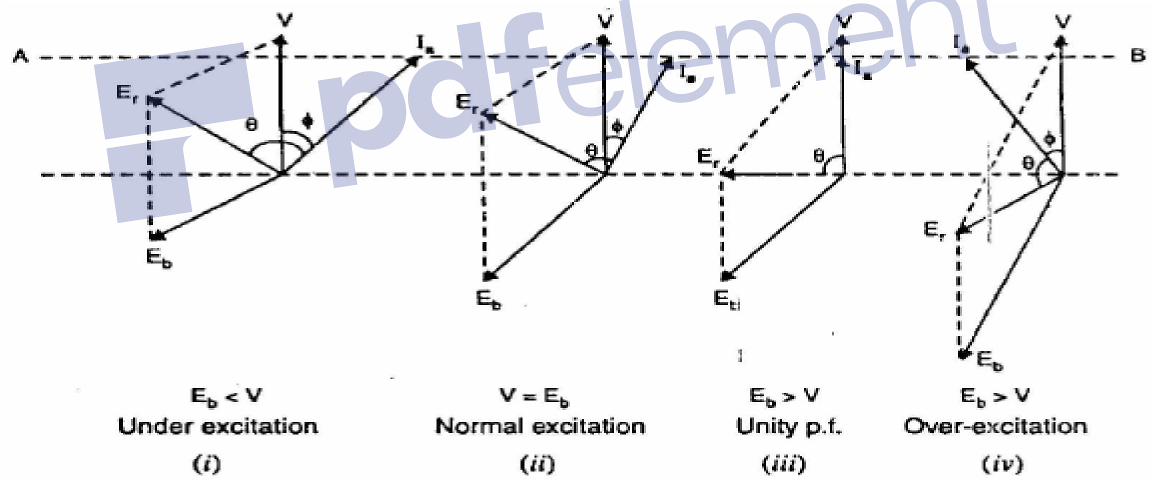


Fig 6.11

Suppose the field excitation is increased until the current Ia is in phase with the applied voltage V, making the p.f. of the synchronous motor unity [See Fig. (6.11 (iii))]. For a given load, at unity p.f. the resultant Er and, therefore, Ia are minimum.

(iii) Over excitation

The motor is said to be overexcited if the field excitation is such that Eb > V. Under-such conditions, current Ia leads V and the motor power factor is leading as shown in Fig. 6.10 (iv)). Note that Er and hence Ia further turn anti-clockwise from the normal excitation position. Consequently, Ia leads V.

From the above discussion, it is concluded that if the synchronous motor is under-excited, it has a lagging power factor. As the excitation is increased, the power factor improves till it becomes unity at normal excitation. Under such conditions, the current drawn from the supply is minimum. If the excitation is further increased (i.e., over excitation), the motor power factor becomes leading. ***Note***. The armature current (Ia) is minimum at unity p.f and increases as the power factor becomes poor, either leading or lagging.

6.10 Phasor Diagrams With Different Excitations

Fig. (6.12) shows the phasor diagrams for different field excitations at constant load. Fig. (6.12 (i)) shows the phasor diagram for normal excitation (Eb = V), whereas Fig. (6.12 (ii)) shows the phasor diagram for under-excitation. In both cases, the motor has lagging power factor.

Fig. (6.12 (iii)) shows the phasor diagram when field excitation is adjusted for unity p.f. operation. Under this condition, the resultant voltage Er and, therefore, the stator current Ia are minimum. When the motor is overexcited, it has leading power factor as shown in Fig. (6.12 (iv)). The following points may be remembered:

(i) For a given load, the power factor is governed by the field excitation; a weak field produces the lagging armature current and a strong field produces a leading armature current.

(ii) The armature current (Ia) is minimum at unity p.f and increases as the p.f. becomes less either leading or lagging.

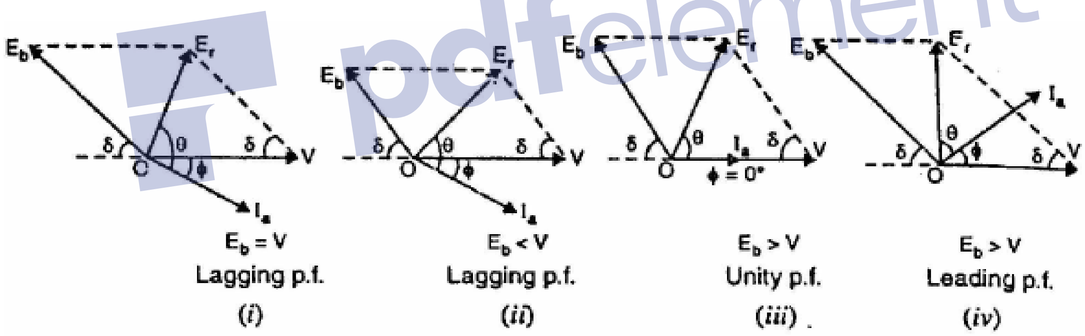


Fig 6.12

6.11 Motor Torque

Gross torque, T =9.55 Pm/ns N-M where Pm = Gross motor output in watts = Eb Ia cos(d - f)

Ns = Synchronous speed in r.p.m.

Shaft torque, Tsh = 9.55 Psoutsh/ns N-M =

It may be seen that torque is directly proportional to the mechanical power because rotor speed (i.e., Ns) is fixed.

6.12 Mechanical Power Developed By Motor

(Armature resistance neglected)Fig. (6.13) shows the phasor diagram of anunder-excited synchronous motor driving amechanical load. Since armature resistance Ra isassumed zero. tanq= Xs/Ra = ¥ and hence q =90°.

Input power/phase = V Ia cos f

Since Ra is assumed zero, stator Cu loss (I Ra)

2a will be zero. Hence input poweris equal to the mechanical power Pm developed by the motor.Mech. power developed/ phase, Pm = V Ia cos f (i)Referring to the phasor diagram in Fig. fig (6.13),

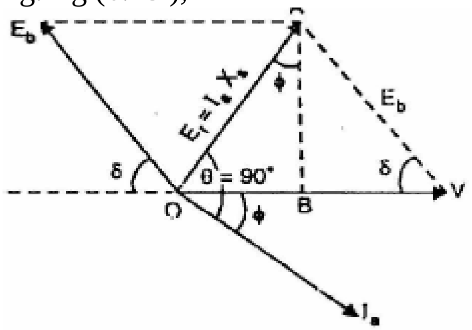


fig 6.13

$$AB = E_r \cos\phi = I_a X_s \cos\phi$$

$$AB = E_b \sin\delta$$

$$E_b \sin\delta = I_a X_s \cos\phi$$

$$I_a \cos\phi = \frac{E_b \sin\delta}{X_s}$$

Substituting the value of $I_a \cos\phi$ in exp. (i) above,

$$P_m = \frac{V E_b}{X_s} \quad \text{per phase}$$

$$= \frac{V E_b}{X_s} \quad \text{for 3-phase}$$

It is clear from the above relation that mechanical power increases with torque angle (in electrical degrees) and its maximum value is reached when $\delta = 90°$ (electrical).

$$P_{max} = \frac{V E_b}{X_s} \quad \text{per phase}$$

Under this condition, the poles of the rotor will be mid-way between N and S poles of the stator.

6.13 Power Factor of Synchronous Motors

In an induction motor, only one winding (i.e., stator winding) produces the necessary flux in the machine. The stator winding must draw reactive power from the supply to set up the flux. Consequently, induction motor must operate at lagging power factor.

But in a synchronous motor, there are two possible sources of excitation; alternating current in the stator or direct current in the rotor. The required flux may be produced either by stator or rotor or both.

(i) If the rotor exciting current is of such magnitude that it produces all the required flux, then no magnetizing current or reactive power is needed in the stator. As a result, the motor will operate at unity power factor.

(ii) If the rotor exciting current is less (i.e., motor is under-excited), the deficit in flux is made up by the stator. Consequently, the motor draws reactive power to provide for the remaining flux. Hence motor will operate at a lagging power factor.

(iii) If the rotor exciting current is greater (i.e., motor is over-excited), the excess flux must be counterbalanced in the stator. Now the stator, instead of absorbing reactive power, actually delivers reactive power to the 3-phase line. The motor then behaves like a source of reactive power, as if it were a capacitor. In other words, the motor operates at a leading power factor.

To sum up, a synchronous motor absorbs reactive power when it is underexcited and delivers reactive power to source when it is over-excited.

6.14 Synchronous Condenser

A synchronous motor takes a leading current when over-excited and, therefore, behaves as a capacitor.

An over-excited synchronous motor running on no-load in known as synchronous condenser.

When such a machine is connected in parallel with induction motors or other devices that operate at low lagging power factor, the leading kVAR supplied by the synchronous condenser partly neutralizes the lagging reactive kVAR of the loads. Consequently, the power factor of the system is improved.

Fig. (11.14) shows the power factor improvement by synchronous condenser method. The 3 - f load takes current IL at low lagging power factor cos fL. The synchronous condenser takes a current Im which leads the voltage by an angle fm. The resultant current I is the vector sum of Im and IL and lags behind the voltage by an angle f. It is clear that f is less than fL so that cos f is greater than cos fL. Thus the power factor is increased from cos fL to cos f. Synchronous condensers are generally used at major bulk supply substations for power factor improvement

Advantages

(i) By varying the field excitation, the magnitude of current drawn by the motor can be changed by any amount. This helps in achieving stepless control of power factor.

(ii) The motor windings have high thermal stability to short circuit currents.

(ii) The faults can be removed easily.

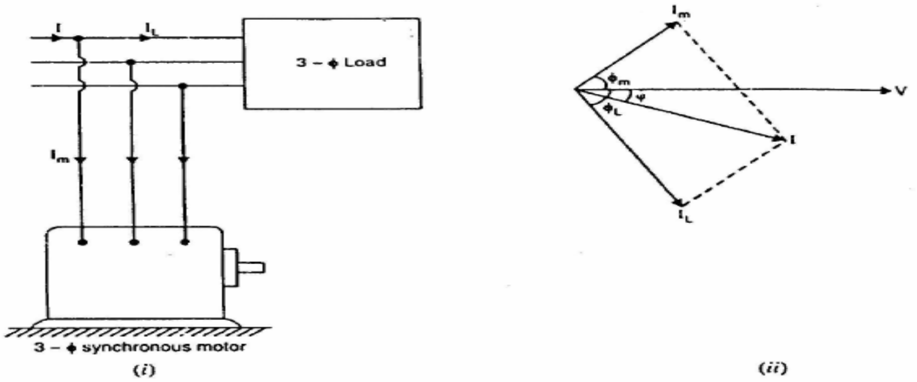


Fig 6.14

Disadvantages

(i) There are considerable losses in the motor.

(ii) The maintenance cost is high.

(iii) It produces noise.
(iv) Except in sizes above 500 RVA, the cost is greater than that of static capacitors of the same rating.
(v) As a synchronous motor has no self-starting torque, then-fore, an auxiliary equipment has to be provided for this purpose.

6.15 Applications of Synchronous Motors

(i) Synchronous motors are particularly attractive for low speeds (< 300 r.p.m.) because the power factor can always be adjusted to unity and efficiency is high.
(ii) Overexcited synchronous motors can be used to improve the power factor of a plant while carrying their rated loads.
(iii) They are used to improve the voltage regulation of transmission lines.
(iv) High-power electronic converters generating very low frequencies enable us to run synchronous motors at ultra-low speeds. Thus huge motors in the 10 MW range drive crushers, rotary kilns and variable-speed ball mills.

UNIT 3. INDUCTION MOTORS

OBJECTIVE

The aim of this chapter is to gather knowledge about the following topics of Induction motors.

1. Construction, types and principle of operation of 3-phase induction motors.
2. Equivalent circuit of 3-phase induction motor.
3. The performance calculation by means of finding torque, slip and efficiency.
4. Different types of starters like auto-transformer starter, star-delta starter.
5. Various methods of speed control 3-phase induction motor.
6. Principle of operation of single phase induction motor.

INTRODUCTION

An **induction motor** (IM) is a type of asynchronous AC motor where power is supplied to the rotating device by means of electromagnetic induction.

The induction motor with a wrapped rotor was invented by Nikola Tesla Nikola Tesla in 1882 in France but the initial patent was issued in 1888 after Tesla had moved to the United States. In his scientific work, Tesla laid the foundations for understanding the way the motor operates. The induction motor with a cage was invented by Mikhail Dolivo-Dobrovolsky about a year later in Europe. Technological development in the field has improved to where a 100 hp (74.6 kW) motor from 1976 takes the same volume as a 7.5 hp (5.5 kW) motor did in 1897. Currently, the most common induction motor is the cage rotor motor.

An electric motor converts electrical power to mechanical power in its rotor (rotating part). There are several ways to supply power to the rotor. In a DC motor this power is supplied to the armature directly from a DC source, while in an induction motor this power is induced in the rotating device. An induction motor is sometimes called a *rotating transformer* because the stator (stationary part) is essentially the primary side of the transformer and the rotor (rotating part) is the secondary side. Induction motors are widely used, especially polyphase induction motors, which are frequently used in industrial drives.

Induction motors are now the preferred choice for industrial motors due to their rugged construction, absence of brushes (which are required in most DC motors) and the ability to control the speed of the motor.

CONSTRUCTION

A typical motor consists of two parts namely stator and rotor like other type of motors.

1. An outside stationary stator having coils supplied with AC current to produce a rotating magnetic field,
2. An inside rotor attached to the output shaft that is given a torque by the rotating field.

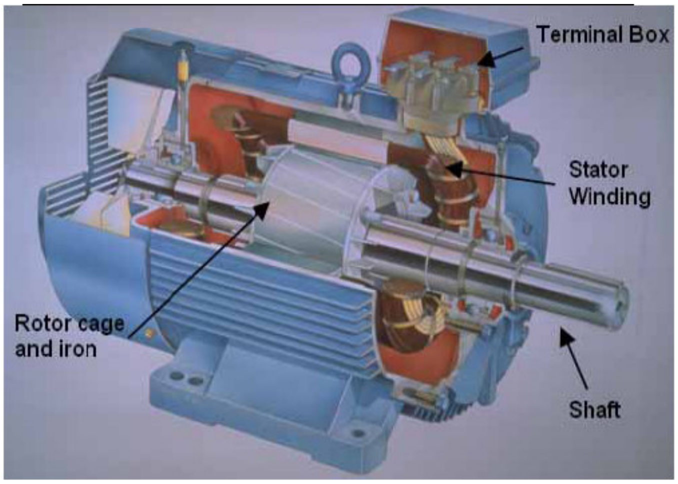


Figure. Induction motor construction

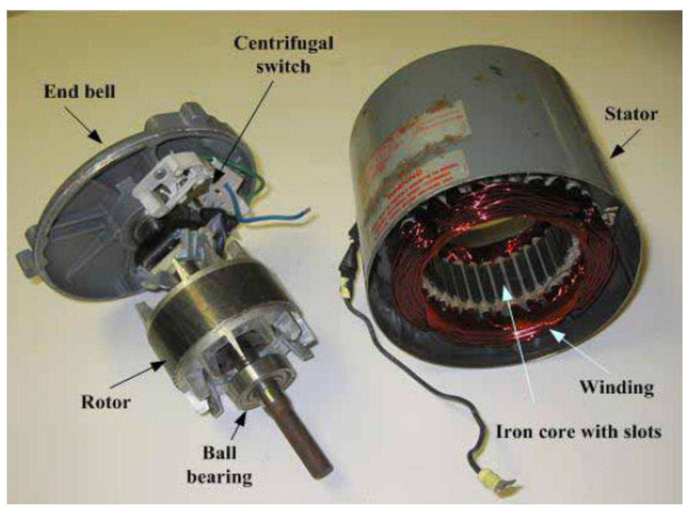


Figure. Induction motor components.

Stator construction

The stator of an induction motor is laminated iron core with slots similar to a stator of a synchronous machine. Coils are placed in the slots to form a three or single phase winding.

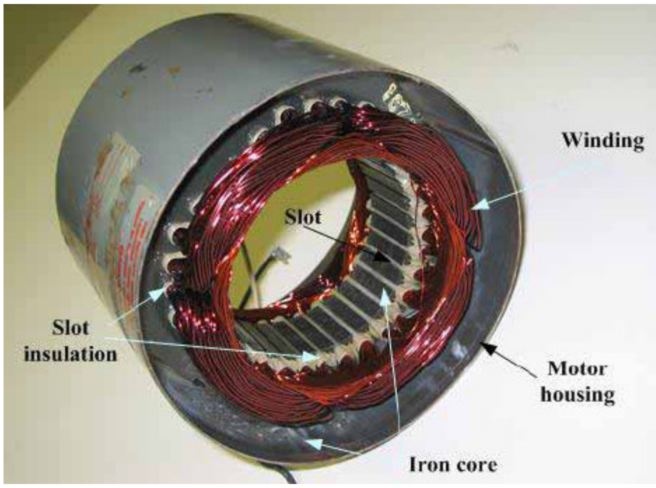


Figure. Single phase stator with windings.

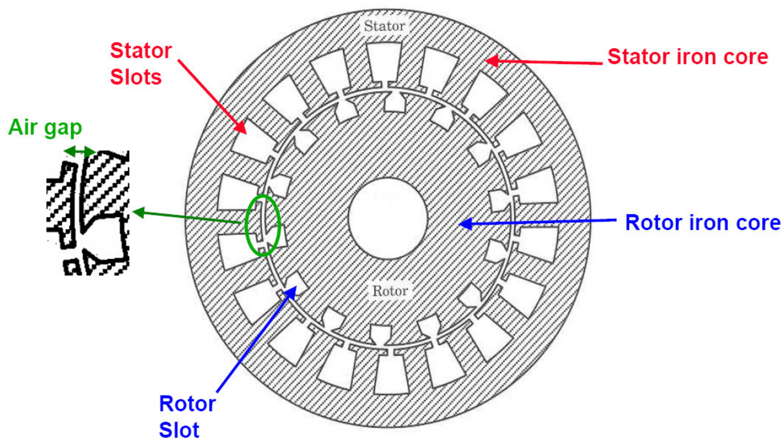


Figure. Induction motor magnetic circuit showing stator and rotor slots

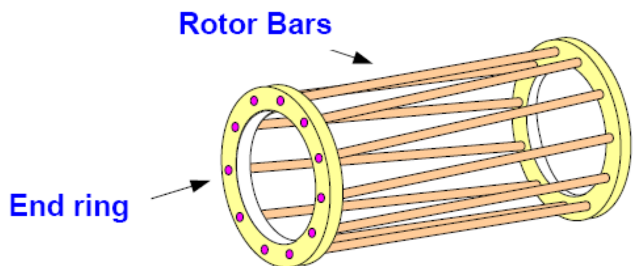
Type of rotors

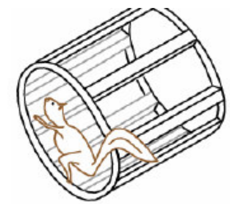
Rotor is of two different types.

1. Squirrel cage rotor
2. Wound rotor

Squirrel-Cage Rotor

In *the squirrel-cage rotor*, the rotor winding consists of single copper or aluminium bars placed in the slots and short-circuited by end-rings on both sides of the rotor. Most of single phase induction motors have Squirrel-Cage rotor. One or 2 fans are attached to the shaft in the sides of rotor to cool the circuit.





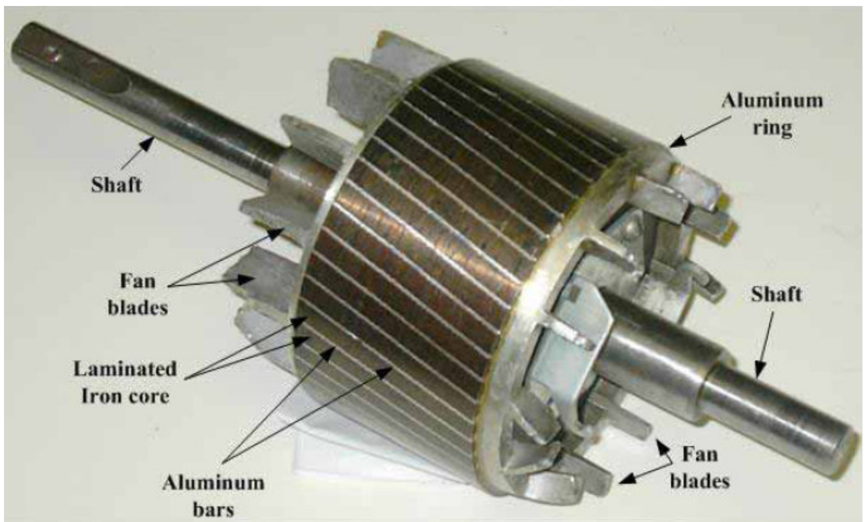


Figure. Squirrel cage rotor

Wound Rotor

In the *wound rotor,* an insulated 3-phase winding similar to the stator winding wound for the same number of poles as stator, is placed in the rotor slots. The ends of the star-connected rotor winding are brought to three slip rings on the shaft so that a connection can be made to it for starting or speed control.

- It is usually for large 3 phase induction motors.
- Rotor has a winding the same as stator and the end of each phase is connected to a slip ring.
- Compared to squirrel cage rotors, wound rotor motors are expensive and require maintenance of the slip rings and brushes, so it is not so common in industry applications.

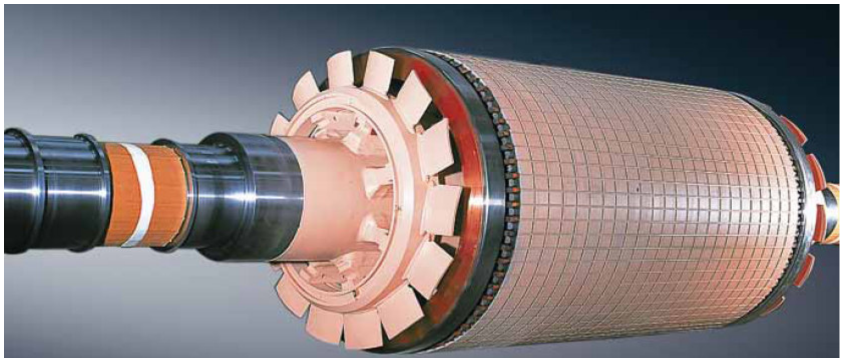


Figure. Wound rotor of a large induction motor. (Courtesy Siemens).

PRINCIPLE OF OPERATION

- An AC current is applied in the stator armature which generates a flux in the stator magnetic circuit.
- This flux induces an emf in the conducting bars of rotor as they are "cut" by the flux while the magnet is being moved ($E = BV$L (Faraday's Law))
- A current flows in the rotor circuit due to the induced emf, which in term produces a force, ($F = BI$L) can be changed to the torque as the output.

In a 3-phase induction motor, the three-phase currents i_a, i_b and $i_{c,}$ each of equal magnitude, but differing in phase by 120°. Each phase current produces a magnetic flux and there is physical 120 °shift between each flux. The total flux in the machine is the sum of the three fluxes. The summation of the three ac fluxes results in a rotating flux, which turns with constant speed and has constant amplitude. Such a magnetic flux produced by balanced three phase currents flowing in thee-phase windings is called a rotating magnetic flux or rotating magnetic field (RMF).RMF rotates with a constant speed (Synchronous Speed). Existence of a RFM is an essential condition for the operation of an induction motor.

If stator is energized by an ac current, RMF is generated due to the applied current to the stator winding. This flux produces magnetic field and the field revolves in the air gap between stator and rotor. So, the magnetic field induces a voltage in the short-circuited bars of the rotor. This voltage drives current through the bars. The interaction of the rotating flux and the rotor current generates a force that drives the motor and a torque is developed consequently. The torque is proportional with the flux density and the rotor bar current (F=BLI). The motor speed is less than the synchronous speed. The direction of the rotation of the rotor is the same as the direction of the rotation of the revolving magnetic field in the air gap.

However, for these currents to be induced, the speed of the physical rotor and the speed of the rotating magnetic field in the stator must be different, or else the magnetic field will not be moving relative to the rotor conductors and no currents will be induced. If by some chance this happens, the rotor typically slows slightly until a current is re-induced and then the rotor continues as before. This difference between the speed of the rotor and speed of the rotating magnetic field in the stator is called *slip*. It is unitless and is the ratio between the relative speed of the magnetic field as seen by the rotor the (*slip speed*) to the speed of the rotating stator field. Due to this an induction motor is sometimes referred to as an asynchronous machine.

SLIP

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

$$n_s = \frac{120f}{p}$$

The stator magnetic field (rotating magnetic field) rotates at a speed, n_s, the synchronous speed. If, n= speed of the rotor, the slip, s for an induction motor is defined as

$$s = \frac{n_s - n}{n_s}$$

At stand still, rotor does not rotate , n = 0, so s = 1.

At synchronous speed, $n = n_S$, s = 0

The mechanical speed of the rotor, in terms of slip and synchronous speed is given by,

$$n=(1-s)\, n_s$$

Frequency of Rotor Current and Voltage

With the rotor at stand-still, the frequency of the induced voltages and currents is the same as that of the stator (supply) frequency, f_e.

If the rotor rotates at speed of n, then the relative speed is the slip speed:

$$n_{slip}=n_s-n$$

n_{slip} is responsible for induction.

Hence, the frequency of the induced voltages and currents in the rotor is, $f_r = sf_e$.

Example1:

A three-phase, 20 hp, 208 V, 60 Hz, six pole, wye connected induction motor delivers 15 kW at a slip of 5%.

Calculate:

a) Synchronous speed
b) Rotor speed
c) Frequency of rotor current

Solution:

Synchronous speed: $n_s = 120\, f / p = (120*60) / 6 = 1200$ rpm

Rotor speed: $n_r = (1-s)\, n_s = (1- 0.05)\,(1200) = 1140$ rpm

Frequency of rotor current: $f_r = s\, f = (0.05)\,(60) = 3$ Hz

EQUIVALENT CIRCUIT

The induction motor consists of a two magnetically connected systems namely, stator and rotor. This is similar to a transformer that also has two magnetically connected systems namely primary and secondary windings. Also, the induction motor operates on the same principle as the transformer. Hence, the induction motor is also called as rotating transformer

The stator is supplied by a balanced three-phase voltage that drives a three-phase current through the winding. This current induces a voltage in the rotor. The applied voltage (V_1) across phase A is equal to the sum of the

–induced voltage (E_1).

–voltage drop across the stator resistance (I_1R_1).

–voltage drop across the stator leakage reactance ($I_1\, j\, X_1$).

Let

I_1 = stator current/phase

R_1 = stator winding resistance/phase

X_1 = stator winding reactance/phase

R_R = stator winding resistance/phase

X_R = stator winding reactance/phase

I_R = rotor current

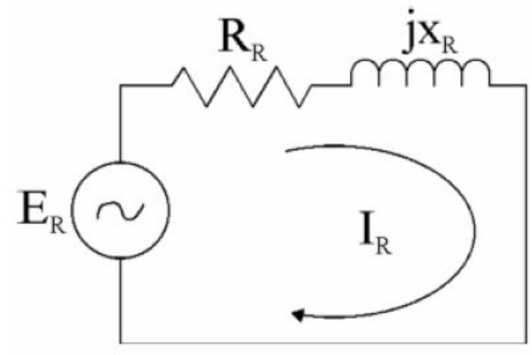
V_1 = applied voltage to the stator/phase

$I_o = I_c + I_m$ (Im-magnetising component, Ic-core loss component)

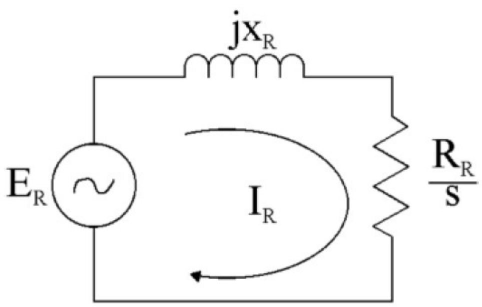
Rotor circuit alone

$$I_R = \frac{E_R}{R_R + jX_R} = \frac{s \cdot E_{R_0}}{R_R + s \cdot jX_{R_0}}$$

$$I_R = \frac{E_{R_0}}{\frac{R_R}{s} + jX_{R_0}}$$



The rotor circuit can be represented as



So, the induction motor can be represented as

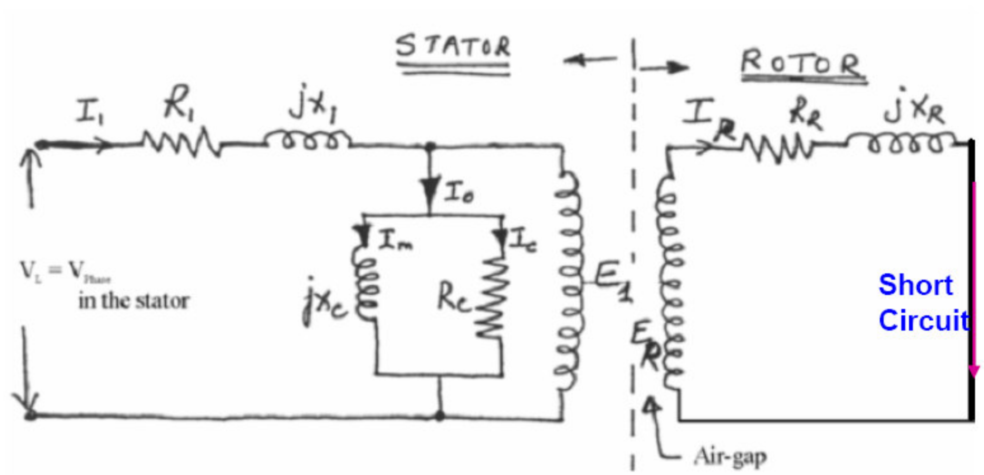


Figure. Equivalent circuit of one phase out of 3 phase of an induction motor

Transformation is done using the effective turns ratio, $a_{eff}$for currents.

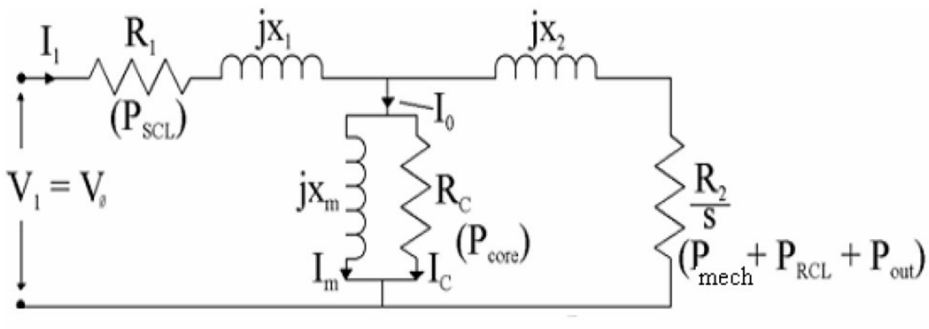
$$I_2 = \frac{I_R}{a_{eff}}$$

Impedance transfer is made using the ratio a_{eff}^2; where R_2 and X_2 are transferred values.

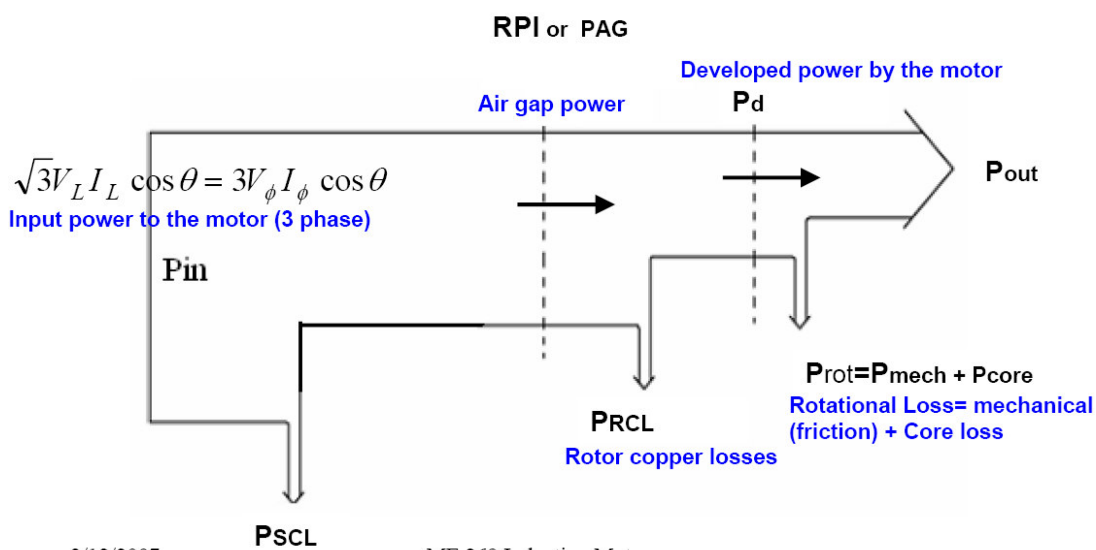
$R_2 = a_{eff}^2 R_R$

$X_2 = a_{eff}^2 X_R$

Equivalent circuit referred to stator is



POWER FLOW



where

P_{SCL} – stator copper losses

P_{RCL} – rotor copper losses

RPI – rotor power input

The concept of the total air gap power can be introduced where:

$$P = P_{ag} = I_2^2 . \frac{R_2}{s} = I_2^2 .(R_2 + \frac{R_2}{s} - \frac{R_2 . s}{s})$$

$$= I_2^2 .(R_2 + \frac{R_2}{s}(1-s))$$

The mechanical power however is only developed across the new variable resistance, hence P_{mech} is:

$$P_{mech} = I_2^2 . \frac{R_2}{s}(1-s)$$

$$= (1-s).P_{ag}$$

$$= \frac{1-s}{s}.P_2$$

As the rotor copper loss is $P_2 = I_2^2R_2 = sP_g$ then a ratio of powers can be defined:

$$P_{ag} : P_2 : P_{mech} = 1 : s : (1-s)$$

The motor torque is given by

$$T_{mech} = \frac{P_{mech}}{\omega_{mech}} = \frac{I_2^2 . \frac{R_2}{s}.(1-s)}{\omega_{synch}.(1-s)} = \frac{1}{\omega_{synch}}.I_2^2 . \frac{R_2}{s}$$

The ideal efficiency can be determined by firstly assuming that the power transferred across the air gap equals the input power.

$$P_{ag} = P_{in}$$

$$P_2 = s.P_{ag}$$

$$P_{out} = P_{mech} = P_{ag}.(1-s)$$

Therefore efficiency is given by

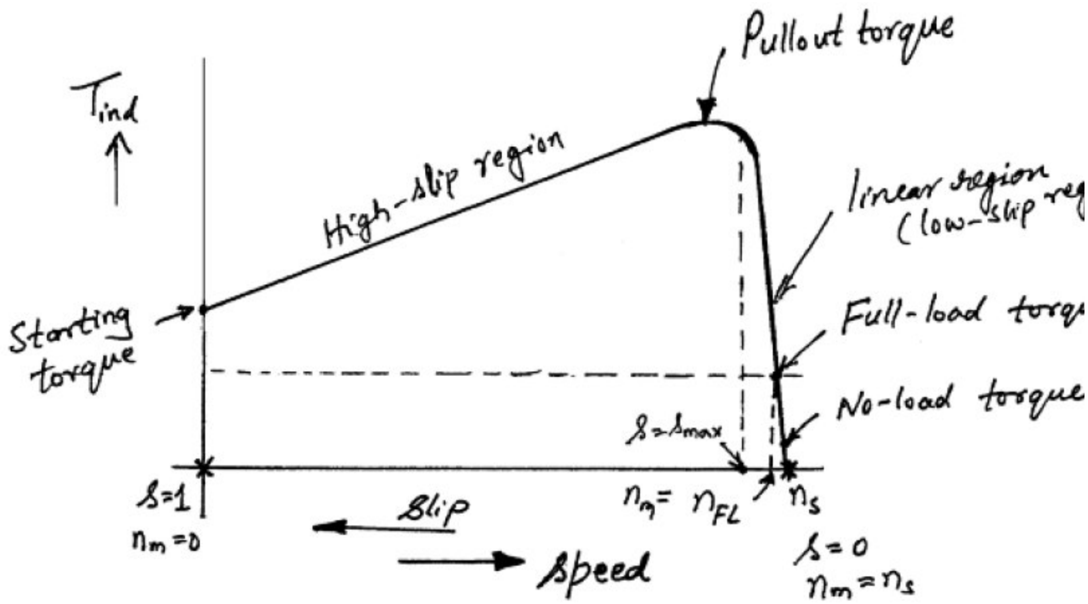
$$Eff_{ideal} = \frac{P_{out}}{P_{in}} = \frac{P_{ag}.(1-s)}{P_{ag}} = (1-s)$$

The efficiency increases as the speed increases, hence an induction machine should always be operated at low values of slip to ensure efficient (and high power factor) operation

TORQUE – SPEED CHARACTERISTICS

For small values of slip *s*, the torque is directly proportional to *s*.

For large values of slip s, the torque is inversely proportional to s.



Example 2

A 480 V, 50 hp, three phase induction motor is drawing 60 A at 0.85 pf lagging. The stator copper losses are 2 kW and the rotor copper losses are 700 W. The friction loss is 600 W and the core losses are 1800 W, find:

- The air gap power.
- The converted power.
- The output power.
- The efficiency of the motor.

Solution

a) $P_{in} = \sqrt{3} V_T I_L \cos(\theta)$

$P_{in} = \sqrt{3}(480)(60)(0.85) = 42.4 \text{ kW}$

$P_{AG} = P_{in} - P_{SCL} = 42.4 - 2 = 40.4\text{kW}$

b) $P_d = P_{AG} - P_{RCL} = 40.4 - 0.7 = 39.7 \text{ kW}$

c) $P_{out} = P_d - P_{rot} = 39.7 - 2.4 = 37.3 \text{ kW}$

d) $\eta = \frac{P_{out}}{P_{in}} = \frac{37.3}{42.4} = 88\%$

Example 3

A 460 V, 25 hp, 60 Hz, four pole, Y-connected induction motor has the following impedances:

$R_1 = 0.641\ \Omega$ $R_2 = 0.332\ \Omega$
$X_1 = 1.106\ \Omega$ $X_2 = 0.464\ \Omega$ $X_m = 26.3\ \Omega$
Mechanical loss is 100 W and core loss is 1 kW for a slip = 2.2%, find:

(a) The speed.
(b) The stator current.
(c) Power factor
(d) The developed and output power
(e) The developed and output torque
(f) Efficiency

Solution:

a) $n_s = \frac{120 f}{P} = \frac{(120)(60)}{4} = 1800 \text{ rpm}$

$n_m = (1-s)n_s = (1-.022)(1800) = 1760 \text{ rpm}$

b) $Z_{total} = \left\{ (\frac{R_2}{s} + jx_2) \parallel (jx_m) \right\} + (R_1 + jx_1) = 14.0$

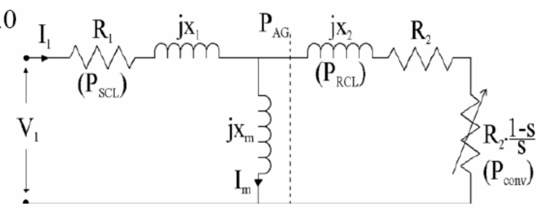
$I_1 = \frac{V_{phase}}{Z_{total}} = 18.88\angle -33.6$

c) $p.f. = \cos(33.6) = 0.833\ lagging$

d) $P_{in} = \sqrt{3}(480)(18.88)(0.833) = 12.53 \text{ kW}$

$P_{SCL} = 3I_1^{\ 2}R_1 = 3(18.88)^2(0.641) = 685 \text{ W}$

$P_{AG} = P_{in} - P_{SCL} = 12{,}530 - 685 = 11.845 \text{kW}$



STARTING OF 3-PHASE INDUCTION MOTORS

There are two important factors to be considered in starting of induction motors:

1. The starting current drawn from the supply, and
2. The starting torque.

The starting current should be kept low to avoid overheating of motor and excessive voltage drops in the supply network. The starting torque must be about 50 to 100% more than the expected load torque to ensure that the motor runs up in a reasonably short time.

- At synchronous speed, s = 0, and therefore , $\frac{R_2}{s} = \infty$ .so $I_2' = 0$.
- The stator current therefore comprises only the magnetising current i.e. $I_1 = I_\varphi$ and is quite therefore quite small.

- At low speeds, $\frac{R_2'}{s} + jX_2 = \infty$ is small, and therefore I_2' is quite high and consequently I_1 is quite large.
- Actually the typical starting currents for an induction machine are ~ 5 to 8 times the normal running current.

Hence the starting currents should be reduced. The most usual methods of starting 3-phase induction motors are:

For slip-ring motors

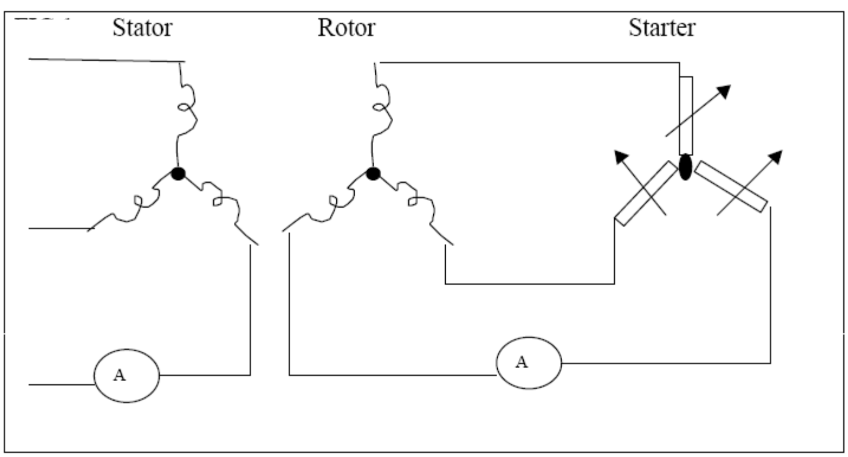
- Rotor resistance starting

For squirrel-cage motors

- Direct-on -line starting
- Star-delta starting
- Autotransformer starting.

1. Rotor resistance starting

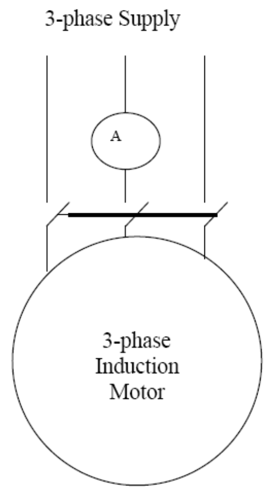
By adding eternal resistance to the rotor circuit any starting torque up to the maximum torque can be achieved; and by gradually cutting out the resistance a high torque can be maintained throughout the starting period. The added resistance also reduces the starting current, so that a starting torque in the range of 2 to 2.5 times the full load torque can be obtained at a starting current of 1 to 1.5 times the full load current.



2. Direct-on-line starting

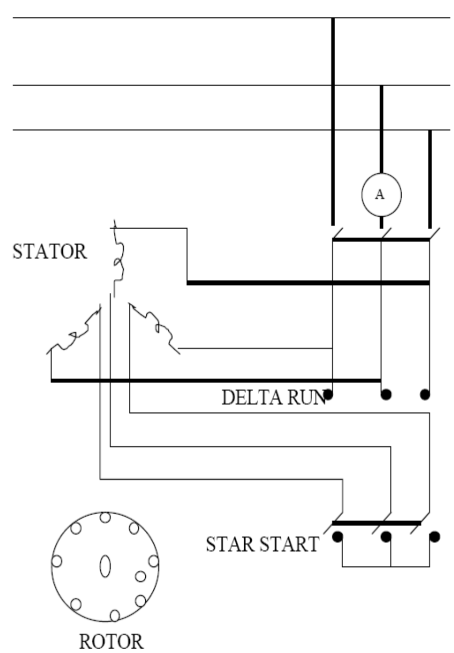
This is the most simple and inexpensive method of starting a squirrel cage induction motor. The motor is switched on directly to full supply voltage. The initial starting current is large, normally about 5 to 7 times the rated current but the starting torque is likely to be 0.75 to 2 times the full load torque. To avoid excessive supply voltage drops because of large starting currents the method is restricted to small motors only.

To decrease the starting current cage motors of medium and larger sizes are started at a reduced supply voltage. The reduced supply voltage starting is applied in the next two methods.



3. Star-Delta starting

This is applicable to motors designed for delta connection in normal running conditions. Both ends of each phase of the stator winding are brought out and connected to a 3-phase change -over switch.

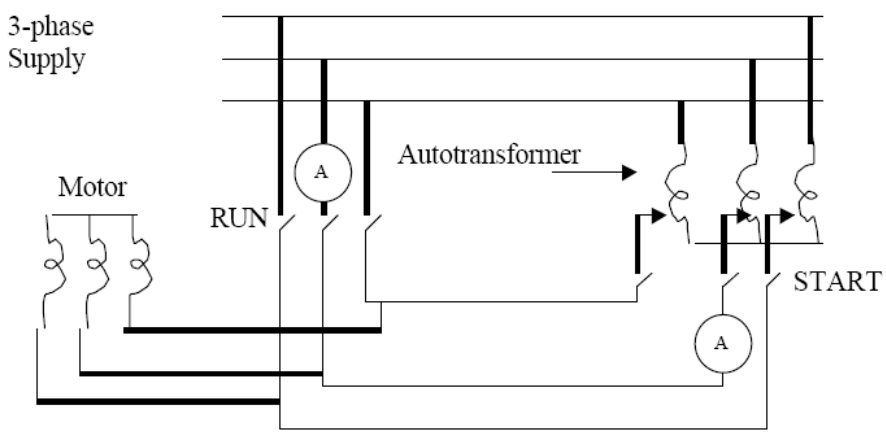


For starting, the stator windings are connected in star and when the machine is running the switch is thrown quickly to the running position, thus connecting the motor in delta for normal operation. The phase voltages & the phase currents of the motor in star connection are reduced to $1/\sqrt{3}$ of the direct -on -line values in delta. The line current is 1/3 of the value in delta.

A disadvantage of this method is that the starting torque (which is proportional to the square of the applied voltage) is also reduced to 1/3 of its delta value.

4. Auto-transformer starting

This method also reduces the initial voltage applied to the motor and therefore the starting current and torque. The motor, which can be connected permanently in delta or in star, is switched first on reduced voltage from a 3-phase tapped auto -transformer and when it has accelerated sufficiently, it is switched to the running (full voltage) position. The principle is similar to star/delta starting and has similar limitations. The advantage of the method is that the current and torque can be adjusted to the required value, by taking the correct tapping on the autotransformer. This method is more expensive because of the additional autotransformer.



SPEED CONTROL OF INDUCTION MACHINES

We have seen the speed torque characteristic of the machine. In the stable region of operation in the motoring mode, the curve is rather steep and goes from zero torque at synchronous speed to the stall torque at a value of slip s = ˆs. Normally ˆs may be such that stall torque is about three times that of the rated operating torque of the machine, and hence may be about 0.3 or less. This means that in the entire loading range of the machine, the speed change is quite small. The machine speed is quite stiff with respect to load changes. The entire speed variation is only in the range n_s to $(1 - s)n_s$, n_s being dependent on supply frequency and number of poles.

The foregoing discussion shows that 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.

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 figure below. These curves show that the slip at maximum torque 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.

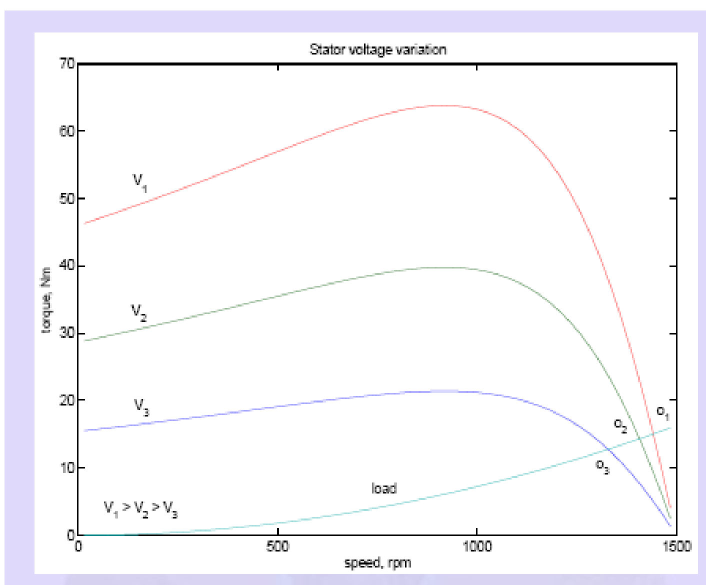


Figure. Speed-torque curves: voltage variation

The figure above 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 α ω^2. Here one can see that it may be possible to run the motor to lower speeds within the range n_s to $(1 - s)n_s$. Further, since the load torque at zero speed is zero, the machine can start even at reduced voltages. This will not be possible with constant torque type of loads. One may note that if the applied voltage is reduced, the voltage across the magnetizing 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 figure.

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. Another use of voltage control is in the so-called 'soft-start' of the machine. This is discussed in the section on starting methods.

2. Rotor resistance control

From the expression for the torque of the induction machine, torque is dependent on the rotor resistance. 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. Figure below 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.

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.

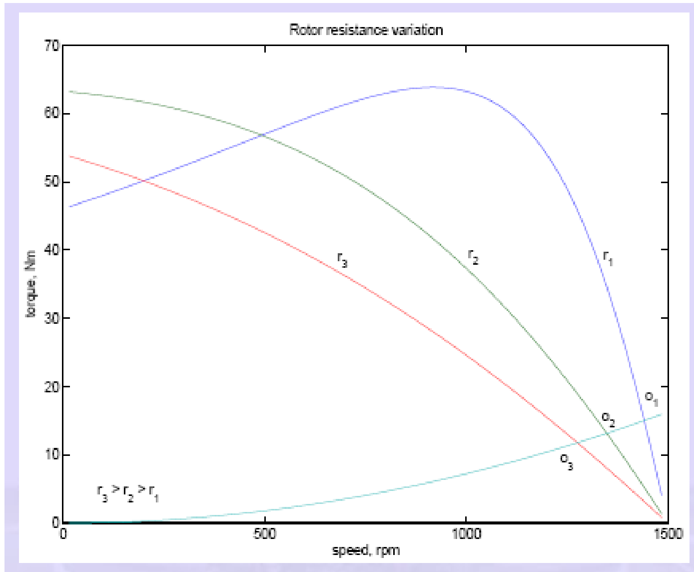


Figure. Speed-torque curves: rotor resistance variation

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 of the chopper presents a variable resistance load to the rotor of the induction machine.

3. Pole changing schemes

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 figure below.

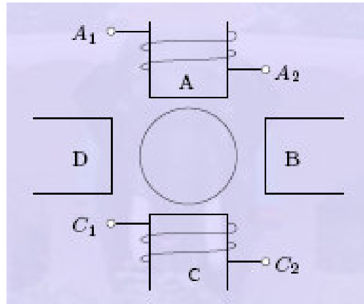
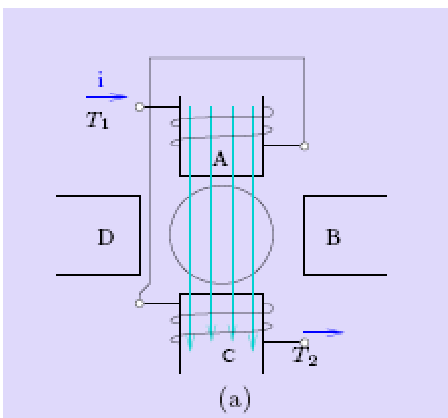
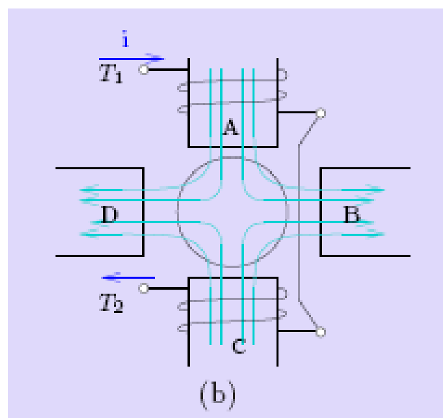


Figure. Pole arrangement

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 — A_2 may be connected to C_1 or C_2. A1 with the other terminal at C then form the terminals of the overall combination. Thus two connections result as shown in figure (a) & (b) below.





Now, for a given direction of current flow at terminal A_1, say into terminal A_1, 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. 31(a) and a four-pole arrangement in fig. 31(b). 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).

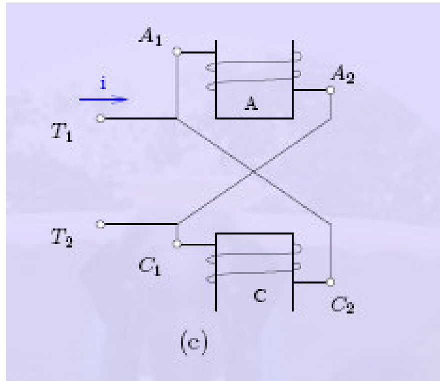


Figure: Pole Changing: Various connections

Further note that irrespective of the connection, the applied voltage is balanced by the series addition of induced emfs 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 figure(c). The terminals T_1 and T_2 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 figure(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.

4. Stator frequency control

The expression for the synchronous speed indicates that by changing the stator frequency also it can be changed. This can be achieved by using power electronic circuits called inverters which convert dc to ac of desired frequency. Depending on the type of control scheme of the inverter, the ac generated may be variable-frequency-fixed-amplitude or variable-frequency variable-amplitude type. Power electronic control achieves smooth variation of voltage and frequency of the ac output. This when fed to the machine is capable of running at a controlled speed. However, consider the equation for the induced emf in the induction machine.

$$V = 4.44 N \O_m f$$

where N is the number of the turns per phase, _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, the above equation is valid.

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.

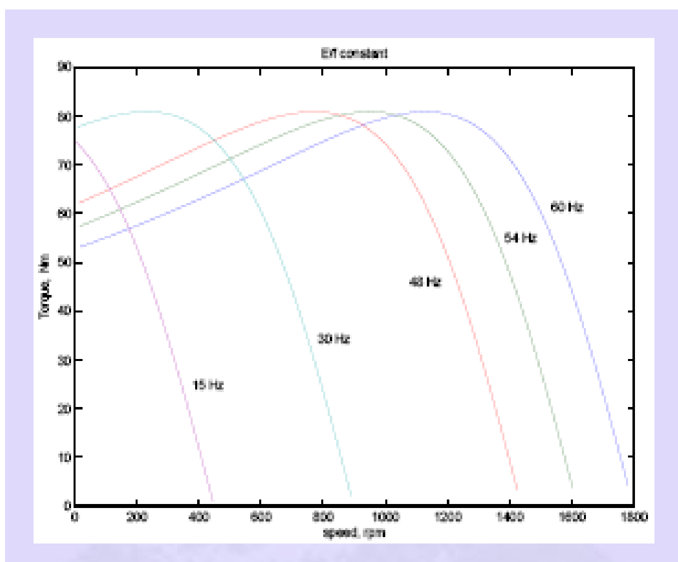


Figure. Torque-speed curves with E/f held constant

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.

SINGLE-PHASE INDUCTION MOTORS

There are probably more single-phase ac induction motors in use today than the total of all the other types put together.

It is logical that the least expensive, lowest maintenance type of ac motor should be used most often. The single-phase ac induction motor fits that description.

Unlike polyphase induction motors, the stator field in the single-phase motor does not rotate. Instead it simply alternates polarity between poles as the ac voltage changes polarity.

Voltage is induced in the rotor as a result of magnetic induction, and a magnetic field is produced around the rotor. This field will always be in opposition to the stator field (Lenz's law applies). The interaction between the rotor and stator fields will not produce rotation, however. The interaction is shown by the double-ended arrow in figure below, view A. Because this force is across the rotor and through the pole pieces, there is no rotary motion, just a push and/or pull along this line.

Figure. Rotor currents in a single-phase ac induction motor.

Now, if the rotor is rotated by some outside force (a twist of your hand, or something), the push-pull along the line in figure 4-10, view A, is disturbed. Look at the fields as shown in figure, view B. At this instant the south pole on the rotor is being attracted by the left-hand pole. The north rotor pole is being attracted to the right-hand pole. All of this is a result of the rotor being rotated 90° by the outside force. The pull that now exists between the two fields becomes a rotary force, turning the rotor toward magnetic correspondence with the stator. Because the two fields continuously alternate, they will never actually line up, and the rotor will continue to turn once started. It remains for us to learn practical methods of getting the rotor to start.

There are several types of single-phase induction motors in use today. Basically they are identical except for the means of starting. In this chapter we will discuss the split-phase and shaded-pole motors; so named because of the methods employed to get them started. Once they are up to operating speed, all single-phase induction motors operate the same.

Split-Phase Induction Motors

One type of induction motor, which incorporates a starting device, is called a split-phase induction motor. Split-phase motors are designed to use inductance, capacitance, or resistance to develop a starting torque. The principles are those that you learned in your study of alternating current.

Capacitor-Start Single Phase Induction Motor

The first type of split-phase induction motor that will be covered is the capacitor-start type. figure below shows a simplified schematic of a typical capacitor-start motor. The stator consists of the main winding and a starting winding (auxiliary). The starting winding is connected in parallel with the main winding and is placed physically at right angles to it. A 90-degree electrical phase difference between the two windings is obtained by connecting the auxiliary winding in series with a capacitor and starting switch. When the motor is first energized, the starting switch is closed. This places the capacitor in series with the auxiliary winding.

The capacitor is of such value that the auxiliary circuit is effectively a resistive-capacitive circuit (referred to as capacitive reactance and expressed as X_C). In this circuit the current leads the line voltage by about 45° (because X_C about equals R). The main winding has enough resistance-inductance (referred to as inductive reactance and expressed as X_L) to cause the current to lag the line voltage by about 45° (because X_L about equals R). The currents in each winding are therefore 90° out of phase - so are the magnetic fields that are generated. The effect is that the two windings act like a two-phase stator and produce the rotating field required to start the motor.

Figure. Capacitor-start, ac induction motor.

When nearly full speed is obtained, a centrifugal device (the starting switch) cuts out the starting winding. The motor then runs as a plain single-phase induction motor. Since the auxiliary winding is only a light winding, the motor does not develop sufficient torque to start heavy loads. Split-phase motors, therefore, come only in small sizes.

Resistance Start Single Phase Induction Motor

Another type of split-phase induction motor is the resistance-start motor. This motor also has a starting winding figure in addition to the main winding. It is switched in and out of the circuit just as it was in the capacitor-start motor. The starting winding is positioned at right angles to the main winding. The electrical phase shift between the currents in the two windings is obtained by making the impedance of the windings unequal.

The main winding has a high inductance and a low resistance. The current, therefore, lags the voltage by a large angle. The starting winding is designed to have a fairly low inductance and a high resistance. Here the current lags the voltage by a smaller angle. For example, suppose the current in the main winding lags the voltage by 70°. The current in the auxiliary winding lags the voltage by 40°. The currents are, therefore, out of phase by 30°. The magnetic fields are out of phase by the same amount. Although the ideal angular phase difference is 90° for maximum starting torque, the 30-degree phase difference still generates a rotating field. This supplies enough torque to start the motor. When the motor comes up to speed, a speed-controlled switch disconnects the starting winding from the line, and the motor continues to run as an induction motor. The starting torque is not as great as it is in the capacitor-start.

Figure. Resistance-start ac induction motor.

Shaded-Pole Induction Motors

The shaded-pole induction motor is another single-phase motor. It uses a unique method to start the rotor turning. The effect of a moving magnetic field is produced by constructing the stator in a special way. This motor has projecting pole pieces just like some dc motors. In addition, portions of the pole piece surfaces are surrounded by a copper strap called a shading coil. A pole piece with the strap in place is shown in figure below.

The strap causes the field to move back and forth across the face of the pole piece. Note the numbered sequence and points on the magnetization curve in the figure. As the alternating stator field starts increasing from zero (1), the lines of force expand across the face of the pole piece and cut through the strap. A voltage is induced in the strap. The current that results generates a field that opposes the cutting action (and decreases the strength) of the main field. This produces the following actions: As the field increases from zero to a maximum at 90°, a large portion of the magnetic lines of force are concentrated in the unshaded portion of the pole (1). At 90° the field reaches its maximum value. Since the lines of force have stopped expanding, no emf is induced in the strap, and no opposing magnetic field is generated. As a result, the main field is uniformly distributed across the pole (2). From 90° to 180°, the main field starts decreasing or collapsing inward. The field generated in the strap opposes the collapsing field. The effect is to concentrate the lines of force in the shaded portion of the pole face (3). You can see that from 0° to 180°, the main field has shifted across the pole face from the unshaded to the shaded portion. From 180° to 360°, the main field goes through the same change as it did from 0° to 180°; however, it is now in the opposite direction (4). The direction of the field does not affect the way the shaded pole works. The motion of the field is the same during the second half-cycle as it was during the first half of the cycle.

Figure. Shaded poles as used in shaded-pole ac induction motors.

The motion of the field back and forth between shaded and unshaded portions produces a weak torque to start the motor. Because of the weak starting torque, shaded-pole motors are built only in small sizes. They drive such devices as fans, clocks, blowers, and electric razors.

SUMMARY

In this chapter, construction and working of 3-phase induction motor has been discussed. The induction motor rotates at a speed less than the synchronous speed and also called asynchronous motor. The difference between the synchronous speed and the rotor speed is the slip speed. Various configuration of the equivalent circuit have been analysed. A general expression for torque has been derived, which is used to plot the torque-slip characteristics of the motor. Various methods of starting and speed control are also discussed. The working principle and types of single phase induction motors have also been discussed.

Short answer questions

1. Why are 3-phase induction motors very popular as drives for industrial applications?
2. What are the various types of 3-phase induction motors as per the rotor construction?
3. List the differences between squirrel cage and slip ring rotor.
4. Define slip of induction motor.
5. A 3-phase induction motor does not run at synchronous speed. Why?
6. Why is the no-load current drawn by 3-phase induction motor so high?
7. Compare the efficiency and operating power factor of single phase induction motor with 3-phase induction motor.
8. Why single phase induction motors are not self-starting?
9. What are the various types of single phase induction motors?
10. How to change the direction of induction motor?

Detailed answer questions

1. With the help of diagrams, explain how a rotating magnetic field is produced in the air gap of a 3-phase induction motor.
2. Explain the principle of operation of 3-phase induction motor.
3. Derive the relationship between the rotor copper losses and the rotor input in a 3-phase induction motor .
4. Explain the effect of slip on the following rotor parameters.

i) frequency ii) induced emf iii) current iv) power factor v)reactance

5. Derive a general expression for the torque developed in a 3-phase induction motor.
6. Sketch and explain the torque-speed characteristics of a 3-phase induction motor.
7. List the various losses that take place in an induction motor.
8. Draw and explain the phasor diagram of a 3-phase induction motor.
9. Develop the equivalent of a 3-phase induction motor.
10. i)Why do we need a starter for starting a 3-phase induction motor?

ii) Draw a neat diagram showing the connections of 3-phase induction motor with star-delta starter. Explain how the above starter reduces the starting current.

11. Draw the diagram of an auto-transformer starter used for 3-phase induction motor and explain its operation.
12. Describe the no-load test and blocked rotor test to determine the parameters of equivalent circuit of 3-phase induction motor.
13. Explain the various techniques used for speed control of 3-phase induction motor.
14. Explain rotor resistance speed control of 3-phase induction motor.
15. Explain the double field revolving theory.
16. Draw and explain the equivalent circuit of a single phase induction motor based on double field revolving theory.