A Course Material on

Electrical Machines-II

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Syllabus

EE8401 Electrical Machines -II

UNIT I SYNCHRONOUS GENERATOR

Constructional details – Types of rotors –winding factors- emf equation – Synchronous reactance –Armature reaction – Phasor diagrams of non salient pole synchronous generator connected to infinite bus--Synchronizing and parallel operation – Synchronizing torque -Change of excitation and mechanical input- Voltage regulation – EMF, MMF, ZPF and A.S.A methods – steady state power angle characteristics– Two reaction theory – slip test -short circuit transients - Capability Curves

UNIT II SYNCHRONOUS MOTOR

Principle of operation – Torque equation – Operation on infinite bus bars - V and Inverted V curves – Power input and power developed equations – Starting methods – Current loci for constant power input, constant excitation and constant power developed-Hunting – natural frequency of oscillations – damper windings- synchronous condenser.

UNIT III THREE PHASE INDUCTION MOTOR

Constructional details – Types of rotors –- Principle of operation – Slip –cogging and crawling- Equivalent circuit – Torque-Slip characteristics - Condition for maximum torque – Losses and efficiency – Load test - No load and blocked rotor tests - Circle diagram – Separation of losses – Double cage induction motors –Induction generators – Synchronous induction motor.

UNIT IV STARTING AND SPEED CONTROL OF THREE PHASE INDUCTION MOTOR

Need for starting – Types of starters – DOL, Rotor resistance, Autotransformer and Star-delta starters – Speed control – Voltage control, Frequency control and pole changing – Cascaded connection-V/f control – Slip power recovery scheme-Braking of three phase induction motor: Plugging, dynamic braking and regenerative braking.

UNIT V SINGLE PHASE INDUCTION MOTORS AND SPECIAL MACHINES

Constructional details of single phase induction motor – Double field revolving theory and operation – Equivalent circuit – No load and blocked rotor test – Performance analysis – Starting methods of single-phase induction motors – Capacitor-start capacitor run Induction motor- Shaded pole induction motor - Linear induction motor – Repulsion motor - Hysteresis motor - AC series motor- Servo motors- Stepper motors - introduction to magnetic levitation systems.

TEXT BOOKS

1. D.P.Kothariand I.J.Nagrath,‘ElectricMachines’,TataMcGrawHillPublishing Company Ltd, 2002.
2. P.S. Bhimbhra,‘ElectricalMachinery’,Khanna Publishers,2003.
3. J.Gnanavadivel, 'Electrical Machines-II', Anuradha Publishers.
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UNIT-I SYNCHRONOUS GENERATOR

UNIT-II SYNCHRONOUS MOTOR

UNIT-III THREE PHASE INDUCTION MOTOR

UNIT-IV STARTING AND SPEED CONTROL OF THREE PHASE INDUCTION MOTOR

UNIT-V SINGLE PHASE INDUCTION MOTORS AND SPECIAL MACHINES

UNIT I SYNCHRONOUS GENERATOR

1.1 Fundamental Principles of A.C. Machines:

AC rotating machines can be classified mainly in two categories **Synchronous Machines** and **Asynchronous Machines.** They are defined as-

- ***Synchronous Machines:***
- Synchronous Generators: A primary source of electrical energy.
- Synchronous Motors: Used as motors as well as power factor compensators (synchronous condensers).
- ***Asynchronous (Induction) Machines:***
- Induction Motors: Most widely used electrical motors in both domestic and industrial applications.
- Induction Generators: This generator runs at asynchronous speed and variable frequency voltage generated. Due to lack of a separate field excitation, these machines are rarely used as generators.

1.2 E.M.F. equation of an elementary alternator single phase

Let us assume that this generator has an armature winding consisting of a total number of full pitched concentrated coils C, each coil having a given number of turns N_c. Then the total number of turns in any given phase of a single-phase generator armature is

$$N_p = CN_c$$

According to Faraday's law of electromagnetic induction the average voltage induced in a single turn of two coil sides is

$$E_{av} = \frac{\phi}{t}$$

The voltage induced in one conductor is $2\phi/(1/n) = 2\phi s$, where n=speed of rotation in r.p.s, for a 2 pole generator. Furthermore, when a coil consisting of N_c turns rotates in a uniform magnetic field, at a uniform speed, the average voltage induced in an armature coil is

$$E_{av_{coil}} = 4\phi N_c n \text{ volts}$$

where ϕ is the number of lines of flux (in Webers) per pole, N_c is number of turns per coil, n is the relative speed in revolutions/second (rps) between the coil of N_c turns and the magnetic field ϕ.

A speed n of 1 rps will produce a frequency f of 1 Hz. Since f is directly proportional and equivalent to n, (for a 2-pole generator) for all the series turns in any phase,

$$\frac{E_{av}}{phase} = 4\phi N_P f \text{ volts}$$

The effective rms value of a sinusoidal ac voltage is 1.11 times the average value. The effective ac voltage per phase is

$$E_{eff} = 4.44\phi N_P f \text{ volts}$$

1.3 E.M.F. equation of an elementary alternator three phase

Let us assume that this generator has an armature winding consisting of a total number of full pitched concentrated coils C, each coil having a given number of turns N_C. Then the total number of turns in any given phase of a 3-phase generator armature is

$$N_P = \frac{CN_C}{3}$$

Voltage equation per phase will be similar in to the single phase alternator

$$E_{ph} = 4.44\phi N_P f$$

The value of line voltage will be different from phase voltage in case of star connected generator. The line value of the emf in case of three phase alternator connected in star will be-

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

The value of line voltage will be same with phase voltage in case of delta connected generator. The line value of the emf in case of three phase alternator connected in delta will be-

$$E_L = E_{Ph}$$

1.4 Relation between speed and frequency

One complete revolution will produce one complete positive and negative pulse each cycle when the number of pole is two. The frequency in cycles per second (Hz) will depend directly on the speed or number of revolutions per second (rpm/60) of the rotating field.

If the ac synchronous generator has multiple poles (having, say, two, four, six, or eight poles...), then for a speed of one revolution per second (1 rpm/60), the frequency per revolution will be one, two, three, or four ..., cycles per revolution, respectively. The frequency per revolution, is therefore, equal to the number of pairs of poles. Since the frequency depends directly on the speed (rpm/60) and also on the number of pairs of poles (P/2), then these two may be combined together into a single equation in which

$$f = \frac{P}{2} * \frac{rpm}{60} = \frac{PN}{120}$$

$$\omega_m = \frac{2*\pi* N}{60}$$

$$N = \frac{\omega_m *60}{2\pi}$$

$$\text{f} = \frac{P}{2} * \frac{\omega_m}{2\pi} \frac{\omega_e}{2\pi}$$

Where

P is the number of poles

N is the speed in rpm (rev/min)

f is. the frequency in hertz

ω_m is the speed in radians per second (rad/s)

ω_e is the speed electrical radians per second.

1.5 Factors affecting the induced emf (Coil Pitch and Distributed Windings)

The emf equation derived in art 1.2 and art 1.3 is applicable when the alternator is having full pitch coil and concentrated winding. But when the alternator armature winding is distributed and short pitched then the per phase emf equation will change and become-

$$E_g = 4.44\phi N_p f k_p k_d$$

Where ***Kp*** is called ***pitch factor*** and ***Kd*** is called ***distribution factor.***

1.5.1 Pitch Factor or Coil Pitch

The ratio of phasor (vector) sum of induced emfs per coil to the arithmetic sum of induced emfs per coil is known as ***pitch factor (Kp)*** or ***coil span factor (Kc)*** which is always less than unity.

Let the coil have a pitch short by angle θ electrical space degrees from full pitch and induced emf in each coil side be ***E***,

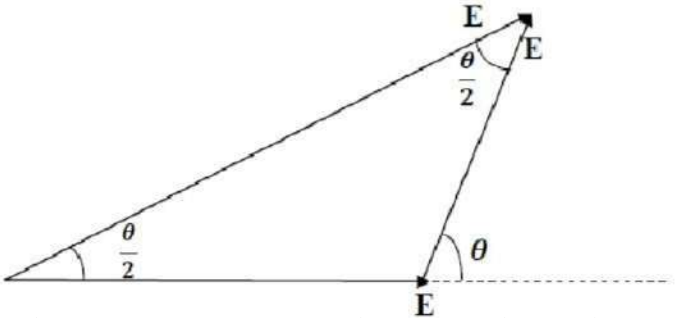


Fig: 1(a) Voltage phasor for short-pitch coil

- If the coil would have been full pitched, then total induced emf in the coil would have been ***2E***.
- when the coil is short pitched by θ electrical space degrees the resultant induced emf, ***ER*** in the coil is phasor sum of two voltages, θ apart

$$E_R = 2E\cos\theta/2$$

$$\text{Pitch Factor, } K_p = \frac{\text{Phasor sum of coil side emfs}}{\text{Arithmatic sum of coil side emfs}} = \frac{2E\cos\frac{\theta}{2}}{2E} = \cos\frac{\theta}{2}$$

The pitch factor of the coil at the n_{th} harmonic frequency can be expressed as

$k_{pn} = \cos n\theta$ where n is the order of harmonic

1.5.2 Distribution Factor

The ratio of the phasor sum of the emfs induced in all the coils distributed in a number of slots under one pole to the arithmetic sum of the emfs induced(or to the resultant of emfs induced in all coils concentrated in one slot under one pole) is known as ***breadth factor (Kb)*** or ***distribution factor (Kd)***

The distribution factor is always less than unity.

Let no. of slots per pole = *Q* and no. of slots per pole per phase = *q*

Induced emf in each coil side = *Ec*

Angular displacement between the slotsγ, o

The emf induced in different coils of one phase under one pole are represented by side AC, CD, DE, EF. Which are equal in magnitude (say each equal Ec) and differ in phaseγ(say by o) from each other.

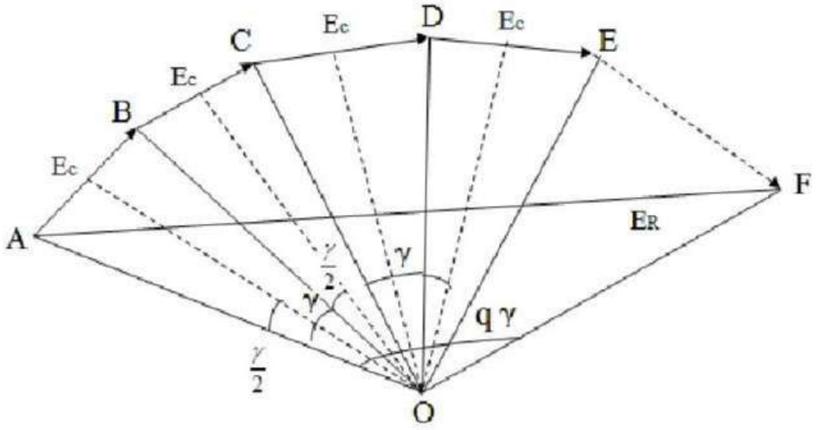


Fig: 1(b)

If bisectors are drawn on AC, CD, DE, EF. they would meet at common point *(O)*. The point *O* would be the center of the circle having AC, CD, DE, EF as the chords and representing the emfs induced in the coils in different slots.

EMF induced in each coil side, $E_c = AC = 2OA\sin\frac{\gamma}{2}$

Arithmatic sum $= q \cdot 2\,OA\sin\frac{\gamma}{2}$

The resultant emf, $E_R = AB = 2 \cdot OA\sin\frac{AOB}{2}$ & distribution factor,

The distribution factor for nth order harmonic component is given as

$$k_{dn} = \frac{\sin\frac{nq\gamma}{2}}{q\sin\frac{n\gamma}{2}}$$, where n is the order of harmonic

1.5.3 Harmonic Effect

- The flux distribution along the air gaps of alternators usually is non- sinusoidal so that the emf in the individual armature conductor likewise is non-sinusoidal

- The sources of harmonics in the output voltage waveform are the non- sinusoidal waveform of the field flux.

- Fourier showed that any periodic wave may be expressed as the sum of a d-c component (zero frequency) and sine (or cosine) waves having fundamental and multiple or higher frequencies, the higher frequencies being called harmonics.

- All the odd harmonics(third, fifth, seventh, night, etc.) are present in the phase voltage to some extent and need to be dealt with in the design of ac machines.

- Because the resulting voltage waveform is symmetric about the center of the rotor flux, no ***even harmonics*** are present in the phase voltage.

- In ***Y- connected***, the *third-harmonic* voltage between any two terminals will be zero. This result applies not only to third-harmonic components but also to any multiple of a third-harmonic component (such as the ninth harmonic). Such special harmonic frequencies are called ***triplen***

Elimination or Suppression of Harmonics

Field flux waveform can be made as much sinusoidal as possible by the following methods:

1. Small air gap at the pole centre and large air gap towards the pole ends
2. ***Skewing:*** skew the pole faces if possible
3. ***Distribution*:** distribution of the armature winding along the air-gap periphery
4. ***Chording:*** with coil-span less than pole pitch
5. Fractional slot winding
6. ***Alternator connections:*** star or delta connections of alternators suppress triplen harmonics from appearing across the lines

1.5.4 Winding Factor

Both distribution factor *(Kd*) and pitch factor *Kp* together is known as ***winding factor Kw.***

$$k_w = k_p k_d$$

$$E_g = 4.44 \Phi N_p f k_w$$

1.6 Armature Reaction

When an alternator is running at no-load, there will be no current flowing through the armature winding. The flux produced in the air-gap will be only due to the rotor ampere turns. When the alternator is loaded, the three-phase currents will produce a totaling magnetic field in the air-gap. Consequently, the air-gap flux is changed from the no-load condition.

The effect of armature flux on the flux produced by field ampere turns (i. e., rotor ampere turns) is called armature reaction.

Two things are worth noting about the armature reaction in an alternator. First, the armature flux and the flux produced by rotor ampere-turns rotate at the same speed (synchronous speed) in the same direction and, therefore, the two fluxes are fixed in space relative to each other.

Secondly, the modification of flux in the air-gap due to armature flux depends on the magnitude of stator current and on the power factor of the load. It is the load power factor which determines whether the armature flux distorts, opposes or helps the flux produced by rotor ampere-turns.

To illustrate this important point, we shall consider the following three cases:

1. When load p.f. is unity
2. When load p.f. is zero lagging
3. When load p.f. is zero leading

When load p.f. is unity

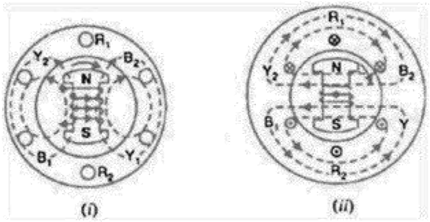


Fig: 1 (c)

Above Fig: 1 (c) shows an elementary alternator on no load. Since the armature is on open-circuit, there is no stator current and the flux due to rotor current is distributed symmetrically in the air-gap as shown in Fig: 1 (d). Since the direction of the rotor is assumed clockwise, the generated e.m.f. in phase R1R2 is at its maximum and is towards the paper in the conductor R1 and outwards in conductor R2. No armature flux is produced since no current flows in the armature winding.

Fig (ii) shows the effect when a resistive load (unity p.f.) is connected across the terminals of the alternator. According to right-hand rule, the current is "in" in the conductors under N-pole and "out" in the conductors under S-pole. Therefore, the armature flux is clockwise due to currents in the top conductors and anti-clockwise due to currents in the bottom conductors. Note that armature flux is at

90° to the main flux (due to rotor current) and is behind the main flux.

In this case, the flux in the air-gap is distorted but not weakened. Therefore, at unity p.f., the effect of armature reaction is merely to distort the main field; there is no weakening of the main field and the average flux practically remains the same. Since the magnetic flux due to stator currents (i.e., armature flux) rotate; synchronously with the rotor, the flux distortion remains the same for all positions of the rotor.

When load Power Factor is Zero lagging

When a pure inductive load (zero p.f. lagging) is connected across the terminals of the alternator, current Fig: 1 (c) shows the condition when the alternator is supplying resistive load. Note that e.m.f. as well as current in phase R1R2 is maximum in the position shown. When the alternator is supplying a pure inductive load, the current in phase R1R2 will not reach its maximum value until N-pole advanced 90° electrical as shown in Fig: 1 (d). Now the armature flux is from right to left and field flux is from left to right All the flux produced by armature current (i.e., armature flux) opposes be field flux and, therefore, weakens it. In other words, armature reaction is directly demagnetizing. Hence at zero p.f. lagging, the armature reaction weakens the main flux. This causes a reduction in the generated e.m.f.

When load Power Factor is Zero leading

When a pure capacitive load (zero p.f. leading) is connected across the terminals of the alternator, the current in armature windings will lead the induced e.m.f. by 90°.

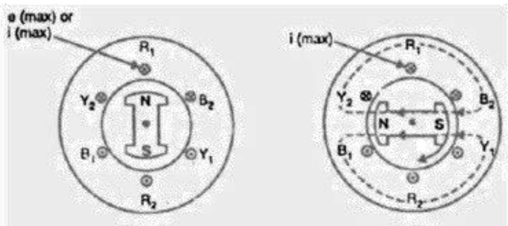


Fig: 1 (d)

Obviously, the effect of armature reaction will be the reverse that for pure inductive load. Thus armature flux now aids the main flux and the generated e.m.f. is increased. Fig: 1 (c) shows the condition when alternator is supplying resistive load.

Note that e.m.f. as well as current in phase R1R2 is maximum in the position shown. When the alternator is supplying a pure capacitive load, the maximum current in R1R2 will occur 90° electrical before the occurrence of maximum induced e.m.f. Therefore, maximum current in phase R1R2 will occur if the

position of the rotor remains 90° behind as compared to its position under resistive load. This is illustrated in Fig: 1 (d). It is clear that armature flux is now in the same direction as the field flux and, therefore, strengthens it. This causes an increase in the generated voltage. Hence at zero p.f. leading, the armature reaction strengthens the main flux.

For intermediate values of p.f, the effect of armature reaction is partly distorting and partly weakening for inductive loads. For capacitive loads, the effect of armature reaction is partly distorting and partly strengthening. Note that in practice, loads are generally inductive.

1.7 Synchronous Generators

Synchronous machines are principally used as ***alternating current (AC) generators***.

- They supply the electric power used by all sectors of modern societies: industrial, commercial, agricultural, and domestic. They
- usually operate together (or in parallel), forming a large power system supplying electrical energy to the loads or consumers.
- are built in large units, their rating ranging from tens to hundreds of megawatts.
- converts mechanical power to ac electric power. The source of mechanical power, ***the prime mover***, may be a diesel engine, a steam turbine, a water turbine, or any similar device.

For high-speed machines, the prime movers are usually ***steam turbines*** employing fossil or nuclear energy resources.

Low-speed machines are often driven by ***hydro-turbines*** that employ water power for generation.

Smaller synchronous machines are sometimes used for private generation and as standby units, with diesel engines or gas turbines as prime movers.

1.7.1 Various Types of Synchronous Machine & Construction

According to the arrangement of the field and armature windings, synchronous machines may be classified as rotating-armature type or rotating-field type.

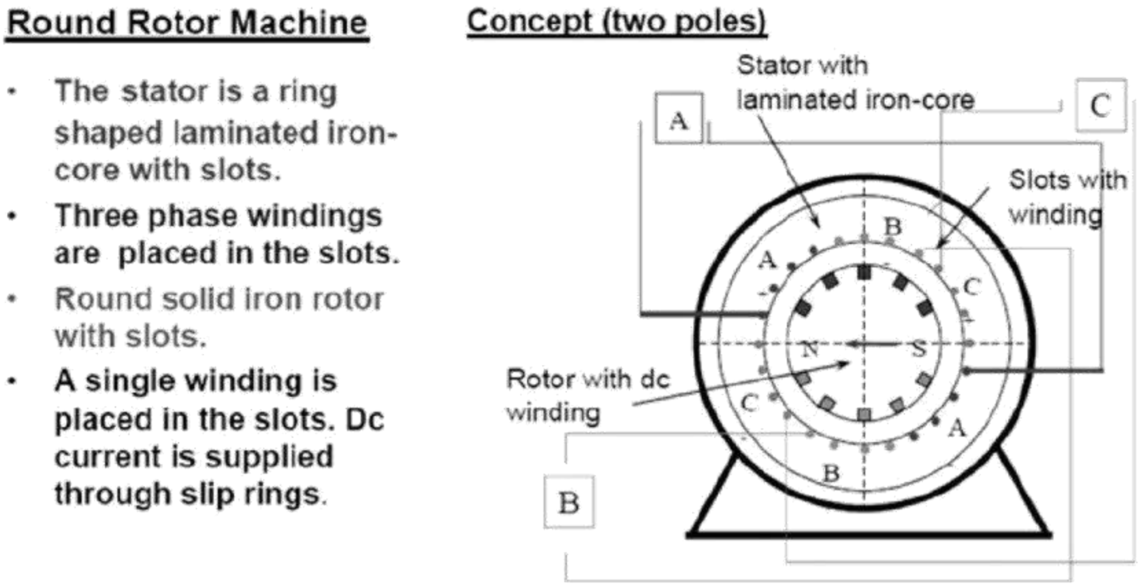
1.7.2 Rotating-Armature Type:

The armature winding is on the rotor and the field system is on the stator.

1.7.3 Rotating-Field Type:

The armature winding is on the stator and the field system is on the rotor.

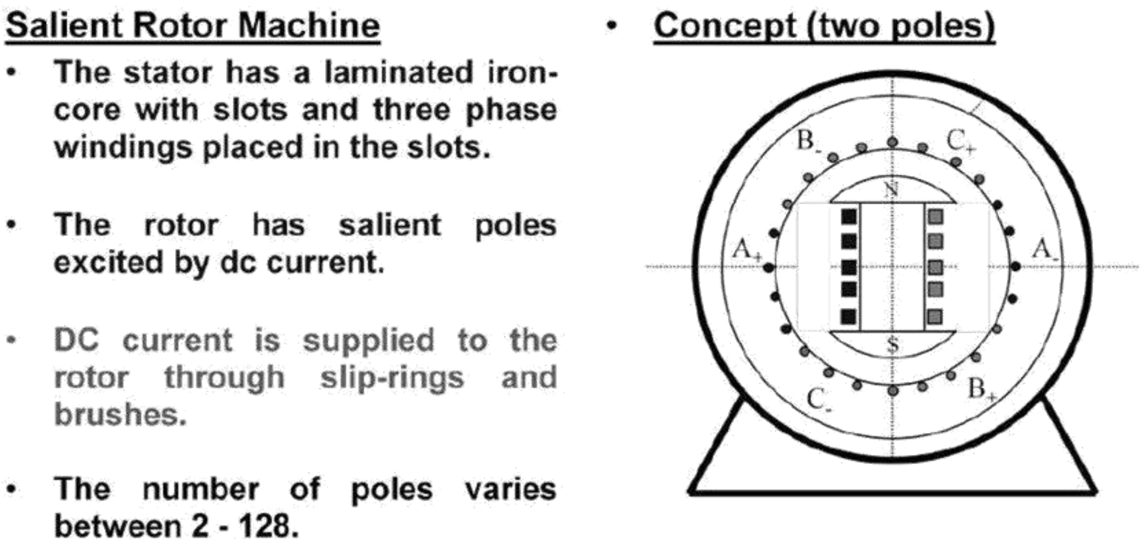
According to the shape of the field, synchronous machines may be classified as ***cylindrical-rotor* (*non-salient pole*) *machines*** and ***salient-pole machines***



Round Rotor Machine

- The stator is a ring shaped laminated iron-core with slots.
- Three phase windings are placed in the slots.
- Round solid iron rotor with slots.
- A single winding is placed in the slots. Dc current is supplied through slip rings.

Concept (two poles)



Salient Rotor Machine

- The stator has a laminated iron-core with slots and three phase windings placed in the slots.
- The rotor has salient poles excited by dc current.
- DC current is supplied to the rotor through slip-rings and brushes.
- The number of poles varies between 2 - 128.

- **Concept (two poles)**

AC winding design

The windings used in rotating electrical machines can be classified as

Concentrated Windings

- All the winding turns are wound together in series to form one multi-turn coil
- All the turns have the same magnetic axis
- Examples of concentrated winding are
  - field windings for salient-pole synchronous machines
  - D.C. machines
  - Primary and secondary windings of a transformer

Distributed Windings

- All the winding turns are arranged in several full-pitch or fractional-pitch coils
- These coils are then housed in the slots spread around the air-gap periphery to form phase or commutator winding
- Examples of distributed winding are
  - Stator and rotor of induction machines
  - The armatures of both synchronous and D.C. machines

Some of the terms common to armature windings are described below:

Conductor. A length of wire which takes active part in the energy- conversion process is a called a conductor.

Turn. One turn consists of two conductors.

Coil. One coil may consist of any number of turns.

Coil -side. One coil with any number of turns has two coil-sides.

The number of conductors (C) in any coil-side is equal to the number of turns (N) in that coil.

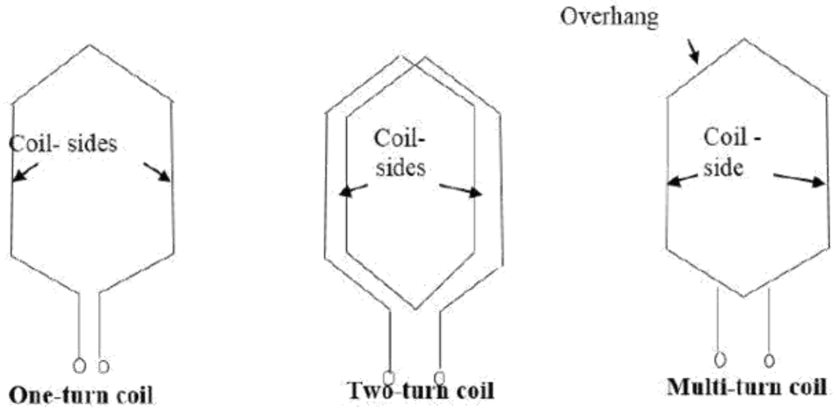


Fig: 1.1

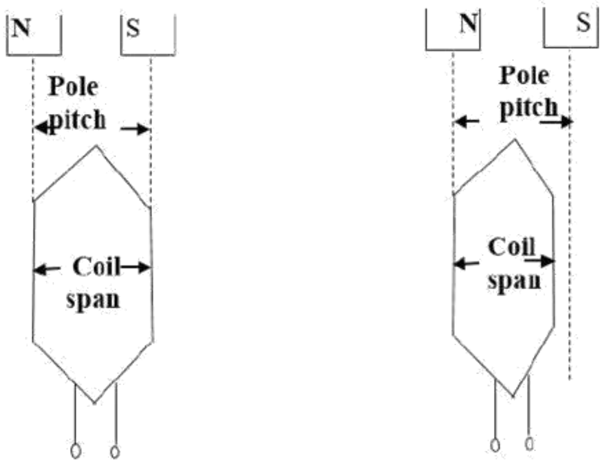
Pole - pitch:- A pole pitch is defined as the peripheral distance between identical points on two adjacent poles. Pole pitch is always equal to 180o electrical.

Coil-span or coil-pitch:- The distance between the two coil-sides of a coil is called coil-span or coil-pitch. It is usually measured in terms of teeth, slots or electrical degrees.

Chorded-coil

- If the coil-span (or coil-pitch) is equal to the pole-pitch, then the coil is termed a ***full-pitch coil***.
- in case the coil-pitch is less than pole-pitch, then it is called ***chorded***, ***short-pitch*** or ***fractional-pitch coil***

Fractional-pitch coil



Full-pitch coil

Short-pitched or chorded coil

Fig: 1.2

In ***AC armature windings***, the separate coils may be connected in several different manners, but the two most common methods are ***lap*** and ***wave.***

1.7.2 Cylindrical Rotor Theory

Similar to the case of DC generator, the behavior 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 induced emf is at its peak by 90 electrical degrees or half a pole-pitch. Likewise for zero power factor leading 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.

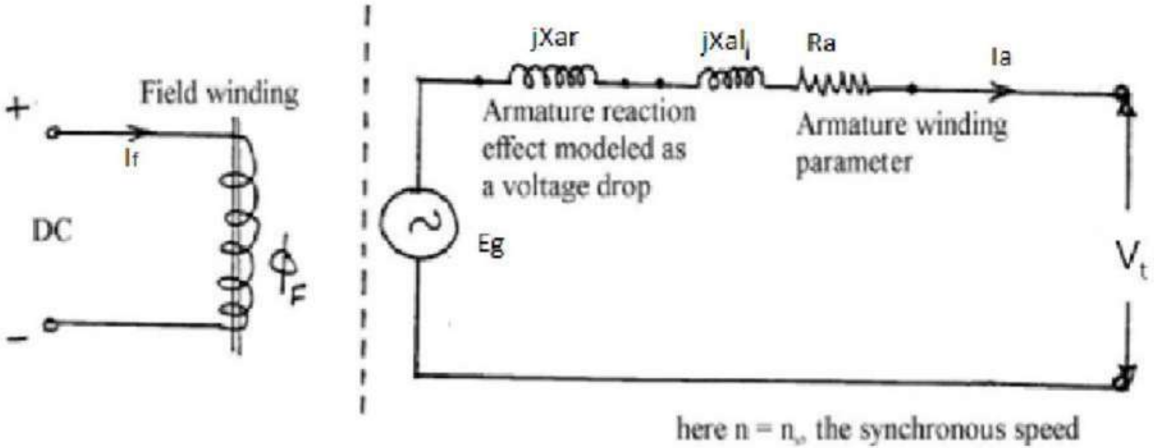


Fig: 1.3 Equivalent circuit of synchronous generator

For synchronous generator the terminal voltage V_t can be written as

$V_t = jI_a X_{al} \quad jI_a X_{ar} \quad I_a R_a E_g$

$V_t =_g \ -jI_a X_s \ -I_a R_a E$

$V_t =_g \ \cdot I_a (R_a + jX_s) =_g \ -I_a Z_s$

$E \qquad\qquad\qquad\qquad E$

Where E_g is the generator induced emf,

I_a is the armature current,

R_a is the armature resistance,

X_{al} is the leakage reactance,

X_{ar} is the armature reaction reactance,

X_s is the synchronous reactance

Z_s is the synchronous impedance

1.7.3 Phasor Diagrams

The complete phasor diagram of an alternator at different load conditions are shown below.

1.7.3.1 For Inductive Load

The alternator is connected with a R-L load then the current lags terminal voltage by an angle θThe phasor diagram is shown below in Fig: 1.4.

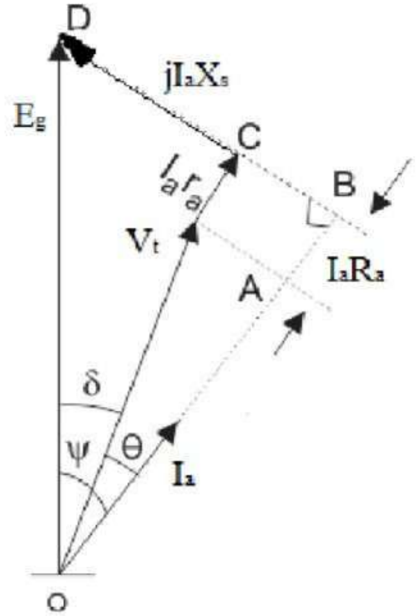


Fig: 1.4

Phasor diagram of an alternator with lagging power factor load

1.7.3.2 For Resistive Load

The alternator is connected with a resistive load then the current remains in same phase with the terminal voltage. The phasor diagram is shown below in Fig: 1.5.

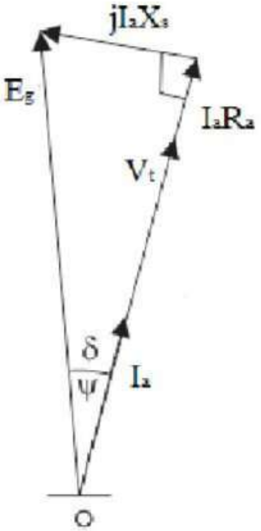


Fig: 1. 5 Phasor diagram of an alternator with unity power factor load

1.7.3.3 For Capacitive Load

When the terminals of the armature of alternator is connected with a R-C load then the current I_a leads the terminal voltage V_t by an angle θ The complete phasor diagram for leading power factor load is shown below in Fig: 1. 6.

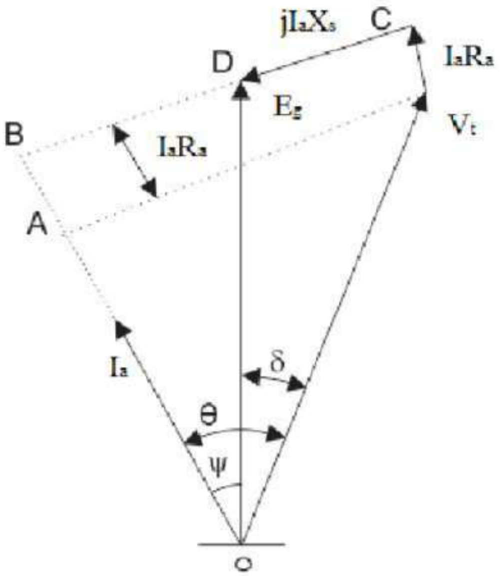


Fig: 1. 6 Phasor diagram of an alternator with leading power factor load

δ is called load angle

θ is load power factor angle

ψ is internal power factor angle

1.8 Open-circuit characteristic (OCC) of a generator

With the armature terminals open, Ia=0, so Eg = V_t It is thus possible to construct a plot of E_g or V_t vs I_f graph. This plot is called open-circuit characteristic (OCC) of a generator. With this characteristic, it is possible to find the internal generated voltage of the generator for any given field current.

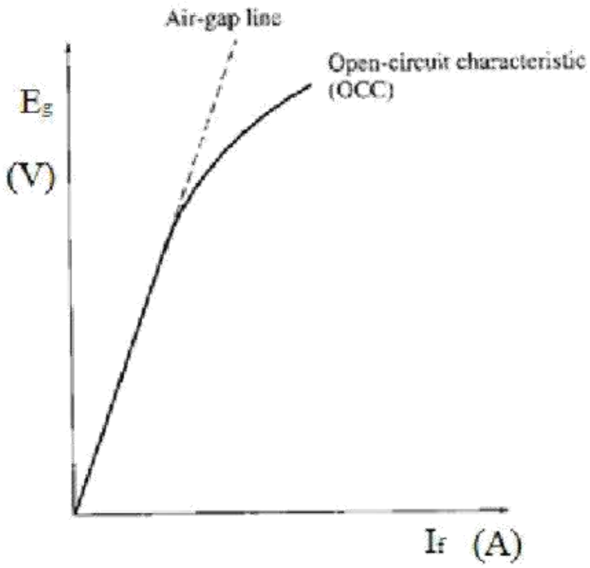


Fig: 1. 7 Open-circuit characteristic of alternator

Initially OCC follows a straight-line relation with the field current as long as the magnetic circuit of the synchronous generator does not saturate. This straight line is appropriately called the ***air-gap line***. Practically due to saturation induced emf bend from the straight line.

1.9 Short Circuit Characteristics (SCC)

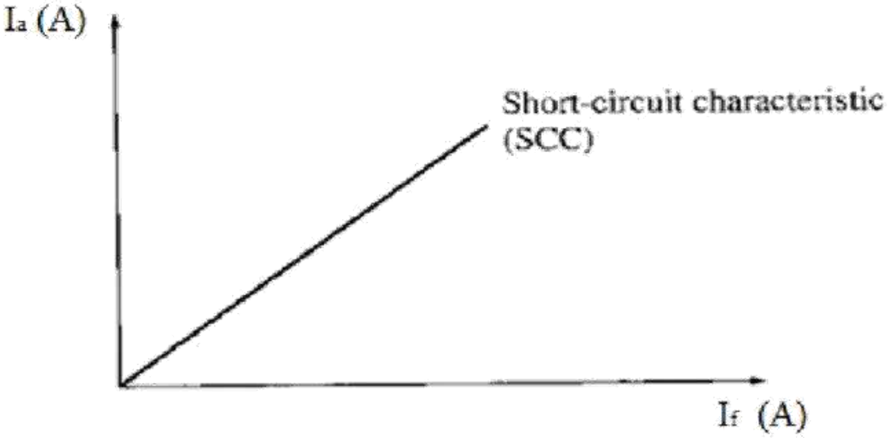


Fig: 1.8 Short-circuit characteristic of alternator

For getting SCC generator is rotated at rated speed with armature terminals short circuited. The field current is adjusted to 0. The armature current is measured as the field current is increased.

1.10 Armature Reaction Reactance

Armature reaction refers to the influence of the armature flux on the field flux in the air gap when the stator windings are connected across a load.

If F_f is the field mmf in the generator under no load, then the generated voltage E_g must lag F_f by 90_o. Per phase armature current I_a produces armature mmf F_a which is in phase with I_a . The effective mmf is F_r.

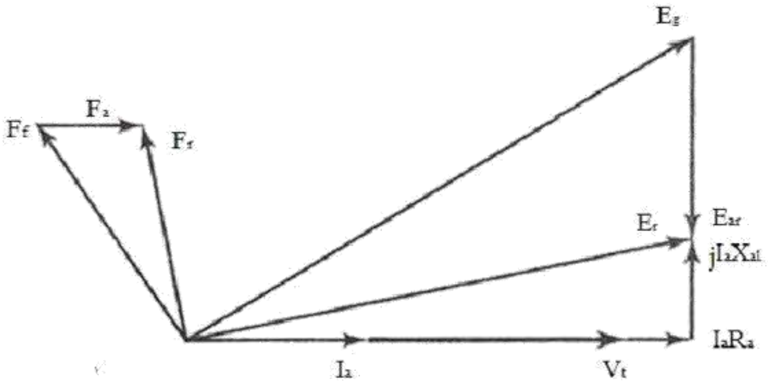


Fig : 1.9 Phasor diagram of an alternator at unity power factor

The armature mmf F_a will induced an emf E_{ar} in the armature winding. E_{ar} is called the armature reaction emf. This emf will lag its mmf by 90_o. Hence the resultant armature voltage is the vector sum of the no-load voltage E_g and armature reaction emf E_{ar} .

$$\overline{E_r} = \overline{E_g} + \overline{E_{ar}}$$

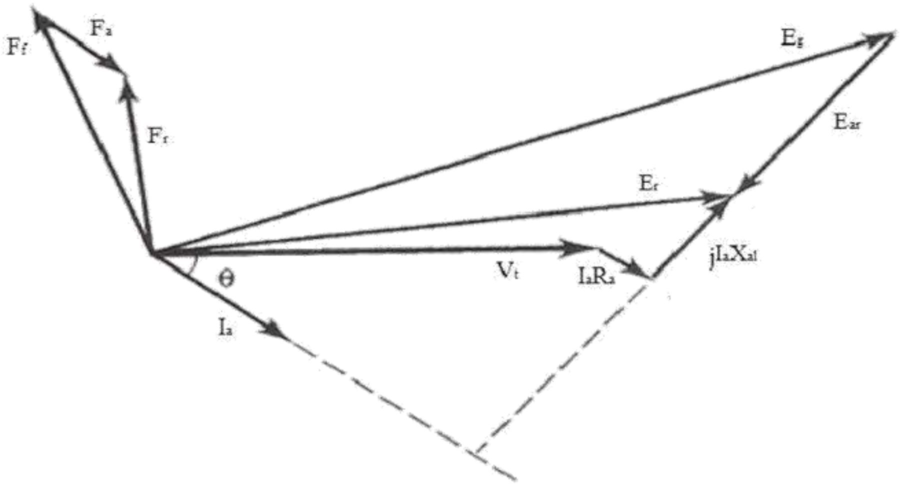


Fig: 1.10 Phasor diagram of an alternator at lagging power factor

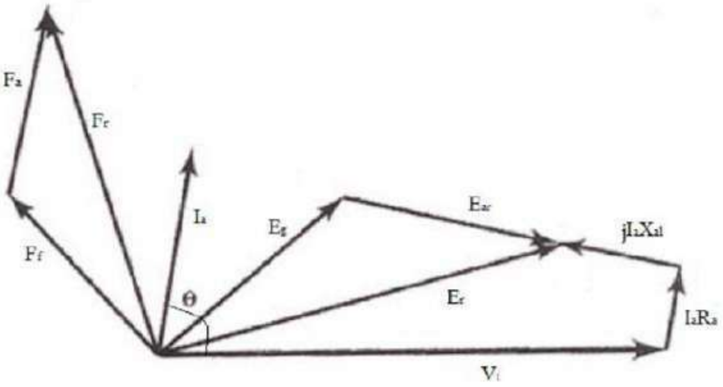


Fig: 1.11 Phasor diagram of an alternator at leading power factor

From the observations of the phasor diagrams for lagging and leading power factors, that the resultant mmf F_r is smaller or larger depending on the power factor. As a result the terminal voltage V_t is larger or smaller than the no-load induced emf when the power factor is leading or lagging.

Since the armature reaction emf E_{ar} lags the armature mmf F_a or I_a by 90^o, so it can be expressed as

$$\underline{E}_{ar} = j\underline{I}_a X_{ar}$$

Where X_{ar} is called **armature reaction reactance.**

1.11 Synchronous reactance

Both the armature reaction reactance and the leakage reactance are present at the same time. The two raeactances are combined together and the sum is called the **Synchronous reactance (X_s).**

$$X_s = X_{al} + X_{ar}$$

The combined result of the Synchronous reactance and armature resistance is called **Synchronous Impedance (Z_s).**

$$\underline{Z}_s = R_a + jX_s$$

1.12 Short Circuit Ratio (SCR)

Ratio of the field current required for the rated voltage at open circuit to the field current required for rated armature current at short circuit.

$$SCR = \frac{I_{f,oc}}{I_{f,sc}}$$

So, $SCR = \frac{1}{X_S}$

1.13 Load Characteristics

Consider a synchronous generator driven at constant speed and with constant excitation. On open circuit the terminal voltage V_t is the same as the open circuit e.m.f. E_g. Suppose a unity-power-factor load be connected to the machine. The flow of load current produces a voltage drop I_aZ_s in the synchronous impedance, and terminal voltage V_t is reduced. Fig. 1.12 shows the phasor diagram for three types of load. It will be seen that the angle between E_g and V_t increases with load, indicating a shift of the flux across the pole faces due to cross- magnetization. The terminal voltage is obtained from the complex summation

$$V_t + I_aZ_s = E_g$$

$$V_t = E_g - I_aZ_s$$

Algebraically this can be written as-

$$V_t = \sqrt{\left(E_g^2 - I_a^2 X_s^2\right)} - I_a r_a$$

For non-inductive load since r_a is negligible compared to X_s

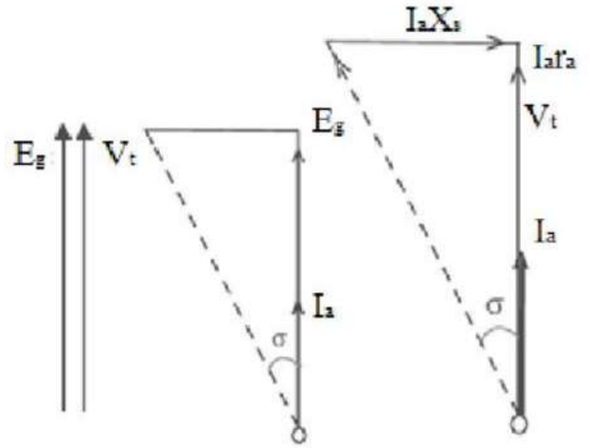
$$V_t^2 + I_a^2 X_s^2 \approx E_g^2 = tant\ Cons$$

so that the V/I curve, Fig. 1.13, is nearly an ellipse with semi-axes E_g and I_{sc}. The current I_{sc} is that which flows when the load resistance is reduced to zero. The voltage V_t falls to zero also and the machine is on short-circuit with $V_t = 0$ and

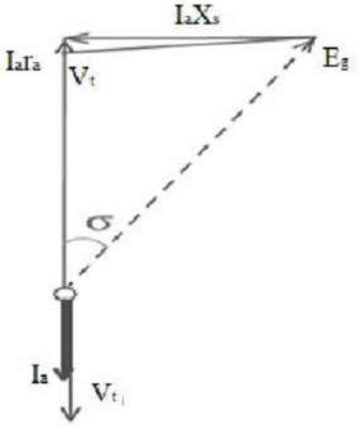
$$I_a = I_{sc} = E_g / Z_s \quad E_g / X_s$$

For a lagging load of zero power-factor, diagram is given in Fig. 1.13. 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

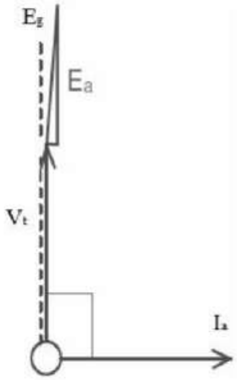
$$V_t \approx E_t - I_a X_s$$



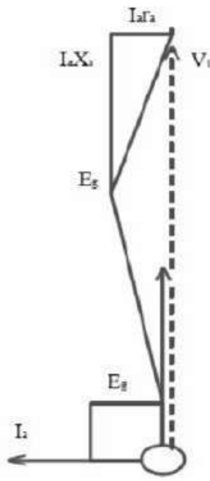
1.12 (i) Phasor diagram for different R loads



(i)



(ii)



(iii)

Fig: 1.13 Variation of voltage with load at constant Excitation

which is the straight line marked for cos ϕ0 lagging in Fig.1.14. A leading load of zero power factor Fig. 1.14 will have the voltage

$$V_t \approx E_t + I_aX_s$$

another straight line for which, by reason of the direct magnetizing effect of leading currents, the voltage increases with load.

Intermediate load power factors produce voltage/current characteristics resembling those in Fig: 1.13 The voltage-drop with load (i.e. the regulation) is clearly dependent upon the power factor of the load. The short-circuit current I_{sc} at which the load terminal voltage falls to zero may be about 150 per cent (1.5 per unit) of normal current in large modern machines.

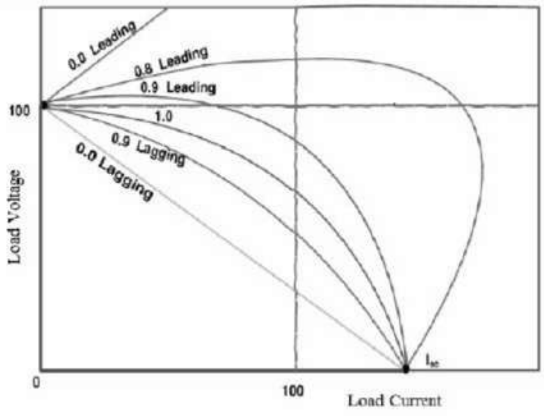


Fig: 1.14 Load characteristics of Alternator

1. 14 Potier Reactance

For obtaining potier reactance Zero Power Factor test is conducted by connecting the alternator to ZPF load and exciting the alternator in such way that the alternator supplies the rated current at rated voltage running at rated speed. To plot ZPF characteristics only two points are required. One point is corresponding to the zero voltage and rated current that can be obtained from scc and the other at rated voltage and rated current under zpf load. This zero power factor curve appears like OCC but shifted by a factor I_aX_L vertically and horizontally by armature reaction mmf as shown below in Fig: 1.15. Following are the steps to draw ZPF characteristics.

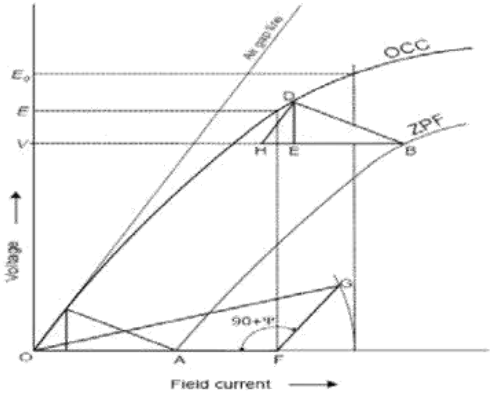


Fig: 1.15

By suitable tests plot OCC and SCC. Draw air gap line. Conduct ZPF test at full load for rated voltage and fix the point B. Draw the line BH with length equal to field current required to produce full load current on short circuit. Draw HD parallel to the air gap line so as to cut the OCC. Draw DE perpendicular to HB or parallel to voltage axis. Now, DE represents voltage drop IXL and BE represents the field current required to overcome the effect of armature reaction.

Triangle BDE is called **Potier triangle** and XL is the **Potier reactance**.

1.15 Voltage Regulation

When an alternator is subjected to a varying load, the voltage at the armature terminals varies to a certain extent, and the amount of this variation determines the regulation of the machine. When the alternator is loaded the terminal voltage decreases as the drops in the machine stars increasing and hence it will always be different than the induced emf.

Voltage regulation of an alternator is defined as the change in terminal voltage from no load to full load expressed as a percentage of rated voltage when 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 the percentage rise in voltage when full load at the specified power-factor is switched off with speed and field current remaining unchanged expressed as a percentage of rated voltage.

Hence regulation can be expressed as

$$\% \text{ Regulation} =(E-V)/V*100$$

where E_0 = No-load induced emf /phase, Vt = Rated terminal voltage/phase at load

1.16 Methods of finding Voltage Regulation:

The voltage regulation of an alternator can be determined by different methods. In case of small generators it can be determined by direct loading whereas in case of large generators it cannot determined by direct loading but will be usually predetermined by different methods. Following are the different methods used for predetermination of regulation of alternators.

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 non-salient pole machines only. As the alternators are manufactured in large capacity direct loading of alternators is not employed for 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.

1.16.1 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.

Determination of synchronous impedance Z_S:

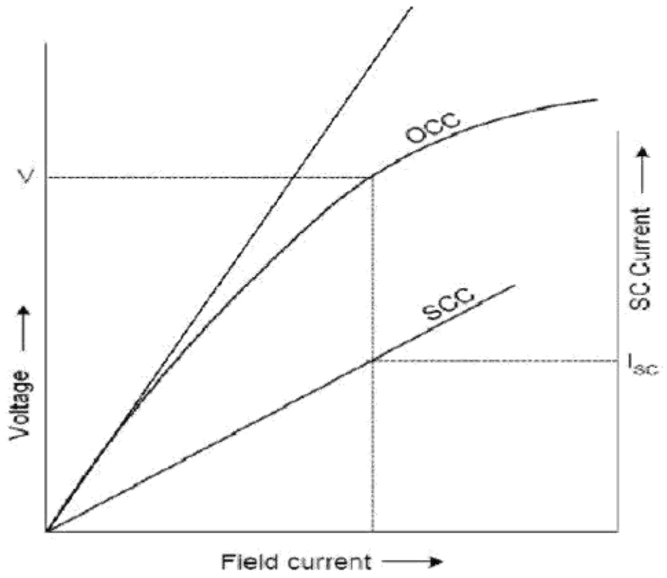


Fig: 1.16 OCC and SCC of alternator

As the terminals of the stator are short circuited in SC test, the short circuit current is circulated against the impedance of the stator called the synchronous impedance. This impedance can be estimated form the oc and sc characteristics.

The ratio of open circuit voltage to the short circuit current at a particular field current, or at a field current responsible for circulating the rated current is called the synchronous impedance.

Synchronous impedance Z_S = (open circuit voltage per phase)/(short circuit current per phase) for same If

Hence Z_S = (Voc) / (Isc) for same If

From Fig: 1.16 synchronous impedance Z_S = V/Isc

Armature resistance R_a of the stator can be measured using Voltmeter - Ammeter method. Using synchronous impedance and armature resistance synchronous reactance and hence regulation can be calculated as follows using emf method.

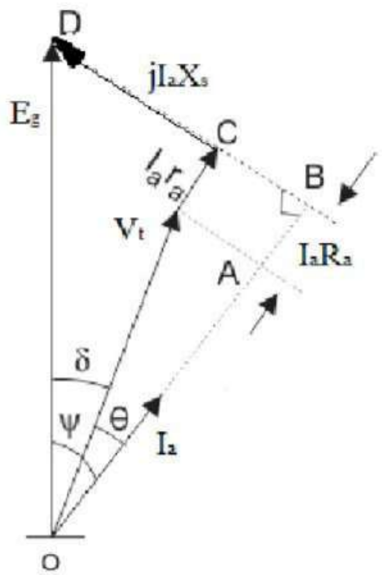


Fig: 1.17

$Z_s = \sqrt{[(R_a)^2 + (X_S)^2]}$ and Synchronous reactance $X_s = \sqrt{[(Z_s)^2 - (R_a)^2]}$

Hence induced emf per phase can be found as $E_g = \sqrt{[(V_t \cos\theta + I_a R_a)^2 + (V_t \sin\theta \pm I_a X_S)^2]}$

where Vt = phase voltage per phase = Vph , Ia = load current per phase

In the above expression in second term + sign is for lagging power factor and - sign is for leading power factor.

$$\% \text{ Regulation} = \frac{E_g - V_t}{V_t}$$

where Eg = no-load induced emf /phase, Vt = rated terminal voltage/phase

Synchronous impedance method is easy but it gives approximate results. This method gives the value of regulation which is greater (poor) than the actual value and hence this method is called pessimistic method. The complete phasor diagram for the emf method is shown in Fig 1.18.

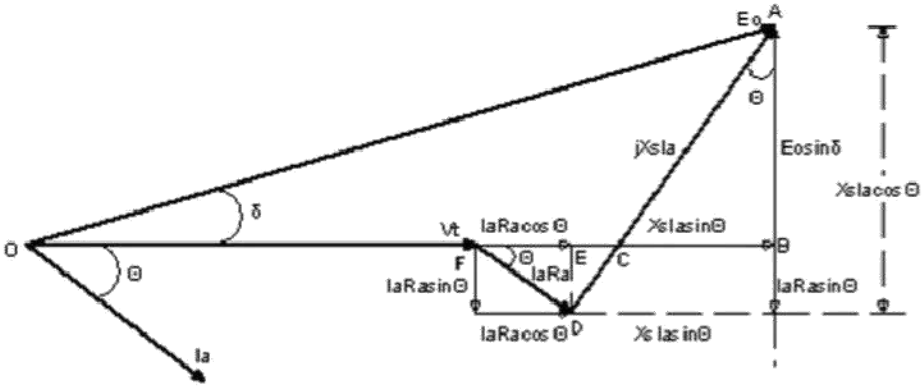


Fig: 1.18

1.13.2 MMF method

This method is also known as amp - turns method. In this method the all the emfs produced by rotor and stator are replaced by their equivalent MMFs (fluxes), and hence called mmf method. In this method also it is assumed that the magnetic circuit is unsaturated. In this method both the reactance drops are replaced by their equivalent mmfs. Fig: 1.19 shows the complete phasor diagram for the mmf method. Similar to emf method OC and SC characteristics are used for the determination of regulation by mmf method. The details are shown in Fig: 1.19. Using the details it is possible determine the regulation at different power factors.

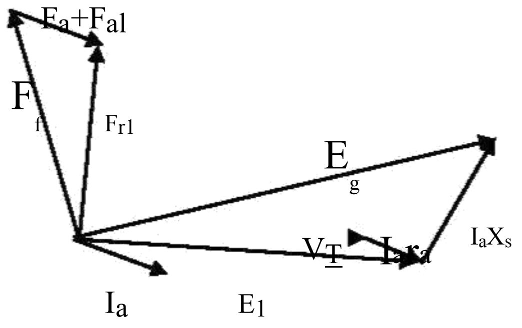


Fig: 1.19

From the phasor diagram it can be seen that the mmf required to produce the emf E1= $(V + IR_a)$ is FR1.In large machines resistance drop may neglected. The mmf required to overcome the reactance drops is (F_a+F_{al}) as shown in phasor diagram. The mmf (F_a+F_{al}) can be found from SC characteristic as under SC condition both reactance drops will be present.

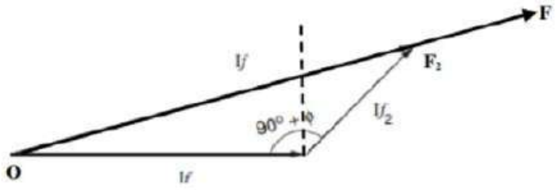
Following procedure can be used for determination of regulation by mmf method.

1. By conducting OC and SC test plot OCC and SCC.
2. From the OCC find the field current *If1* required to produce the voltage, E1= (V + IR_a).
3. From SCC find the magnitude of field current *If2* ($\propto F_a + F_{al}$) to produce the required armature current. $F_a + F_{al}$ can also found from ZPF characteristics.
4. Draw *If2* at angle (90+Φ) from *If1*, where Φ is the phase angle of current w. r. t voltage. If current is leading, take the angle of Φ *If2* as (90-).
5. Determine the resultant field current, *If* and mark its magnitude on the field current axis.
6. From OCC. find the voltage corresponding to *If,* which will be *E0* and hence find the regulation.

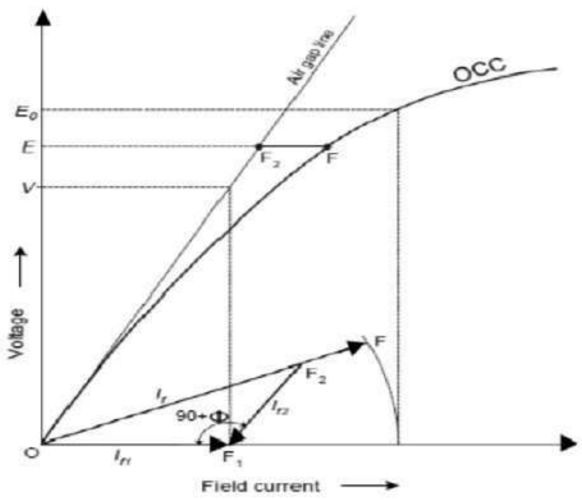
Because of the assumption of unsaturated magnetic circuit the regulation computed by this method will be less than the actual and hence this method of regulation is called optimistic method.

1.13.3 ASA Modified MMF Method:

ASA or modified mmf method consider saturation effect for calculation of regulation. In the mmf method the total mmf F computed is based on the assumption of unsaturated magnetic circuit which is unrealistic. In order to account for the partial saturation of the magnetic circuit it must be increased by a certain amount FF2 which can be computed from occ, scc and air gap lines as explained below referring to Fig: 1.20 (i) and (ii).



(i)



(ii)

Fig: 1.20

If1 is the field current required to induce the rated voltage on open circuit. Draw *If2* with length equal to field current required to circulate rated current during short circuit condition at an angle Φ (90+) from *If1*. The resultant of *If1* and *If2* gives *If* (OF2 in figure). Extend OF2 upto F so that F2F accounts for the additional field current required for accounting the effect of partial saturation of magnetic circuit. F2F is found for voltage E (refer to phasor diagram of mmf method) as shown in Fig: 1.20. Project total field current OF to the field current axis and find corresponding voltage E0 using OCC. Hence regulation can found by ASA method which is more realistic.

1.13.4 Zero Power Factor (ZPF) method or Potier Triangle Method:

During the operation of the alternator, resistance voltage drop I_aR_a and armature leakage reactance drop I_aX_L are actually emf quantities and the armature reaction reactance is a mmf quantity. To determine the regulation of the alternator by this method OCC, SCC and ZPF test details and characteristics are required. AS explained earlier oc and sc tests are conducted and OCC and SCC are drawn. ZPF test is conducted by connecting the alternator to ZPF load and exciting the alternator in such way that the alternator supplies the rated current at rated voltage running at rated speed. To plot ZPF characteristics only two points are required. One point is corresponding to the zero voltage and rated current that can be obtained from scc and the other at rated voltage and rated current under zpf load. This zero power factor curve appears like *OCC* but shifted by a factor I_aX_L vertically and horizontally by armature reaction mmf as shown below in Fig: 1.21. Following are the steps to draw ZPF characteristics.

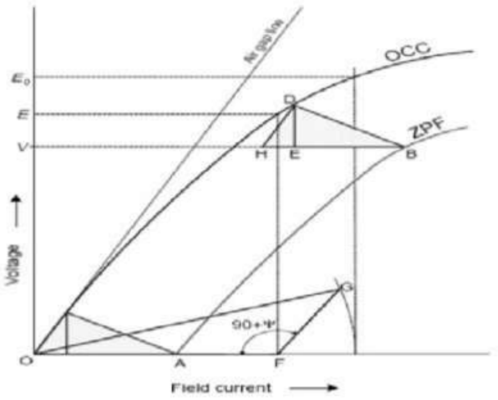


Fig: 1.21

By suitable tests plot OCC and SCC. Draw air gap line. Conduct ZPF test at full load for rated voltage and fix the point B. Draw the line BH with length equal to field current required to produce full load current on short circuit. Draw HD parallel to the air gap line so as to cut the OCC. Draw DE perpendicular to HB or parallel to voltage axis. Now, DE represents voltage drop *IXL* and BE represents the field current required to overcome the effect of armature reaction.

Triangle BDE is called Potier triangle and XL is the Potier reactance. Find E from *V, IRa*, *IXL* Φ and . Use the expression $\sqrt{}E = [(V\Phi\cos + I_aRa)_2 + (\Phi V_t \sin) + I_aX_L)_2]$ to compute E. Find field current corresponding to *E*. 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).

The resultant field current is given by OG. Mark this length on field current axis. From OCC find the corresponding *E0*. Find the regulation.

1.14 Power angle characteristics

When the synchronous generator feeding power to the infinite bus-bar at constant terminal voltage V_t as shown in single line diagram in Fig: 1.22 the phasor diagram for lagging power factor is shown if Fig: 1.23. For large size of generator armature resistance r_a is negligible.

Fig: 1.22 Cylindrical-rotor alternator connected to infinite bus-bar single line diagram

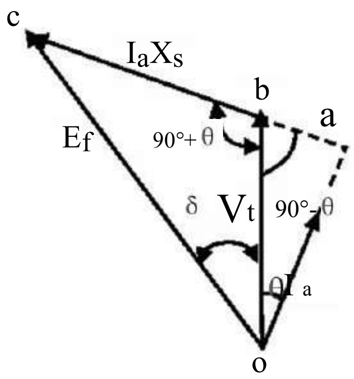


Fig: 1.23 Phasor diagram of an alternator for lagging power factor load with neglected armature resistance

The per phase power delivered to the infinite bus is given by

$$P = V_t I_a \cos\theta$$

It is seen that $\angle oba = 90 - \theta$ and $\angle obc = 180 - (90 - \theta) = 90 + \theta$. The triangle obc reveals that

$$\frac{bc}{\sin\angle boc} = \frac{oc}{\sin\angle obc} \text{ or } \frac{X_s I_a}{\sin\delta} = \frac{E_f}{\sin(90+\theta)}$$

or, $X_s I_a \sin(90 + \theta) = E_f \sin\delta$

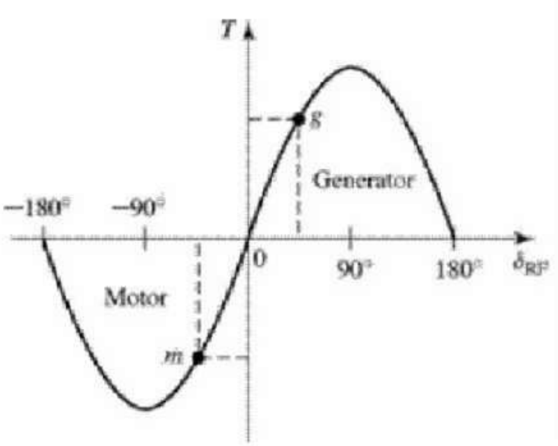
$X_s I_a \cos\theta = E_f \sin\delta$

$$I_a \cos\theta = \frac{E_f \sin\delta}{X_s}$$

Substitution of value of $I_a \cos\theta$ in power equation

$$P = \frac{E_f V_t \sin}{X_s}$$

The variation of power as derived above with respect to power-angle δ is plotted in Fig; 1.24. The power versus load angle characteristic curve has a sinusoidal shape and is usually called power-angle characteristic of the cylindrical-rotor synchronous machine. The power P, for generator is taken as positive and therefore, for motor as negative.



Fig; 1.24 Power angle characteristic

Salient pole alternators and Blondel's Two Reaction Theory

The details of synchronous generators developed so far is applicable to only round rotor or non-salient pole alternators. In such machines the air gap is uniform throughout and hence the effect of mmf will be same whether it acts along the pole axis or the inter polar axis. Hence reactance of the stator is same throughout 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 are called 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 of the stator cannot be same when the mmf is acting along d - axis and q-axis. As the length of the air gap 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-axis more flux is produced than q-axis. Therefore the reactance due to armature reaction will be different along 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 taken as two components - one acting along the direct axis (coinciding with the main field pole axis) and the other 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 the same magnetic circuit. Hence the effect of the armature reaction cannot be taken into account by considering only the synchronous reactance, in the case of a salient pole synchronous machine.

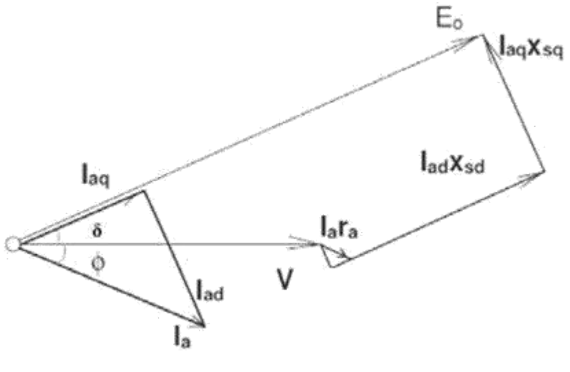
In fact, the direct-axis component F_{ad} acts over a magnetic circuit identical with that of the main field system and produces a comparable effect while the quadrature-axis component F_{aq} acts along the interpolar axis, resulting in an altogether smaller effect and, in addition, a flux distribution totally different from that of F_{ad} 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 the performance obtained from an actual test.

Direct-axis and Quadrature-axis Synchronous Reactances

Blondel's two-reaction theory considers the effects of the quadrature and direct-axis components of the armature reaction separately. Neglecting saturation, their different effects are considered by assigning to each an appropriate value of armature-reaction "reactance," respectively x_{ad} and x_{aq} . The effects of armature resistance and true leakage reactance (X_L) may be treated separately, or may be added to the armature reaction coefficients on the assumption that they are the same, for either the direct-axis or quadrature-axis components of the armature current (which is almost true). Thus the combined reactance values can be expressed as,

$X_{sd} = x_{ad} + x$, and $X_{sq} = x_{aq} + x$, for the direct- and cross-reaction axes respectively.

In a salient-pole machine, x_{aq}, the quadrature-axis reactance is smaller than x_{ad}, the direct-axis reactance, since the flux produced by a given current component in that axis is smaller as the reluctance of the magnetic path consists mostly of the interpolar spaces. It is essential to clearly note the difference between the quadrature and direct-axis components I_{aq}, and I_{ad} of the armature current I_a, and the reactive and active components I_{aa} and I_{ar}. Although both pairs are represented by phasors in phase quadrature, the former are related to the induced emf E_t while the latter are referred to the 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, shown in Fig



Phasor diagram of salient-pole alternator

$$I_{aq} = I_a \cos(\delta+\varphi); \quad I_{ad} = I_a \sin(\delta+\varphi); \quad \text{and} \quad I_a = \sqrt{[(I_{aq})^2 + (I_{ad})^2]}$$

$$I_{aa} = I_a \cos\varphi; \quad I_{ar} = I_a \sin\varphi; \quad \text{and} \quad I_a = \sqrt{[(I_{aa})^2 + (I_{ar})^2]}$$

where δ = torque or power angle and φ = the p.f. angle of the load.

Power Angle Characteristic of Salient Pole Machine

Neglecting the armature winding resistance, the power output of the generator is given by:

$$P = V * I_a * \cos\phi$$

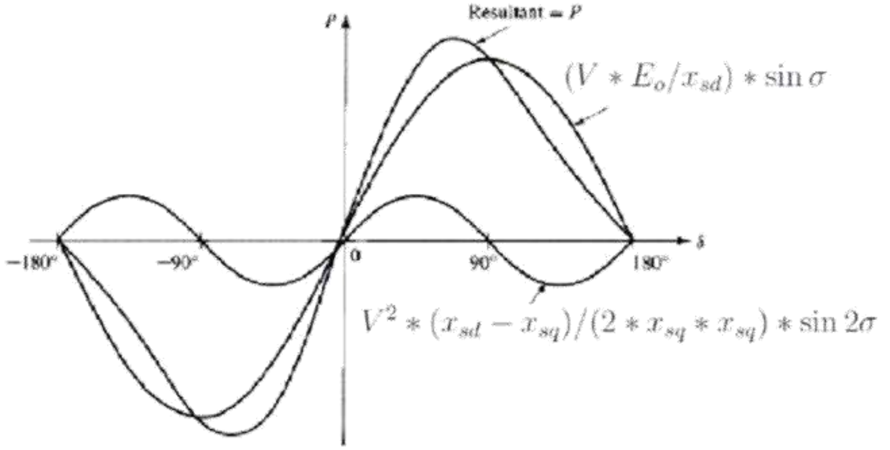
This can be expressed in terms of $\sigma\sigma$,

$$\begin{aligned} I_a * \cos\phi &= I_{aq} * \cos\sigma + I_{ad} * \sin\sigma \\ V * \cos\sigma &= E_o - I_{ad} * x_{sd} \\ \text{and } V * \sin\sigma &= I_{aq} * x_{sd} \end{aligned}$$

Substituting these in the expression for power, we have.

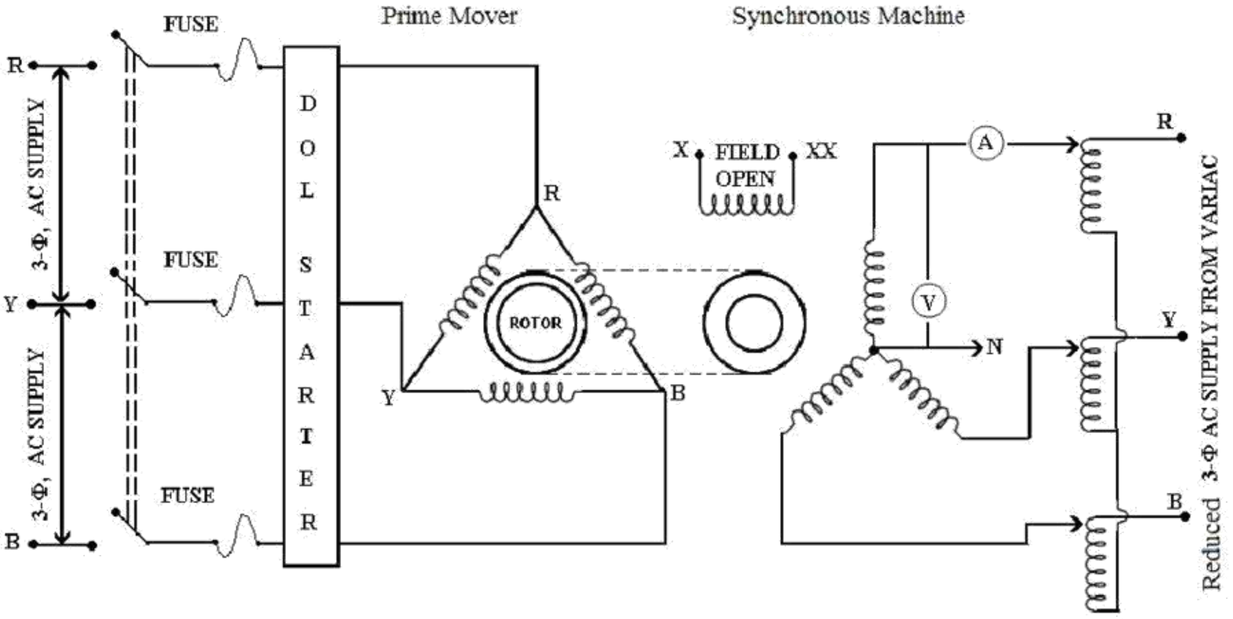
$$\begin{aligned} P &= V[(V * \sin\sigma / x_{sd}) * \cos\sigma + (E_o - V * \cos\sigma)/x_{sd} * \sin\sigma] \\ &= (V * E_o / x_{sd}) * \sin\sigma + V^2 * (x_{sd} - x_{sq})/(2 * x_{sq} * x_{sq}) * \sin 2\sigma \end{aligned}$$

synchronous machine. This also shows that it is possible to generate an emf even if the excitation E_0 is zero. However this magnitude is quite less compared with that obtained with a finite E_0. Likewise It is clear from the above expression that the power is a little more than that for a cylindrical rotor synchronous machine, as the first term alone represents the power for a cylindrical rotor synchronous machine. A term in (sin 2 $\sigma\sigma$) is added into the power - angle characteristic of a non-salient pole we can show that the machine develops a torque - called the reluctance torque - as this torque is developed due to the variation of the reluctance in the magnetic circuit even if the excitation E_0 is zero. Fig: shows the typical power angle characteristic of a salient pole alternator.



Slip Test

From this test the values of X_d and X_q are determined by applying a balance reduced external voltage (say, V volts, around 25% of rated value) to the armature. The field winding remains unexcited. The machine is run at a speed a little less than the synchronous speed (the slip being less than 1%) using a prime mover (or motor). Connection diagram is shown in circuit diagram.



Due to voltage V applied to the stator terminal a current I will flow causing a stator mmf. This stator mmf moves slowly relative to the poles and induced an emf in the field circuit in a similar fashion to that of rotor in an induction motor at slip frequency. The effect will be that the stator mmf will moves slowly relative to the poles.

The physical poles and the armature-reaction mmf are alternately in phase and out, the change occurring at slip frequency. When the axis of the pole and the axis of the armature reaction mmf wave coincide, the armature mmf acts through the field magnetic circuit. Since the applied voltage is constant, the air-gap flux would be constant. When crest of the rotating armature mmf is in line with the field-pole axis, minimum air-gap offers minimum reluctance thus the current required in armature for the establishment of constant air-gap flux must be minimum. Constant applied voltage minus the minimum impedance voltage drop in the armature terminal gives maximum armature terminal voltage. Thus the d-axis synchronous reactance is given by

$$X_d = \frac{\text{Maximum armature terminal voltage per phase}}{\text{Minimum armature current per phase}}$$

Similarly

$$X_q = \frac{\text{Minimum armature terminal voltage per phase}}{\text{Maximum armature current per phase}}$$

Parallel Operation of Alternators

The operation of connecting an alternator in parallel with another alternator or with common bus-bars is known as ***synchronizing***. Generally, alternators are used in a power system where they are in parallel with many other alternators. It means that the alternator is connected to a live system of constant voltage and constant frequency. Often the electrical system, to which the alternator is connected, has already so many alternators and loads connected to it that no matter what power is delivered by the incoming alternator, the voltage and frequency of the system remain the same. In that case, the alternator is said to be connected to ***infinite*** bus-bars.

For proper synchronization of alternators, the following four conditions must be satisfied

1. The terminal voltage (effective) of the incoming alternator must be the same as bus-bar voltage.
2. The speed of the incoming machine must be such that its frequency (= *PN*/60) equals bus-bar frequency.
3. The phase of the alternator voltage must be identical with the phase of the bus-bar voltage.
4. The phase angle between identical phases must be zero.

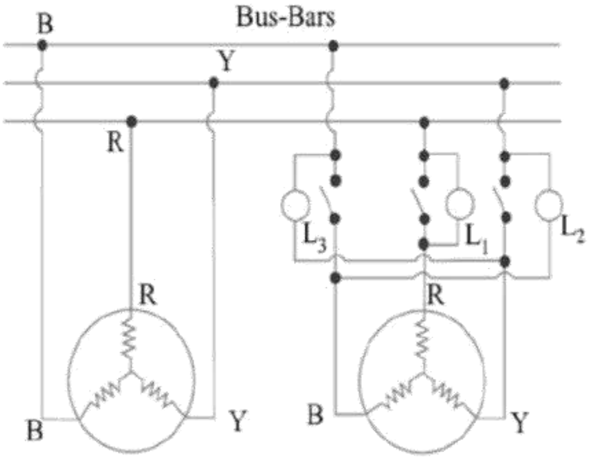
It means that the switch must be closed at (or very near) the instant the two voltages have correct phase relationship.

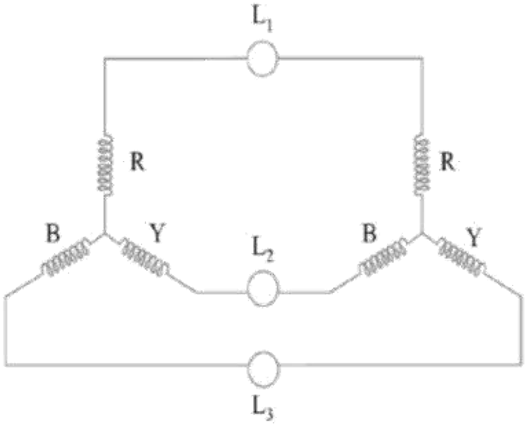
Condition (1) is indicated by a voltmeter, conditions (2), (3) and (4) are indicated by synchronizing lamps or a synchronoscope.

The synchronizing lamp method is consists of 3 lamps connected between the phases of the running 3-ph generator and the incoming generator as shown in Fig:

In three phase alternators, it is necessary to synchronize one phase only, the other two phases be will then synchronized automatically. However, first it is necessary that the incoming alternator is correctly 'phased out' *i.e.* the phases are connected in the proper order of R, Y &B not R, B, Y etc.

Lamp L1 is connected between R and R', $L2$ between Y and B' (not Y and Y') and $L3$ between B and Y' (and not B and B') as shown in Fig:





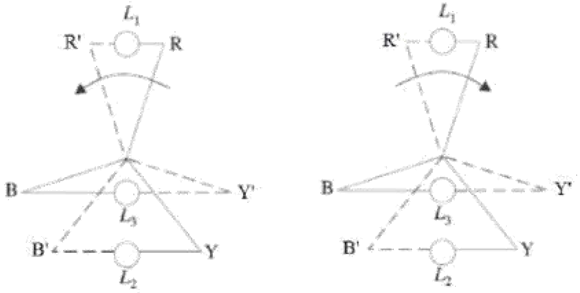


Fig: 2.6

Two set of star vectors will rotate at unequal speeds if the frequencies of the two are different. If the incoming alternator is running faster, then voltage star $R'\,Y'\,B'$ appear to rotate anticlockwise with respect to the bus-bar voltage star RYB at a speed corresponding to the difference between their frequencies. With reference to Fig: 2.6, it is seen that voltage across $L1$ is RR' to be increasing from zero, and that across $L2$ is YB' which is decreasing, having just passed through its maximum, and that across $L3$ BY' which is increasing and approaching its maximum. Hence the lamps will light up one after the other in the order 2, 3, 1,2,3,1 or 1, 2, 3. If the incoming alternator is running slower, then the sequence of light up will be 1, 3, 2. Synchronization is done at the moment the uncrossed lamp $L1$ is in the middle of the dark period and other two lamps are equally bright. Hence this method of synchronization is known as two bright one dark lamp method.

It should be noted that synchronization by lamps is not quite accurate, because to a large extent, it depends on the sense of correct judgment of the operator. Hence, to eliminate the element of personal judgment in routine operation of alternators, the machines are synchronized by a more accurate device called a synchronoscope as shown in Fig: It consists of 3 stationary coils and a rotating iron vane which is attached to a pointer. Out of three coils, a pair is connected to one phase of the line and the other to the corresponding machine terminals, potential transformer being usually used. The pointer moves to one side or the other from its vertical position depending on whether the incoming machine is too fast or too slow. For correct speed, the pointer points vertically up.

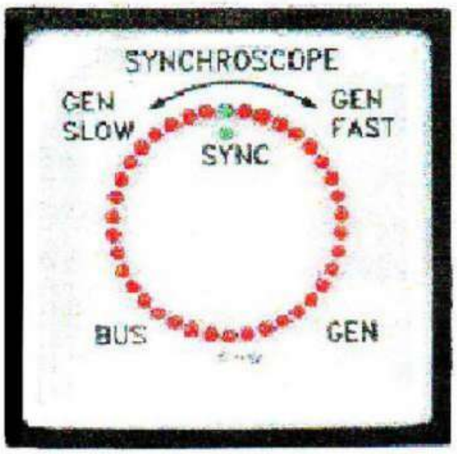
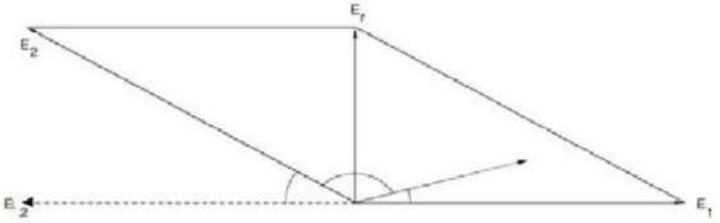


Fig:

Synchronizing Current:

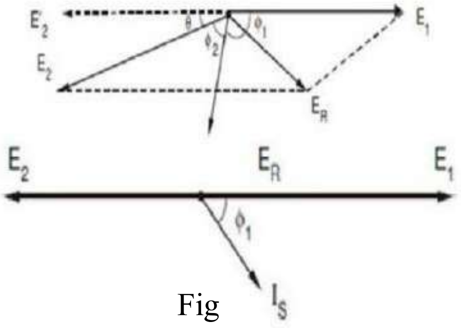
If two alternators generating exactly the same emf are perfectly synchronized, there is no resultant emf acting on the local circuit consisting of their two armatures connected in parallel. No current circulates between the two and no power is transferred from one to the other. Under this condition emf of alternator 1, i.e. E1 is equal to and in phase opposition to emf of alternator 2, i.e. E2 as shown in the Figure .There is, apparently, no force tending to keep them in synchronism, but as soon as the conditions are disturbed a synchronizing force is developed, tending to keep the whole system stable. Suppose one alternator falls behind a little in phase by an angle . The two alternator emfs now produce a resultant voltage and this acts on the local circuit consisting of the two armature windings and the joining connections. In alternators, the synchronous reactance is large compared with the resistance, so that the resultant circulating current Is is very nearly in quadrature with the resultant emf Er acting on the circuit. Figure represents a single phase case, where E1 and E2 represent the two induced emfs, the latter having fallen back slightly in phase. The resultant emf, Er, is almost in quadrature with both the emfs, and gives rise to a current, *Is*, lagging behind *Er* by an angle approximating to a right angle. It is, thus, seen that *E*1 and *Is* are almost in phase. The first alternator is generating a power *E*1 *Is* cos 1, which is positive, while the second one is generating a power *E*2 *Is* cos 2, which is negative, since cos 2 is negative. In other words, the first alternator is supplying the second with power, the difference between the two amounts of power represents the copper losses occasioned by the current *Is* flowing through the circuit which possesses resistance. This power output of the first alternator tends to retard it, while the power input to the second one tends to accelerate it till such a time that *E*1 and *E*2 are again in phase opposition and the machines once again work in perfect synchronism. So, the action helps to keep both machines in stable synchronism. The current, *Is*, is called the synchronizing current.



Fig

Effect of Change of Excitation:

A change in the excitation of an alternator running in parallel with other affects only its KVA output; it does not affect the KW output. A change in the excitation, thus, affects only the power factor of its output. Let two similar alternators of the same rating be operating in parallel, receiving equal power inputs from their prime movers. Neglecting losses, their kW outputs are therefore equal. If their excitations are the same, they induce the same emf, and since they are in parallel their terminal voltages are also the same. When delivering a total load of I amperes at a power-factor of cos ϕ, each alternator delivers half the total current and $I_1 = I_2 = I/2$.



Fig

Since their induced emfs are the same, there is no resultant emf acting around the local circuit formed by their two armature windings, so that the synchronizing current, Is, is zero. Since the armature resistance is neglected, the vector difference between $E_1 = E_2$ and V is equal to, $I_1X_{s1} = I_2X_{s2}$, this vector leading the current I by 90_0, where X_{S1} and X_{S2} are the synchronous reactances of the two alternators respectively.

Now consider the effect of reducing the excitation of the second alternator. E_2 is therefore reduced as shown in Figure. This reduces the terminal voltage slightly, so let the excitation of the first alternator be increased so as to bring the terminal voltage back to its original value. Since the two alternator inputs are unchanged and losses are neglected, the two kW outputs are the same as before. The current I_2 is changed due to the change in E_2, but the active components of both I_1 and I_2 remain unaltered. It can be observed that there is a small change in the load angles of the two alternators, this angle being slightly increased in the case of the weakly excited alternator and slightly decreased in the case of the strongly excited alternator. It can also be observed that $I_1 + I_2 = I$, the total load current.

Effect of Change of Input Torque

The amount of power output delivered by an alternator running in parallel with others is governed solely by the power input received from its prime mover. If two alternators only are operating in parallel the increase in power input may be accompanied by a minute increase in their speeds, causing a proportional rise in frequency. This can be corrected by reducing the power input to the other alternator, until the frequency is brought back to its original value. In practice, when load is transferred from one alternator to another, the power input to the alternator required to take additional load is increased, the power input to the other alternator being simultaneously decreased. In this way, the change in power output can be effected without measurable change in the frequency. The effect of increasing the input to one prime mover is, thus, seen to make its alternator take an increased share of the load, the other being relieved to a corresponding extent. The final power-factors are also altered, since the ratio of the reactive components of the load has also been changed. The power-factors of the two alternators can be brought back to their original values, if desired, by adjusting the excitations of alternators.

Load Sharing

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

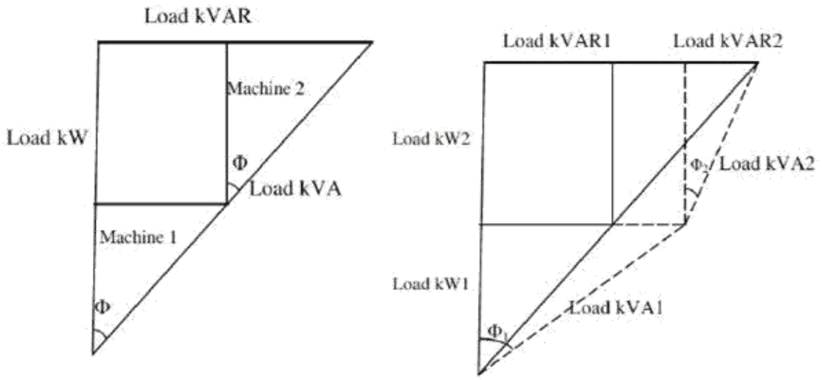


Fig: 2.9

Sharing of load when two alternators are in parallel

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

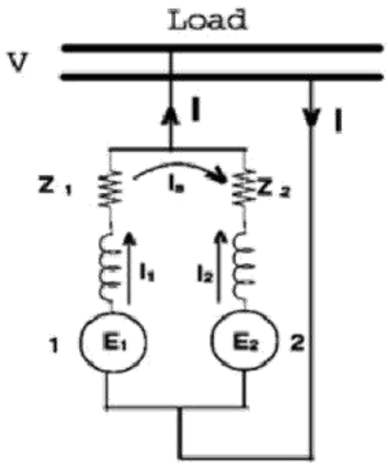


Fig:

Let E_1, E_2 be the induced emf per phase,
Z_1, Z_2 be the impedances per phase,
I_1, I_2 be the current supplied by each machine per phase
Z be the load impedance per phase,
V be the terminal voltage per phase

From the circuit we have $V = E_1 - I_1Z_1 = E_2 - I_2Z_2$
and hence, $I_1 = E_1 - V/Z1$ and $I_2 = E_2 - V/Z_2$

and also $V = (I_1 + I_2)\, Z = IZ$
solving above equations

$$I_1 = [(E_1 - E_2)\, Z + E_1 Z_2] / [\, Z(Z_1 + Z_2) + Z_1Z_2]$$

$$I_2 = [(E_2 - E_1)\, Z + E_2 Z_1] / [\, Z(Z_1 + Z_2) + Z_1Z_2]$$

The total current $I = I_1 + I_2 = [E_1Z_2 + E_2Z_1] / [\, Z(Z_1 + Z_2) + Z_1Z_2]$

And the circulating current or synchronizing current $I_S = (E_1 - E_2) / (Z_1 + Z_2)$

Prime-mover Governor Characteristic

The transfer of active power between alternators in parallel is accomplished by adjustment of the no-load speed setting of the respective prime-mover governors, and the transfer of reactive power is accomplished by adjustment of the respective field rheostats or voltage regulators .A typical prime-mover governor characteristic, shown in Fig: , is a plot of prime-mover speed (or generator frequency) vs. active power. Although usually drawn as a straight line, the actual characteristic has a slight curve. The drooping characteristic shown in the figure provides inherent stability of operation when paralleled with other machines. Machines with zero droop, called isochronous machines, are inherently unstable when operated in parallel; they are subject to unexpected load swings, unless electrically controlled with solid-state regulators.

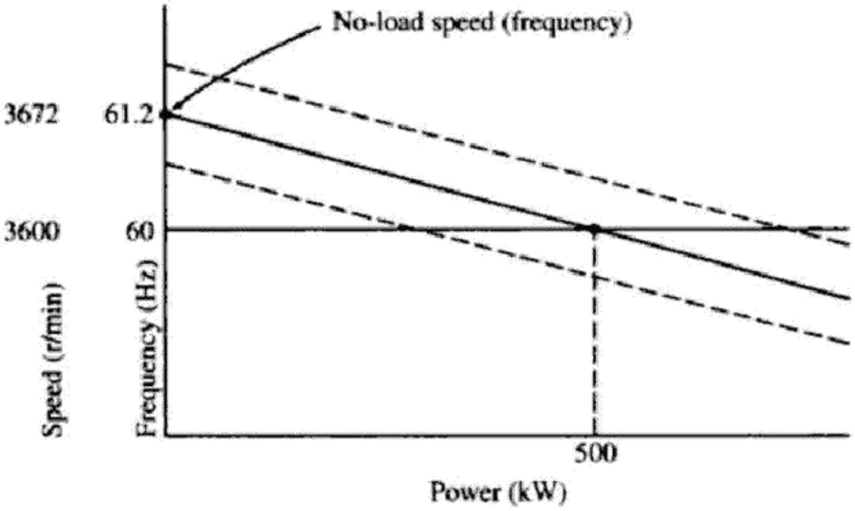
The no-load speed setting (and hence the no-load frequency setting) of a synchronous generator can be changed by remote control from the generator panel by using a remote-control switch. The switch actuates a servomotor that repositions the no-load speed setting of the governor, raising or lowering the characteristic without changing its slope. Curves for different no-load speed settings are shown with broken lines in Figure

Governor Speed Regulation

Governor speed regulation (GSR) is defined as:

$$\mathrm{GSR} = \frac{n_{\mathrm{nl}} - n_{\mathrm{rated}}}{n_{\mathrm{rated}}} = \frac{f_{\mathrm{nl}} - f_{\mathrm{rated}}}{f_{\mathrm{rated}}}$$

Where, n_{rated} = rated speed (r/min)
n_{nl} = no-load speed (r/min)
f_{rated} = rated frequency (Hz) & f_{nl} = no-load frequency (Hz)



$$\mathrm{GD} = \frac{\Delta f}{\Delta P} = \frac{f_{\mathrm{nl}} - f_{\mathrm{rated}}}{P_{\mathrm{rated}}}$$

UNIT II SYNCHRONOUS MOTORS

It may be recalled that a D.C. generator can be run as a D.C. motor. In same way, 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 it found very useful applications because they possess other unique electrical properties.

General Physical Concept

Let assume that the armature winding (laid out in the stator) of a 3-phase synchronous machine is connected to a suitable balanced 3-phase source and the field winding to a D.C source of rated voltage. The current flowing through the field coils will set up stationary magnetic poles of alternate North and South. On the other hand, the 3-phase currents flowing in the armature winding produce a rotating magnetic field rotating at synchronous speed. In other words there will be moving North and South poles established in the stator due to the 3-phase currents i.e at any location in the stator there will be a North pole at some instant of time and it will become a South pole after a time period corresponding to half a cycle. (after a time = $1/2f$, where f = frequency of the supply). Assume that the stationary South pole in the rotor is aligned with the North pole in the stator moving in clockwise direction at a particular instant of time, as shown in Figure below. These two poles get attracted and try to maintain this alignment (as per Lenz's law) and hence the rotor pole tries to follow the stator pole as the conditions are suitable for the production of torque in the clockwise direction. However, the rotor cannot move instantaneously due to its mechanical inertia, and so it needs some time to move. In the meantime, the stator pole would quickly (a time duration corresponding to half a cycle) change its polarity and becomes a South pole. So the force of attraction will no longer be present and instead the like poles experience a force of repulsion as shown in Figs. In other words, the conditions are now suitable for the production of torque in the anticlockwise direction. Even this condition will not last longer as the stator pole would again change to North pole after a time of $1/2f$. Thus the rotor will experience an alternating force which tries to move it clockwise and anticlockwise at twice the frequency of the supply, i.e. at intervals corresponding to $1/2f$ seconds. As this duration is quite small compared to the mechanical time constant of the rotor, the rotor cannot respond and move in any direction. The rotor continues to be stationary only.

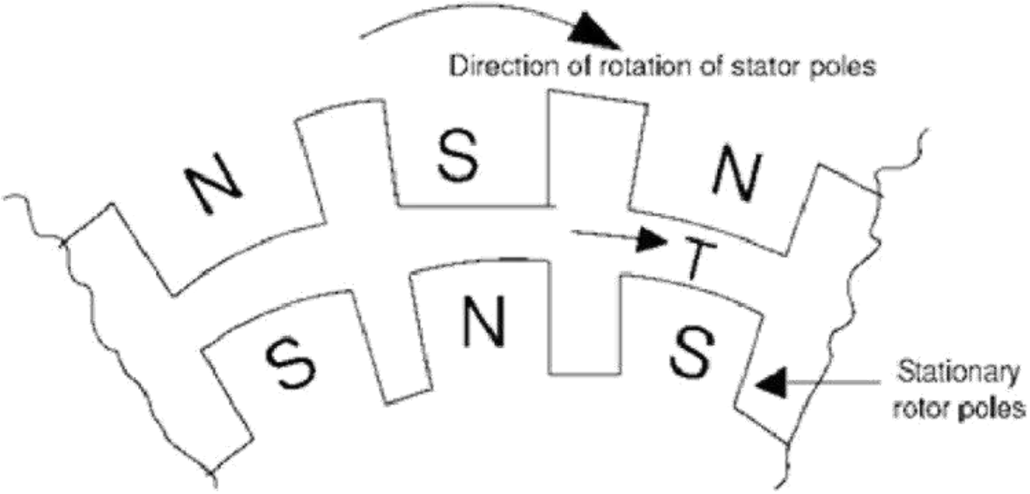


Fig:

On the contrary if the rotor is brought to near synchronous speed by some external device say a small motor mounted on the same shaft as that of the rotor, the rotor poles get locked to the unlike poles in the stator and the rotor continues to run at the synchronous speed even if the supply to the motor is disconnected. Thus the synchronous rotor cannot start rotating on its own when the rotor and stator are supplied with rated voltage and frequency and hence the synchronous motor has no starting torque. So, some special provision has to be made either inside the machine or outside of the machine so that the rotor is brought to near about its synchronous speed. At that time, if the armature is supplied with electrical power, the rotor can pull into step and continue to run at its synchronous speed.

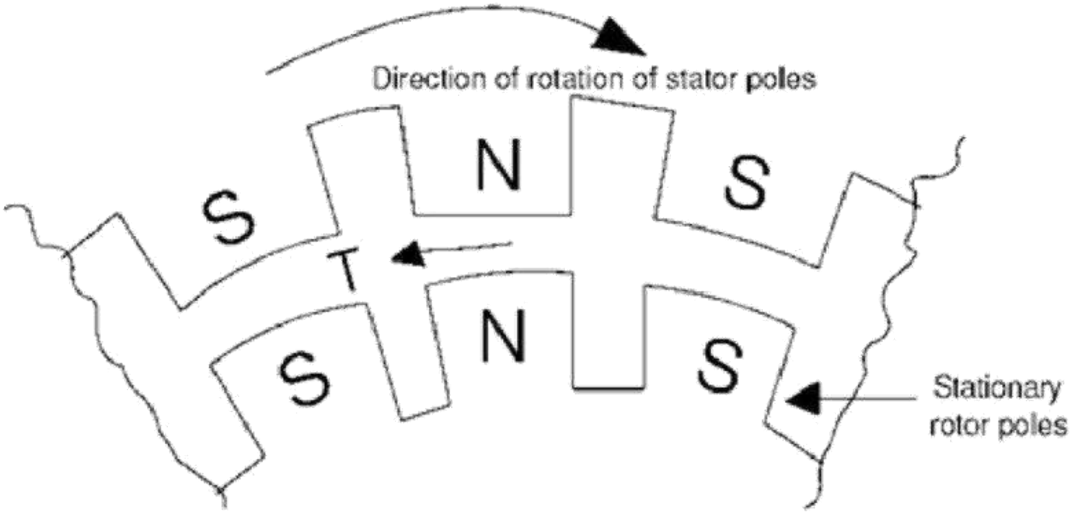


Fig:

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 armature winding in the slots of the stator core and receives power from a 3-phase supply [See (Fig:)].
(ii) a rotor that has a set of salient poles excited by direct current to form alternate N and S poles. The exciting coils are connected in series to two slip rings and direct current is fed into the winding from an external exciter mounted on the rotor shaft. The stator is wound for the same number of poles as the rotor poles. As in the case of an induction motor, the number of poles determines the synchronous speed of the motor,

$$N_s = 120f/P$$

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.

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 N_S and S_S. 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 N_s (= 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., N_S - S_S) and a pair of stationary rotor poles (i.e., N_R - S_R).

(ii) Suppose at any instant, the stator poles are at positions A and B as shown in Fig: 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: Now SS and NR attract 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. Hence, a synchronous motor has no self- starting torque i.e., a synchronous motor cannot start by itself.

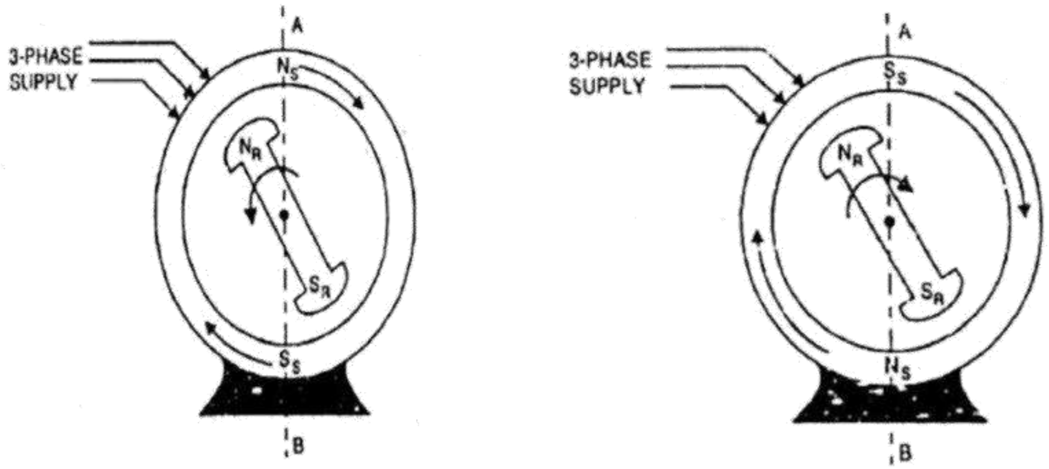


Fig:

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: (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.

(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: (i). This resistance combines with synchronous reactance and gives the synchronous impedance of the machine.

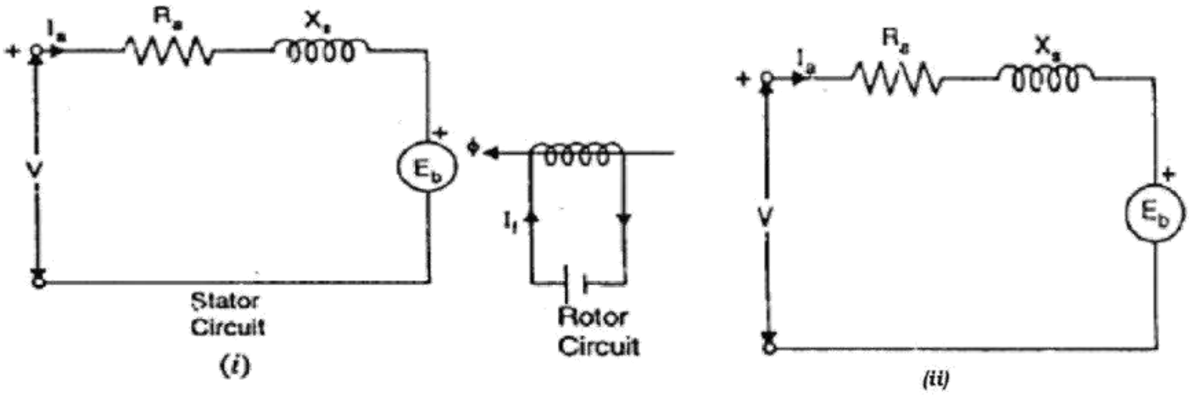


Fig:

(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: 2.23 (i). This generated e.m.f. E_b is known as back e.m.f. and opposes the stator voltage V. The magnitude of E_b depends upon rotor speed and rotor flux ϕ per pole. Since rotor speed is constant; the value of E_b depends upon the rotor flux per pole i.e. exciting rotor current I_f.

Fig: 2.23 (i) shows the schematic diagram for one phase of a star-connected synchronous motor while Fig: 2.23 (ii) shows its equivalent circuit. Referring to the equivalent circuit in Fig: 2.23 (ii). Net voltage/phase in stator winding is

Er = V - Eb phasor difference

Armature current/phase,

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

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

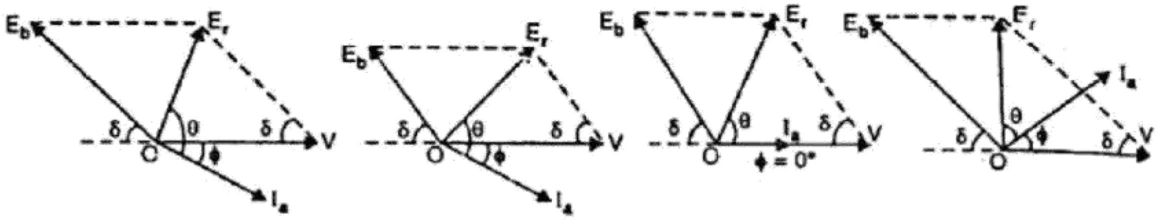
This equivalent circuit helps considerably in understanding the operation of a synchronous motor. A synchronous motor is said to be normally excited if the field excitation is such that Eb = V. If the field excitation is such that Eb < V, the motor is said to be under-excited. The motor is said to be 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.

2.12 Phasor Diagram

Fig: 2.24 shows the phasor diagrams for different field excitations at constant load. Fig: 2.24 (i) shows the phasor diagram for normal excitation (Eb = V), whereas Fig: 2.24 (ii) shows the phasor diagram for under-excitation. In both cases, the motor has lagging power factor. Fig: 2.24 (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: 2.24 (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



$E_b = V$ Lagging p.f. (i)

$E_b < V$ Lagging p.f. (ii)

$E_b > V$ Unity p.f. (iii)

$E_b > V$ Leading p.f. (iv)

Fig: 2.24

Torque and Power Relations

Motor Torque

Gross torque, T =9.55 Pm/Ns N-M where Pm = Gross motor output in watts = Eb Ia cos(d - ф) Ns = Synchronous speed in r.p.m.

Shaft torque, Tsh = 9.55 Psh_{out}/Ns N-M

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

Mechanical Power Developed

Neglecting the armature resistance Fig: 2.25 shows the phasor diagram of an under-excited synchronous motor driving a mechanical load. Since armature resistance Ra is assumed zero. tanq= Xs/Ra = ¥ and hence q =90°.

Input power/phase = V Ia cos ф

Since Ra is assumed zero, stator Cu loss $(I\ Ra)_2$ will be zero. Hence input power is equal to the mechanical power Pm developed by the motor.

Mechanical power developed/ phase, Pm = V Ia cos ф, referring to the phasor diagram in Fig: .

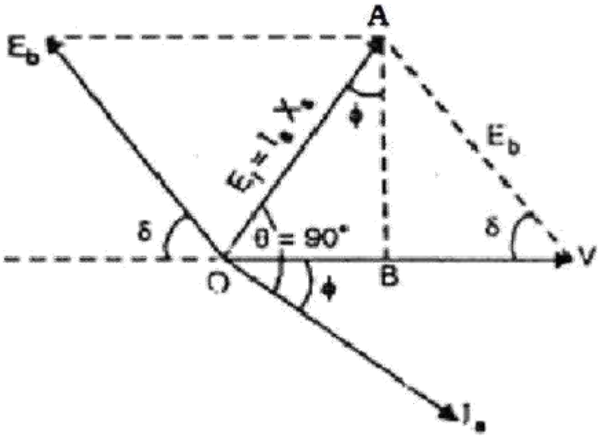


Fig:

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

$$AB = E_b \sin\delta$$

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

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

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

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

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

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

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

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

V-Curves and Inverted V-Curves

It is clear from above discussion that if excitation is varied from very low (under excitation) to very high (over excitation) value, then current Ia decreases, becomes minimum at unity p.f. and then again increases. But initial lagging current becomes unity and then becomes leading in nature. This can be shown as in the Fig: 2.26.

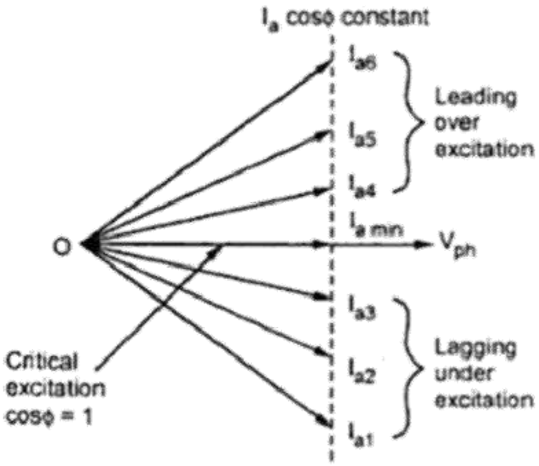


Fig: 2.26

Excitation can be increased by increasing the field current passing through the field winding of synchronous motor. If graph of armature current drawn by the motor (Ia) against field current (I_f) is plotted, then its shape looks like an english alphabet V. If such graphs are obtained at various load conditions we get family of curves, all looking like V. Such curves are called V-curves of synchronous motor. These are shown in the Fig: 2.27 (a).

As against this, if the power factor (cos Φ) is plotted against field current (I_f), then the shape of the graph looks like an inverted V. Such curves obtained by plotting p.f. against If, at various load conditions are called Inverted V-curves of synchronous motor. These curves are shown in the Fig: 2.27 (b).

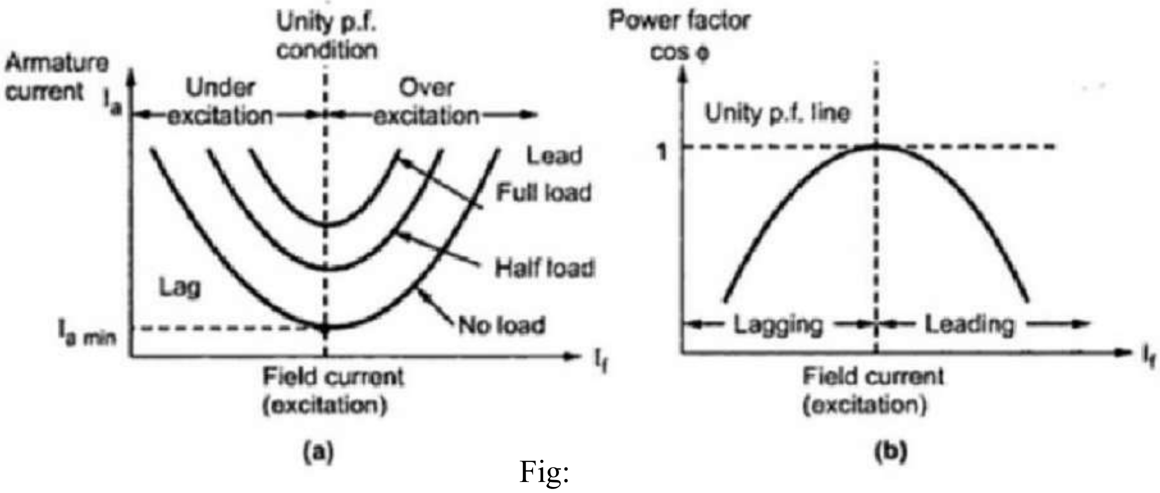


Fig:

Typically, the synchronous machine V-curves are provided by the manufacturer so that the user can determine the resulting operation under a given set of conditions.

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 V*Ia *cos ф) is also constant. This means that the in-phase component Ia cos ϕ 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 synchronous motor for different values of field excitation. Note that extremities of current phasor Ia lie on the straight line AB. hence the power factor cos φ of the motor changes. Fig: shows the phasor diagram of the synchronous motor.

(i) Under excitation

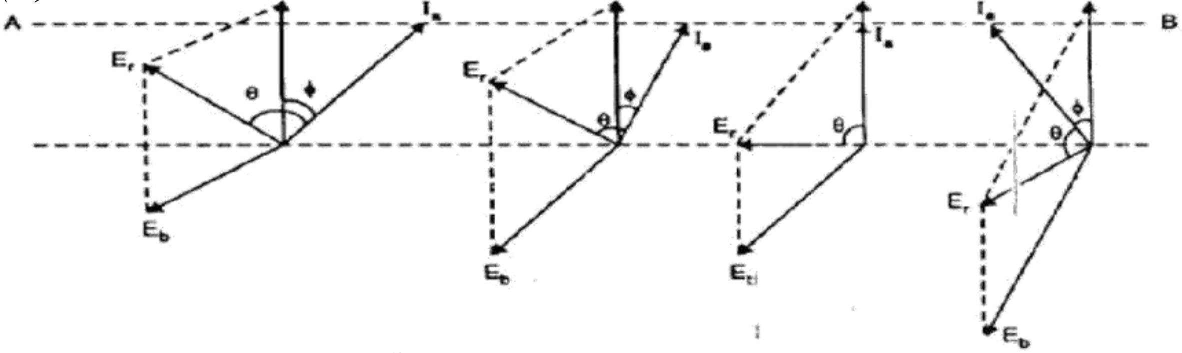
The motor is said to be under-excited if the field excitation is such that Eb < V. Under such conditions, the current Ia lags behind V so that motor power factor is lagging as shown in Fig: (i). This can be easily explained. Since Eb < V, the net voltage Er is decreased and turns clockwise. As angle $\delta\delta$ (= 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: 2.28 (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 ϕ) is unchanged, the stator current Ia must decrease with increase in p.f.

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: 2.28 (iii)]. For a given load, at unity p.f. the resultant Er and, therefore, Ia are minimum.

(iii) Over excitation



$E_b < V$
Under excitation
(*i*)

$V = E_b$
Normal excitation
(*ii*)

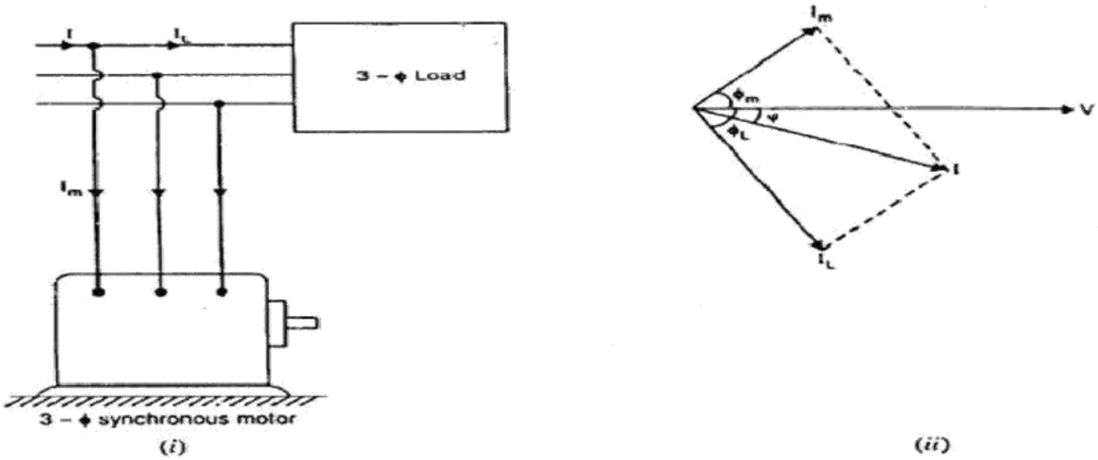
$E_b > V$
Unity p.f.
(*iii*)

$E_b > V$
Over-excitation
(*iv*)

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: 2.28 (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.

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: 2.29 shows the power factor improvement by synchronous condenser method. The 3 - f load takes current IL at low lagging power factor cos ϕ_L. 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 I_L and lags behind the voltage by an angle ϕ. It is clear that ϕ is less than ϕ_L so that cos f is greater than cos ϕ_L. Thus the power factor is increased from cos ϕ_L to cos ϕ. Synchronous condensers are generally used at major bulk supply substations for power factor improvement.



(i) (ii)

Fig:

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 step less control of power factor.

(ii) The motor windings have high thermal stability to short circuit currents. (iii)
The faults can be removed easily.

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.

Methods of starting synchronous motor

There are three chief methods that are used to start a synchronous motor:

1. To reduce the speed of the rotating magnetic field of the stator to a low enough value that the rotor can easily accelerate and lock in with it during one half-cycle of the rotating magnetic

field's rotation. This is done by reducing the frequency of the applied electric power. This method is usually followed in the case of inverter-fed synchronous motor operating under variable speed drive applications.

2. To use an external prime mover to accelerate the rotor of synchronous motor near to its synchronous speed and then supply the rotor as well as stator. Of course care should be taken to ensure that the directions of rotation of the rotor as well as that of the rotating magnetic field of the stator are the same. This method is usually followed in the laboratory- the synchronous machine is started as a generator and is then connected to the supply mains by following the synchronization or paralleling procedure. Then the power supply to the prime mover is disconnected so that the synchronous machine will continue to operate as a motor.
3. To use damper windings if these are provided in the machine. The damper windings are provided in most of the large synchronous motors in order to nullify the oscillations of the rotor whenever the synchronous machine is subjected to a periodically varying load.

Motor Starting by reducing the supply Frequency

If the rotating magnetic field of the stator in a synchronous motor rotates at a low enough speed, there will be no problem for the rotor to accelerate and to lock in with the stator's magnetic field. The speed of the stator magnetic field can then be increased to its rated operating speed by gradually increasing the supply frequency '*f*' up to its normal 50- or 60-Hz value.

But the usual power supply systems generally regulate the frequency to be 50 or 60 Hz as the case may be. However, variable-frequency voltage source can be obtained from a dedicated generator only in the olden days and such a situation was obviously impractical except for very unusual or special drive applications. But the present day solid state power converters offer an easy solution to this. We now have the rectifier- inverter and cycloconverters, which can be used to convert a constant frequency AC supply to a variable frequency AC supply. With the development of such modern solid-state variable-frequency drive packages, it is thus possible to continuously control the frequency of the supply connected to the synchronous motor all the way from a fraction of a hertz up to and even above the normal rated frequency. If such a variable-frequency drive unit is included in a motor-control circuit to achieve speed control, then starting the synchronous motor is very easy-simply adjust the frequency to a very low value for starting, and then raise it up to the desired operating frequency for normal running.

When a synchronous motor is operated at a speed lower than the rated speed, its internal generated voltage applied to the motor must be reduced proportionally with the frequency in order to keep the stator current within the rated value. Generally, the voltage in any variable-frequency power supply voltage (usually called the counter EMF) $E_A = K\varphi\varphi\ \omega\omega$ will be smaller than normal. As such the terminal varies roughly linearly with the output frequency.

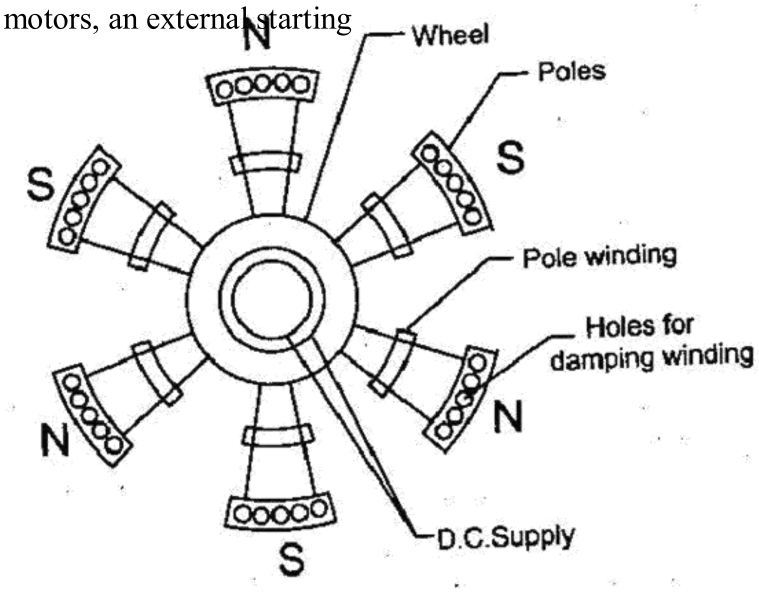
Motor Starting with an External Motor

The second method of starting a synchronous motor is to attach an external starting motor (pony motor) to it and bring the synchronous machine to near about its rated speed (but not exactly equal to it, as the synchronization process may fail to indicate the point of closure of the main switch connecting the synchronous machine to the supply system) with the pony motor. Then the output of the synchronous machine can be synchronised or paralleled with its power supply system as a

generator, and the pony motor can be detached from the shaft of the machine or the supply to the pony motor can be disconnected. Once the pony motor is turned OFF, the shaft of the machine slows down, the speed of the rotor magnetic field B_R falls behind B_{net}, momentarily and the synchronous machine continues to operate as a motor. As soon as it begins to operate as a motor the synchronous motor can be loaded in the usual manner just like any motor.

This whole procedure is not as cumbersome as it sounds, since many synchronous motors are parts of motor-generator sets, and the synchronous machine in the motor-generator set may be started with the other machine serving as the starting motor. Moreover, the starting motor is required to overcome only the mechanical inertia of the synchronous machine without any mechanical load (load is attached only after the synchronous machine is paralleled to the power supply system). Since only the motor's inertia must be overcome, the starting motor can have a much smaller rating than the synchronous motor it is going to start.

Generally most of the large synchronous motors have brushless excitation systems mounted on their shafts. It is then possible to use these exciters as the starting motors. For many medium-size to large synchronous motors, an external starting



motor or starting by using the exciter may be the only possible solution, because the power systems they are tied to may not be able to handle the starting currents needed to use the damper (amortisseur) winding.

Motor Starting by using damper (Amortisseur) Winding

As already mentioned earlier most of the large synchronous motors are provided with damper windings, in order to nullify the oscillations of the rotor whenever the synchronous machine is subjected to a periodically varying load. Damper windings are special bars laid into slots cut in the pole face of a synchronous machine and then shorted out on each end by a large shorting ring, similar to the squirrel cage rotor bars. A salient pole rotor with sets of damper windings is shown in Fig

When the stator of such a synchronous machine is connected to the 3-Phase AC supply, the machine starts as a 3-Phase induction machine due to the presence of the damper bars, just like a squirrel cage induction motor. Just as in the case of a 3-Phase squirrel cage induction motor, the applied voltage must be suitably reduced so as to limit the starting current to the safe rated value. Once the motor picks up to a speed near about its synchronous speed, the DC supply to its field winding is connected and the synchronous motor pulls into step i.e. it continues to operate as a Synchronous motor running at its synchronous speed.

Performance Characteristic

The effects of changes in mechanical or shaft load on armature current, power angle, and power factor can be seen from the phasor diagram shown in Fig: As the applied stator voltage, frequency, and field excitation are assumed, constant. The initial load conditions, are represented by the thick lines. The effect of increasing the shaft load to twice its initial value are represented by the light lines indicating the new steady state conditions. When the shaft load is doubled both Ia cos ϕ and Ef sin δ are doubled. While redrawing the phasor diagrams to show new steady-state conditions, the line of action of the new jIaXs phasor must be perpendicular to the new Ia phasor. Furthermore, as shown in Fig: if the excitation is not changed, increasing the shaft load causes the locus of the Ef phasor to follow a circular arc, thereby increasing its phase angle with increasing shaft load. Note also that an increase in shaft load is also accompanied by a decrease in ϕ ; resulting in an increase in power factor.

As additional load is placed on the machine, the rotor continues to increase its angle of lag relative to the rotating magnetic field, thereby increasing both the angle of lag of the counter EMF phasor and the magnitude of the stator current. It is interesting to note that during all this load variation, however, except for the duration of transient conditions whereby the rotor assumes a new position in relation to the rotating magnetic field, the average speed of the machine does not change. As the load is being increased, a final point is reached at which a further increase in δ fails to cause a corresponding increase in motor torque, and the rotor pulls out of synchronism. In fact as stated earlier, the rotor poles at this point, will fall behind the stator poles such that they now come under the influence of like poles and the force of attraction no longer exists. Thus, the point of maximum torque occurs at a power angle of approximately 90° for a cylindrical-rotor machine. This maximum value of torque that causes a synchronous motor to pull out of synchronism is called the pull-out torque. In actual practice, the motor will never be operated at power angles close to 90° as armature current will be many times its rated value at this load.

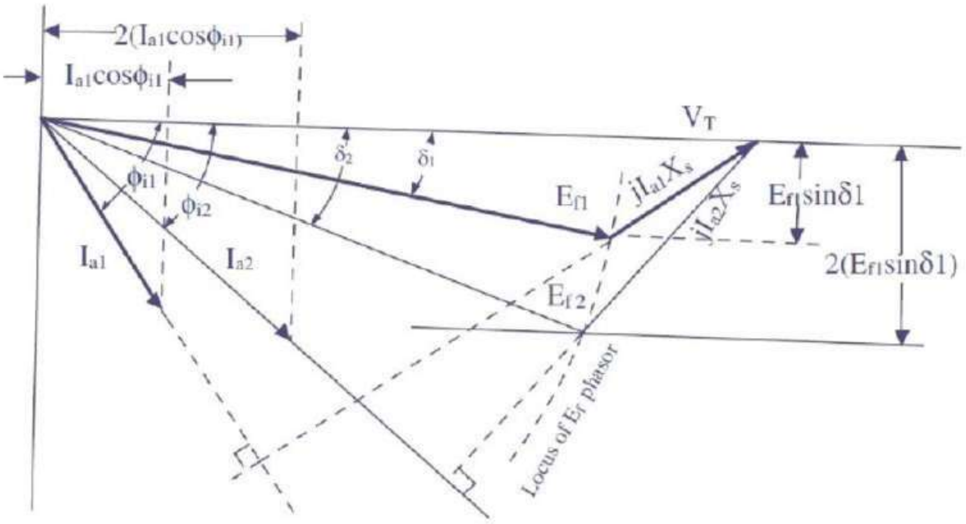


Fig:

Effect of changes in field excitation on synchronous motor performance

As increasing the strength of the magnets will increase the magnetic attraction, and thereby cause the rotor magnets to have a closer alignment with the corresponding opposite poles of the rotating magnetic poles of the stator. This will obviously result in a smaller power angle. When the shaft load is assumed to be constant, the steady-state value of Ef sin δ must also be constant. An increase in Ef will cause a transient increase in Ef sin δ, and the rotor will accelerate. As the rotor changes its angular position, δ decreases until Ef sin δ has the same steady-state value as before, at which time the rotor is again operating at synchronous speed, as it should run only at the synchronous speed. This change in angular position of the rotor magnets relative to the poles of rotating magnetic field of the stator occurs in a fraction of a second. The effect of changes in field excitation on armature current, power angle, and power factor of a synchronous motor operating with a constant shaft load, from a constant voltage, constant frequency supply, is illustrated in Fig: 2.32. For a constant shaft load,

$$E_{f1}\sin\delta_1 = E_{f2}\sin\delta_2 = E_{f3}\sin\delta_3 = E_f\sin\delta$$

This is shown in Fig. 57, where the locus of the tip of the Ef phasor is a straight line parallel to the V_T phasor. Similarly, for a constant shaft load,

$$I_{a1}\cos\phi_{i1} = I_{a2}\cos\phi_{i2} = I_{a3}\cos\phi_{i3} = I_a\cos\phi_i$$

This is also shown in Fig. 57, where the locus of the tip of the Ia phasor is a line perpendicular to the VT phasor.

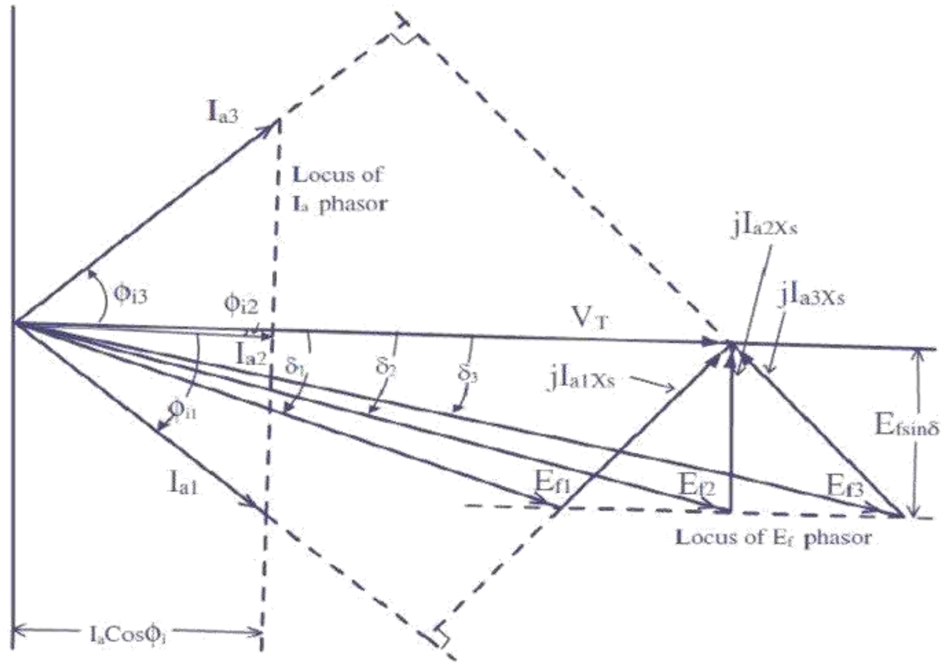


Fig:

Note that increasing the excitation from Ef1 to Ef3 in Fig: caused the phase angle of the current phasor with respect to the terminal voltage VT (and hence the power factor) to go from lagging to leading. The value of field excitation that results in unity power factor is called normal excitation. Excitation greater than normal is called over excitation, and excitation less than normal is called under excitation. Furthermore, as indicated in Fig: 2.32, when operating in the overexcited mode, |Ef | > |VT |. In fact a synchronous motor operating under over excitation condition is sometimes called a synchronous condenser.

Power Factor Characteristic 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 under excited and delivers reactive power to source when it is over-excited.

Hunting and Damper Winding:

Hunting:

Sudden changes of load on synchronous motors may sometimes set up oscillations that are superimposed upon the normal rotation, resulting in periodic variations of a very low frequency in speed. This effect is known as hunting or phase-swinging. Occasionally, the trouble is aggravated by the motor having a natural period of oscillation approximately equal to the hunting period. When the synchronous motor phase-swings into the unstable region, the motor may fall out of synchronism.

Damper winding:

The tendency of hunting can be minimized by the use of a damper winding. Damper windings are placed in the pole faces. No emfs are induced in the damper bars and no current flows in the damper winding, which is not operative. Whenever any irregularity takes place in the speed of rotation, however, the polar flux moves from side to side of the pole, this movement causing the flux to move backwards and forwards across the damper bars. Emfs are induced in the damper bars forwards across the damper winding. These tend to damp out the superimposed oscillatory motion by absorbing its energy. The damper winding, thus, has no effect upon the normal average speed, it merely tends to damp out the oscillations in the speed, acting as a kind of electrical flywheel. In the case of a three-phase synchronous motor the stator currents set up a rotating mmf rotating at uniform speed and if the rotor is rotating at uniform speed, no emfs are induced in the damper bars. Fig: shows a salient pole synchronous motor with damper winding.

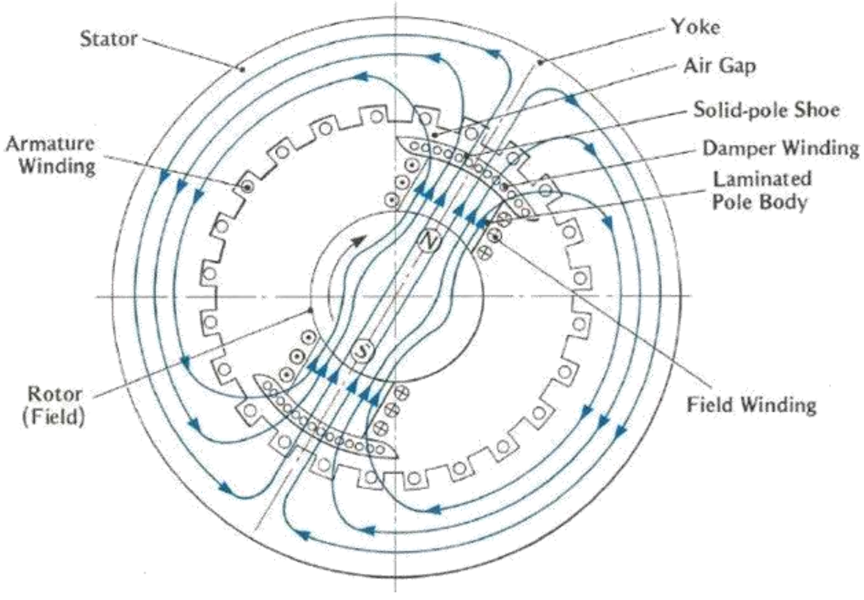


Fig:

Synchronous Induction Motor

In the applications where high starting torque and constant speed are desired then synchronous induction motor can be used. It has the advantages of both synchronous motor and induction motor. The synchronous motor gives constant speed whereas induction motors can be started against full load torque.

Consider a normal slip ring induction motor having three phase winding on the rotor .The motor is connected to the exciter which gives D.C. supply to the rotor through slip rings. One phase carries full D.C. current while the other two carries half the full D.C. current as they are connected in parallel. Due to this D.C. excitation, permanent poles (N and S) formed on the rotor.

Initially it is run as a slip ring induction motor with the help of starting resistances. When the resistances are cut out the motor runs with a slip. Now the connections are changed and the exciter is connected in series with the rotor windings which will remain in the circuit permanently.

As the motor is running as induction motor initially high starting torque (up to twice full load value) can be developed. When the D.C. excitation is provided it is pulled into synchronism and starts running at constant speed. Thus synchronous induction motor provides constant speed, large starting torque, low starting current and power factor correction.

UNIT III THREE PHASE INDUCTION MOTOR

3.1 Three Phase Induction Motor

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

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

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

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

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

3.2 Types and Construction of Three Phase Induction Motor

Three phase induction motors are constructed into two major types:

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

3.2.1 *Squirrel cage Induction Motors*

(a) Stator Construction

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

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

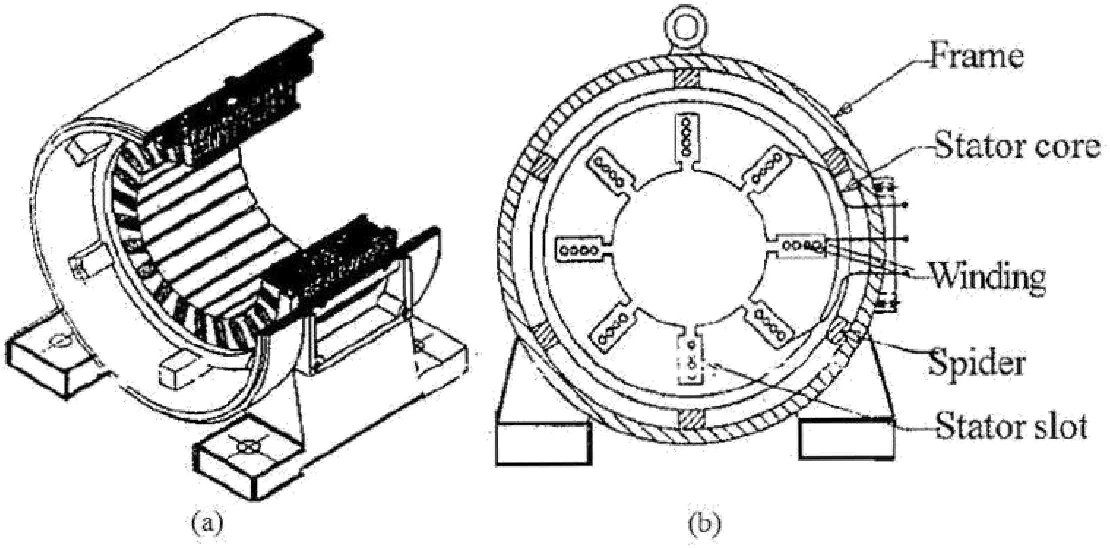


Fig: 3.1

(b) Rotor Construction

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

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

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

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

(c) End Shields

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

3.2.2 *Slip ring Induction Motors*

(a) Stator Construction

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

(b) Rotor Construction

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

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

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

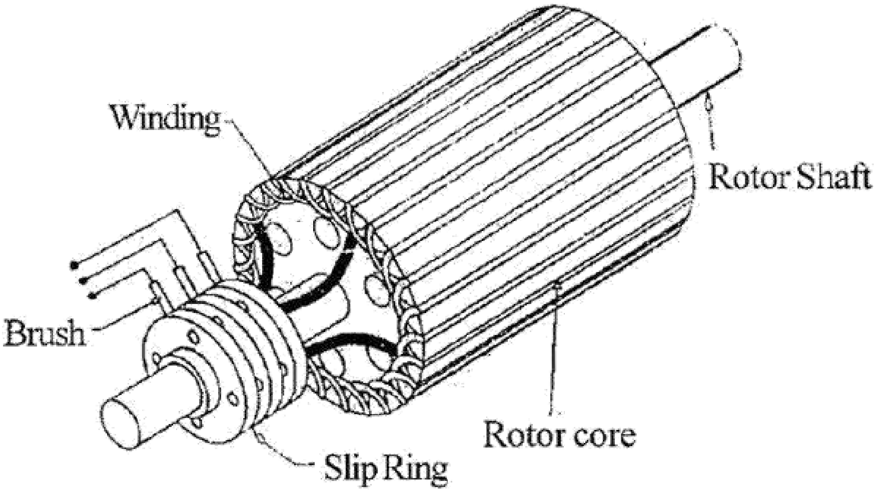


Fig: 3.2

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

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

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

3.2.3 Comparison of Squirrel Cage and Slip Ring Motor

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

3.3 Principle of Operation

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

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

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

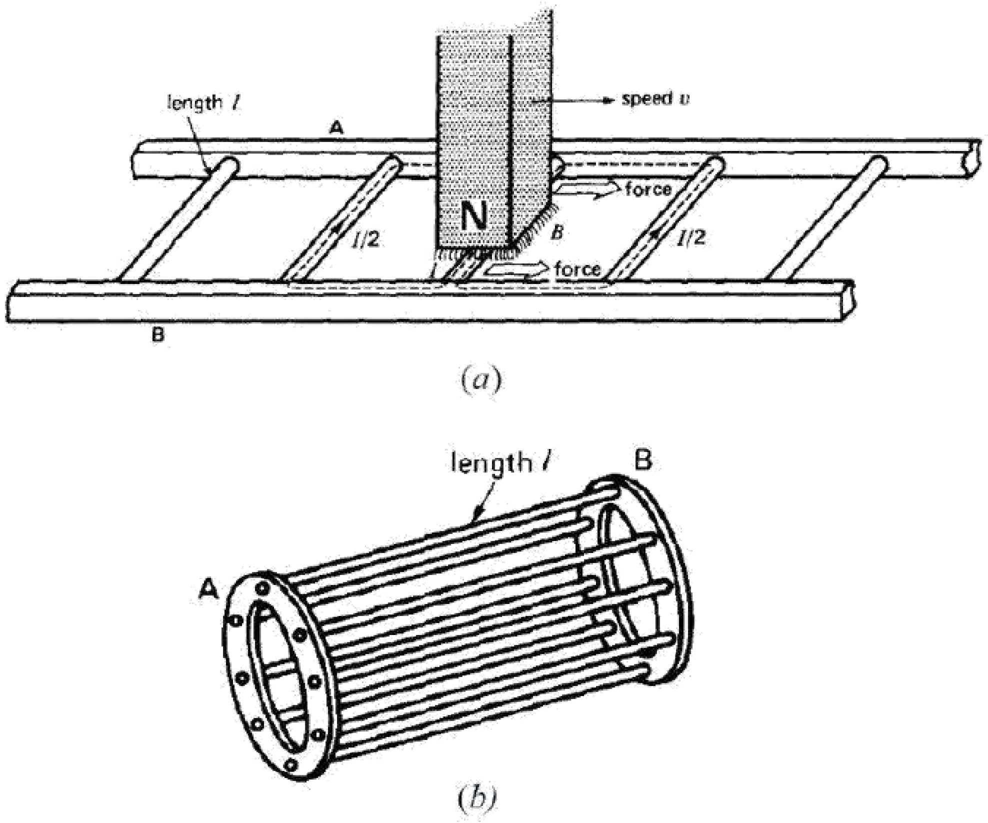


Fig: 3.3

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

3.4 Rotating Magnetic Field and Induced Voltages

Consider a simple stator having 6 salient poles, each of which carries a coil having 5 turns (Fig.3.4). Coils that are diametrically opposite are connected in series by means of three jumpers that respectively connect terminals a-a, b-b, and c-c. This creates three identical sets of windings AN, BN, CN, which are mechanically spaced at 120 degrees to each other. The two coils in each winding produce magneto motive forces that act in the same direction.

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

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

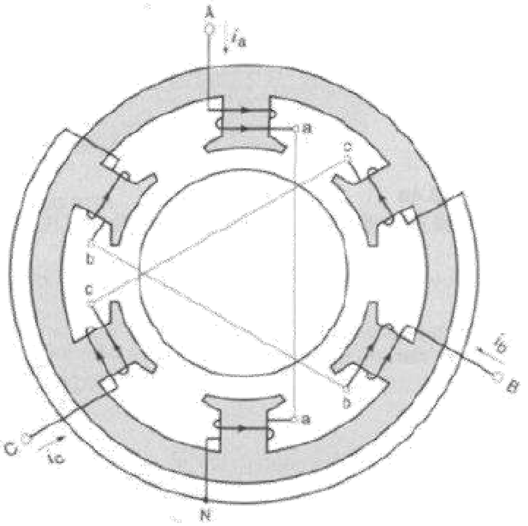


Fig: 3.4 Elementary stator having terminals A, B, C connected to a 3-phase source (not shown). Currents flowing from line to neutral are considered to be positive.

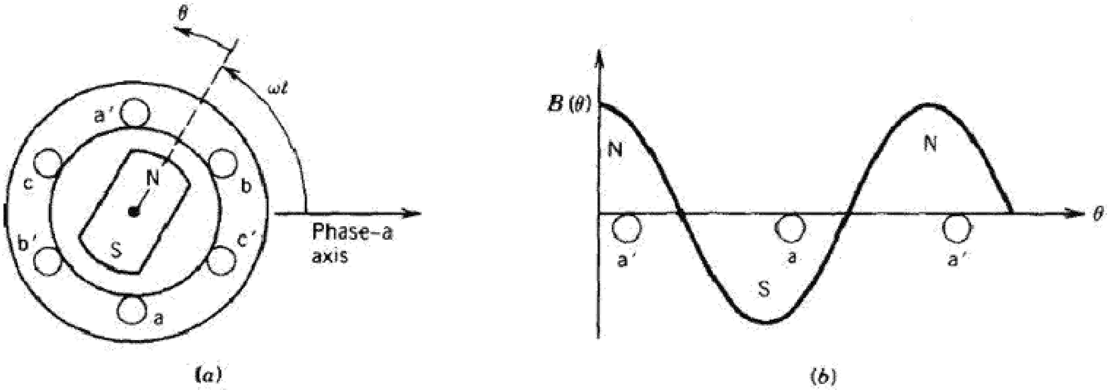


Fig: 3.5 Air gap flux density distribution.

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

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

The air gap flux per pole, ϕ_P, is:

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

Where,

l is the axial length of the stator.

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

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

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

Hence,

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

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

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

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

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

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

the *rms* value of the induced voltage is:

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

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

The above equation also shows the rms voltage per phase. The N is the total number of series turns per phase with the turns forming a concentrated full-pitch winding. In an actual AC machine each phase winding is distributed in a number of slots for better use of the iron and copper and to improve the waveform. For such a distributed winding, the EMF induced in various coils placed in different slots are not in time phase, and therefore the phasor sum of the EMF is less than their numerical sum when they are connected in series for the phase winding. A reduction factor K_W, called the winding factor, must therefore be applied. For most three-phase machine windings K_W is about 0.85 to 0.95.

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

$$Erms = 4.44fN_{ph}\phi_pK_W$$

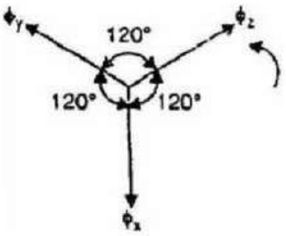
Where N_{ph} is the number of turns in series per phase.

3.5 Alternate Analysis for Rotating Magnetic Field

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

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

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



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

At instant 1 [See Fig. 3.6 (ii) and Fig. 3.6 (iii)], the current in phase X is zero and currents in phases Y and Z are equal and opposite. The currents are flowing outward in the top conductors and inward in the bottom conductors. This establishes a resultant flux towards right. The magnitude of the resultant flux is constant and is equal to 1.5 ϕ_m as proved under:

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

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

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

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

So,

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

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

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

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

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

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

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

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

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

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

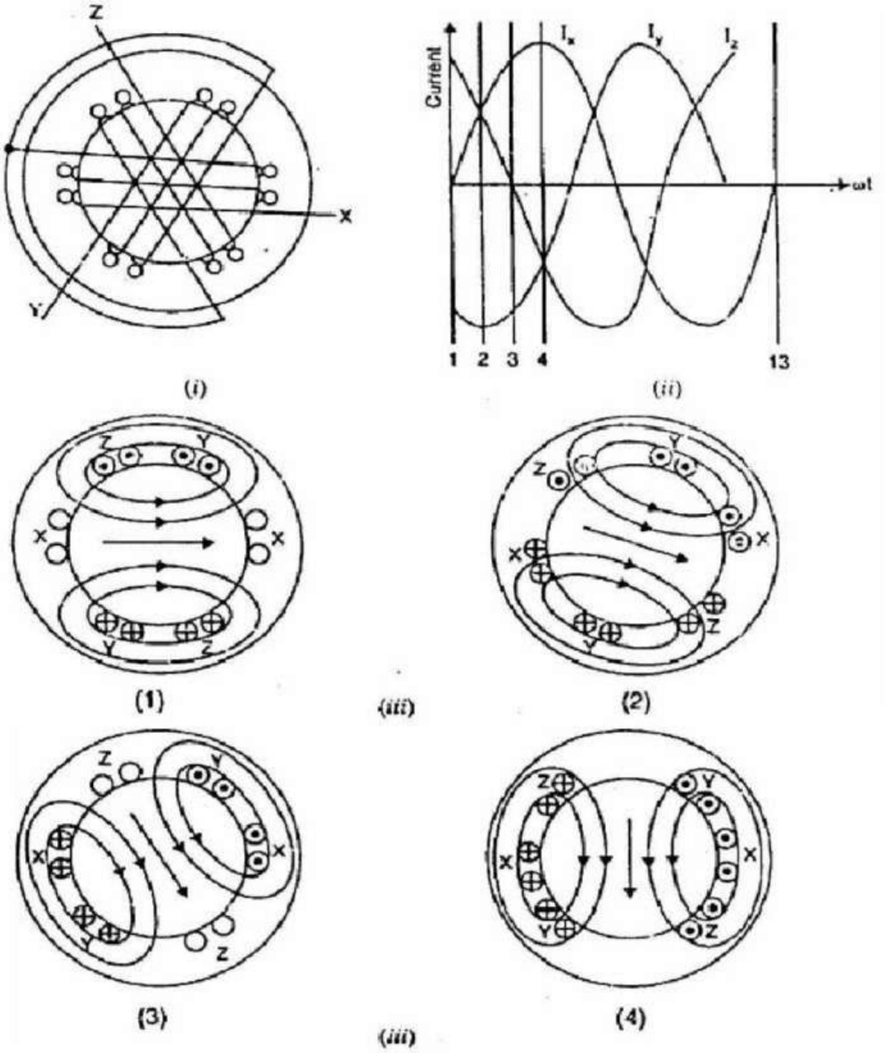
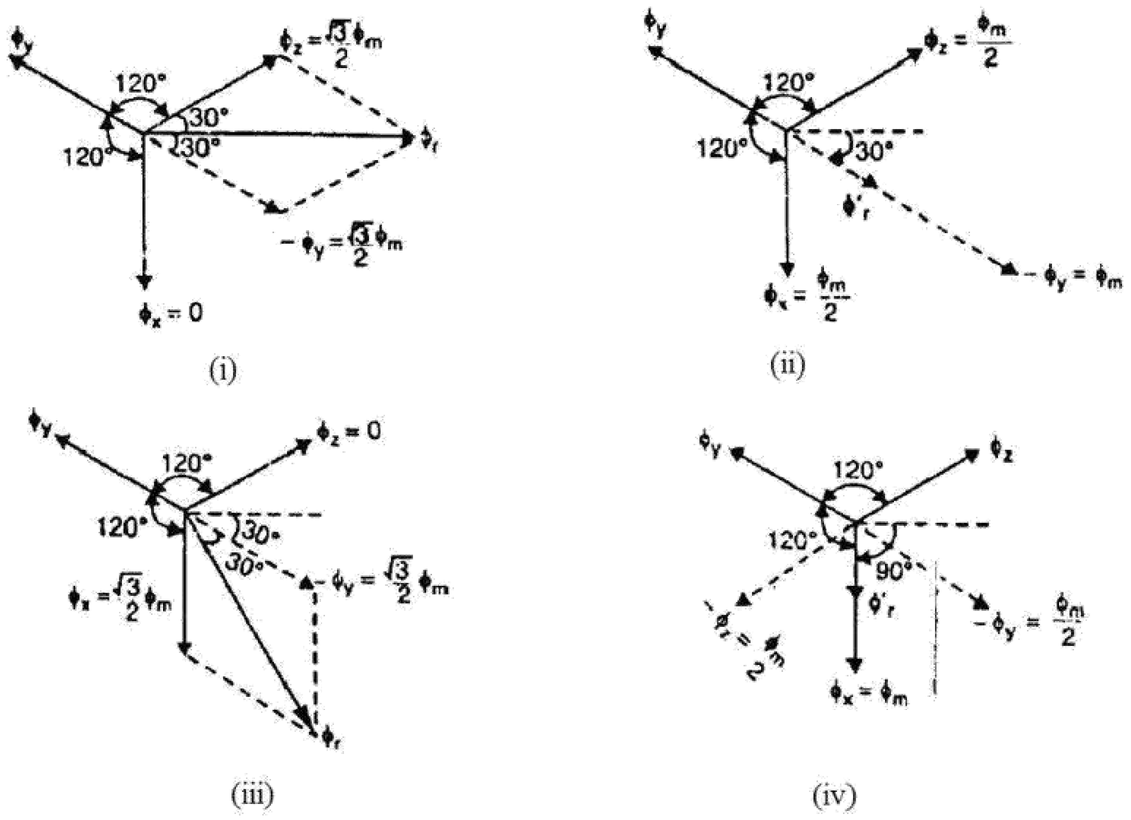


Fig: 3.6

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



(i)

(ii)

(iii)

(iv)

Fig: 3.7

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

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

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

$$\phi_z = \phi_m \sin(-180°) = 0$$

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

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

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

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

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

$$\phi_x = \phi_m \sin 90° = \phi_m$$

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

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

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

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

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

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

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

3.5.1 Speed of rotating magnetic field

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

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

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

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

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

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

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

3.5.2 Direction of rotating magnetic field

The phase sequence of the three-phase voltage applied to the stator winding in Fig. 3.6 (ii) is X-Y-Z. If this sequence is changed to X-Z-Y, it is observed that direction of rotation of the field is reversed i.e., the field rotates counter clockwise rather than clockwise. However, the number of poles and the speed at which the magnetic field rotates remain unchanged. Thus it is necessary only to change the phase sequence in order to change the direction of rotation of the magnetic field. For a three-phase supply, this can be done by interchanging any two of the three lines. As we shall see, the rotor in a 3-phase induction motor runs in the same direction as the rotating magnetic field. Therefore, the direction of rotation of a 3-phase induction motor can be reversed by interchanging any two of the three motor supply lines.

3.5.3 Slip

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

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

(i) The quantity $N_s - N$ is sometimes called slip speed.

(ii) When the rotor is stationary (i.e., $N = 0$), slip, $s = 1$ or 100 %.

(iii) In an induction motor, the change in slip from no-load to full-load is hardly 0.1% to 3% so that it is essentially a constant-speed motor.

3.5.4 Rotor Current Frequency

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

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

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

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

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

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

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

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

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

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

3.6 Phasor Diagram of Three Phase Induction Motor

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

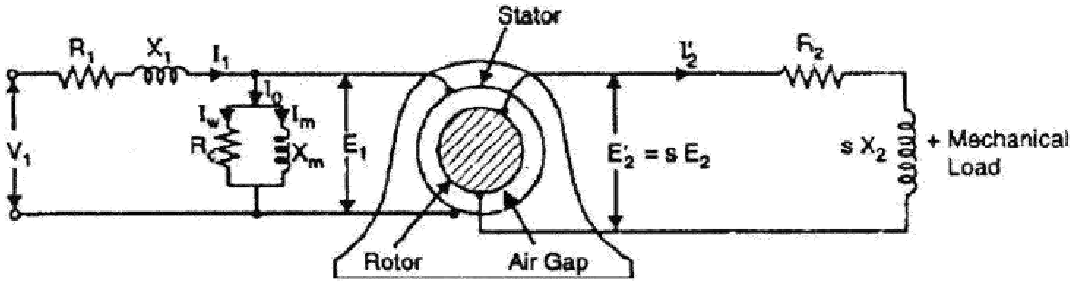


Fig: 3.8

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

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

$\therefore V_1 = E_1 + I_1 (R_1 \quad j X_1)$ ...phasor sum

$- \qquad +$

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

$\therefore I_0 \quad I_w \quad I_m$

Rotor circuit. Here R2 and X2 represent the rotor resistance and standstill rotor reactance per phase respectively. At any slip s, the rotor reactance will be X_2 .The induced voltage/phase in the rotor is E'_2 = s E2 = s K **E1**. Since the rotor winding is short-circuited, the whole of e.m.f. E'_2 is used up in circulating the rotor current I'_2.

$= \qquad +$

$\therefore E'_2 \qquad I'_2 (R_2 \quad j\, s\, X_2)$

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

$= \quad +$

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

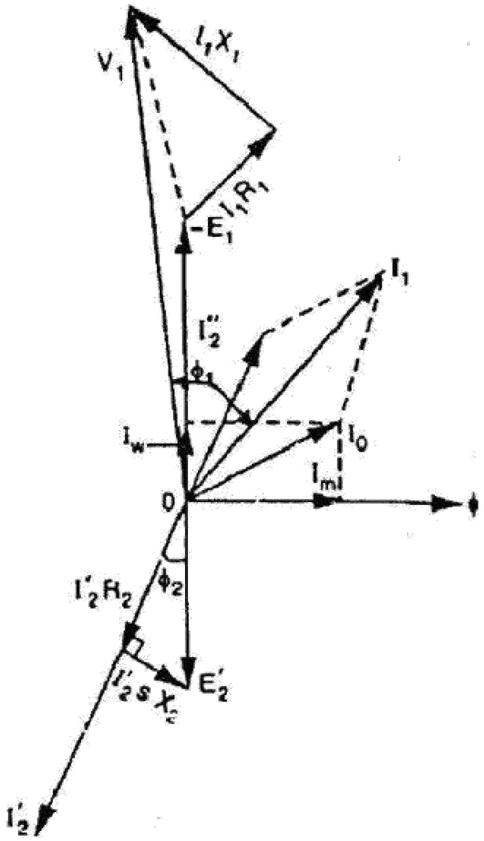


Fig: 3.9

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

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

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

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

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

3.7 Equivalent Circuit of Three Phase Induction Motor

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

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

Mathematically, this value is unaltered by writing it as:

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

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

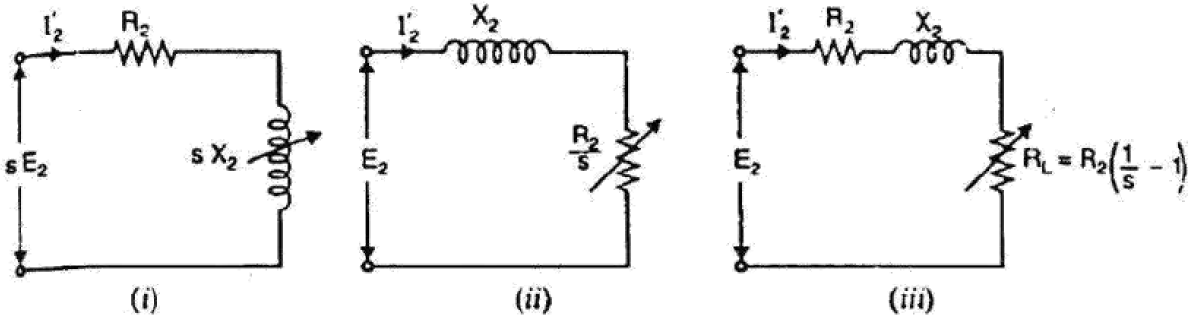


Fig: 3.10

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

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

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

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

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

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

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

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

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

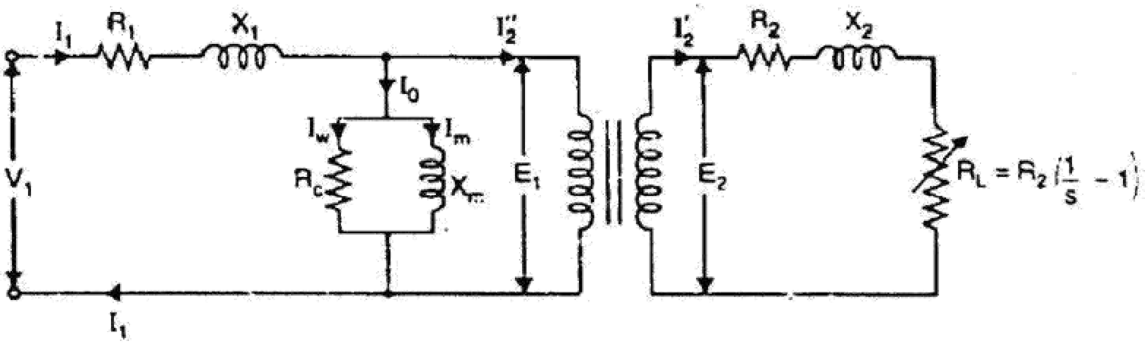


Fig: 3.11

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

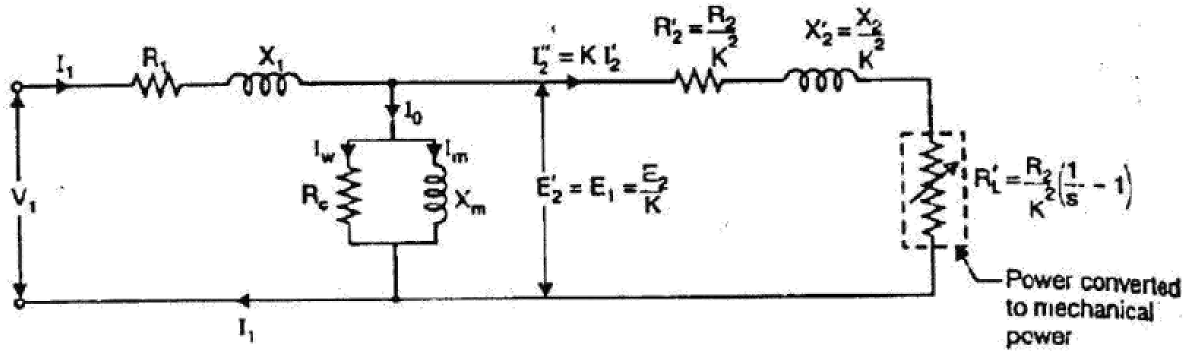


Fig: 3.12

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

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

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

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

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

3.8 Power and Torque Relations of Three Phase Induction Motor

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

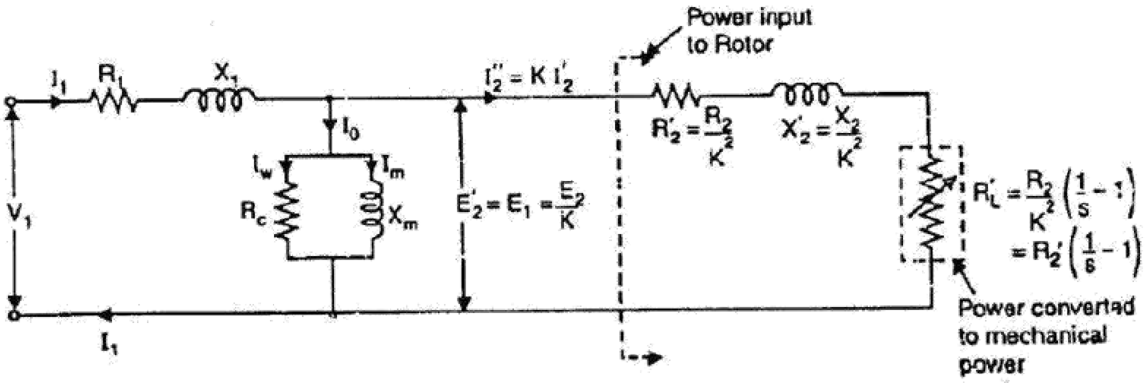


Fig: 3.13

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

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

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

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

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

Total mechanical power developed by the rotor is

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

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

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

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

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

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

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

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

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

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

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

3.9 Induction Motor Torque

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

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

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

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

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

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

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

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

3.10 Rotor Output

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Note.

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

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

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

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

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

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

3.11.1 Torque Equations

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

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

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

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

As shown in Sec. 8.16, under running conditions,

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

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

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

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

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

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

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

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

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

3.11.2 Rotor Torque

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

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

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

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

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

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

3.11.3 Starting Torque (Ts)

Let,

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

X_2 = rotor reactance per phase at standstill

R_2 = rotor resistance per phase

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

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

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

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

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

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

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

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

where K_1 is another constant.

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

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

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

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

3.11.4 Condition for Maximum Starting Torque

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

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

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

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

$$\text{or} \qquad R_2^2 + X_2^2 = 2R_2^2$$

$$\text{or} \qquad R_2 = X_2$$

Hence starting torque will be maximum when:

Rotor resistance/phase = Standstill rotor reactance/phase

Under the condition of maximum starting torque, $2\phi = 45°$ and rotor power factor is 0.707 lagging.

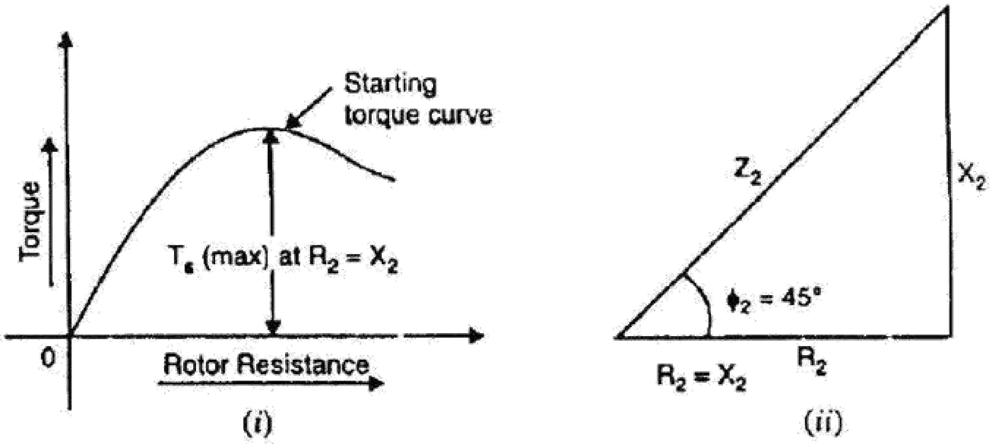


Fig: 3.14

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

3.11.5 Effect of Change of Supply Voltage

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

Since $E_2 \propto$ Supply voltage V

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

where K_2 is another constant.

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

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

3.12 Circle Diagram

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

3.12.1 Approximate Equivalent Circuit of Induction Motor

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

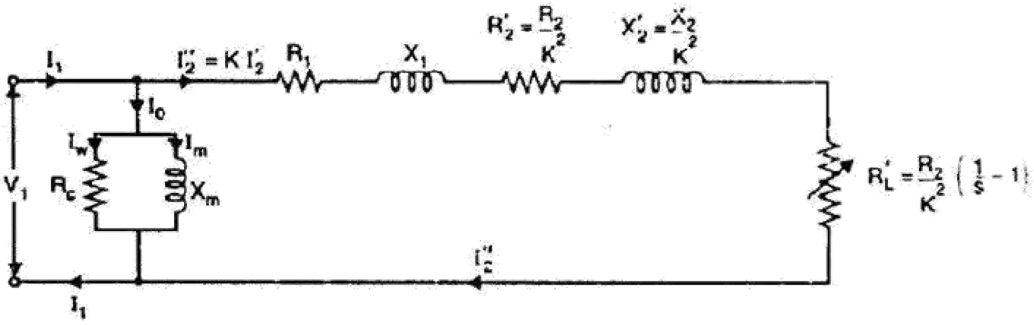


Fig: 3.15

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

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

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

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

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

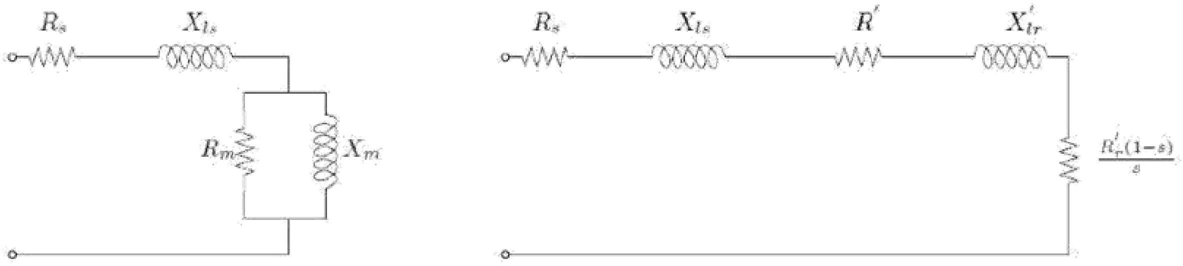
3.12.2 Tests to Determine the Equivalent Circuit Parameters

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

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

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

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



(a) No-load equivalent

(b) Blocked rotor equivalent

Fig: 3.16

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

1. *No-load test*

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

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

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

The power drawn is given by

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

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

2. *Blocked-rotor Test*

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

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

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

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

Note that this test only enables us to determine the series combination of the resistance and the reactance only and not the individual values. Generally, the individual values are assumed to be equal; the assumption Rs = R′r, and Xs = X′r suffices for most purposes.

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

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

3.12.3 Construction of Circle Diagram

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

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

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

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

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

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

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

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

8. To find the operating points corresponding to maximum power and maximum torque, draw tangents to the circle diagram parallel to the output line and torque line respectively. The points at which these tangents touch the circle are respectively the maximum power point and maximum torque point.

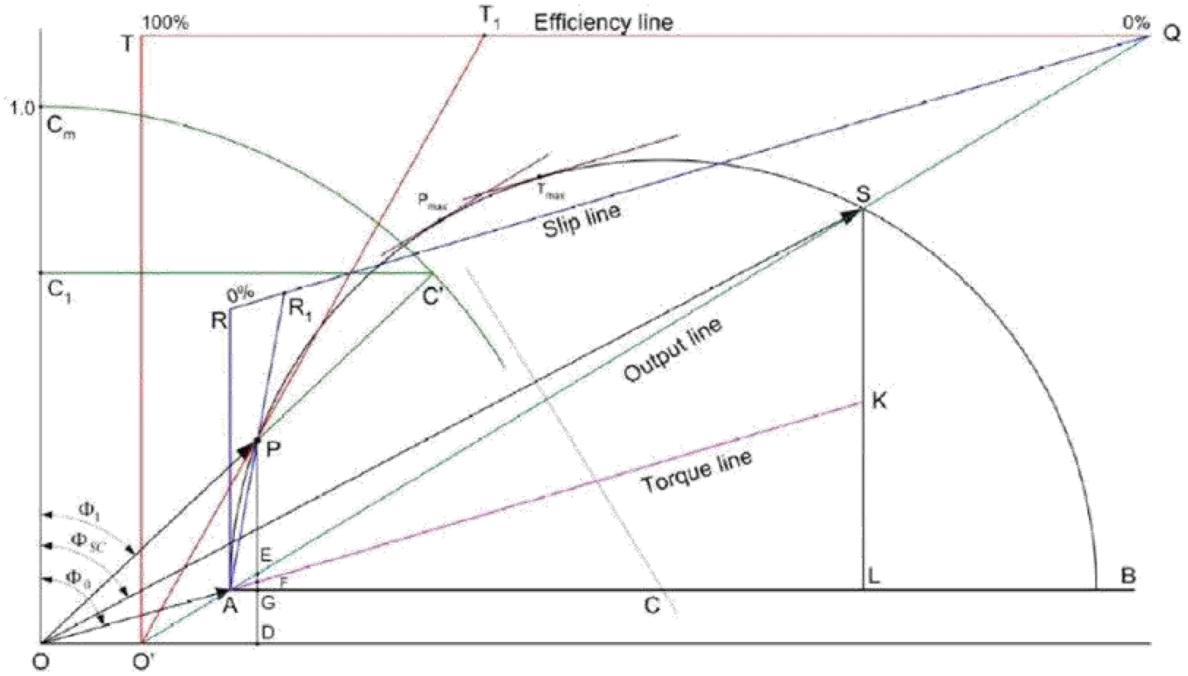


Fig: 3.17 Construction of Circle Diagram

Efficiency line

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

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

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

Slip Line

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

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

Power Factor Curve

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

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

3.13 Performance Characteristics of Three phase Induction Motor

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

3.13.1 The complete torque-speed characteristic

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

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

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

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

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

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

where ω_m is the synchronous speed in radians per second and s is the slip. Further, this is the torque produced per phase. Hence the overall torque is given by

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

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

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

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

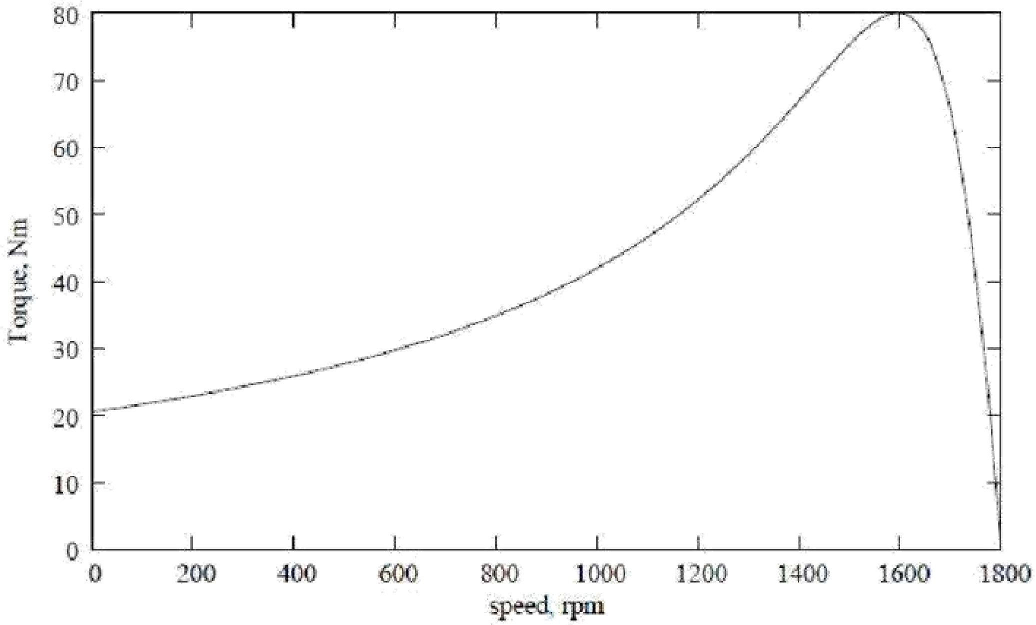


Fig: 3.18

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

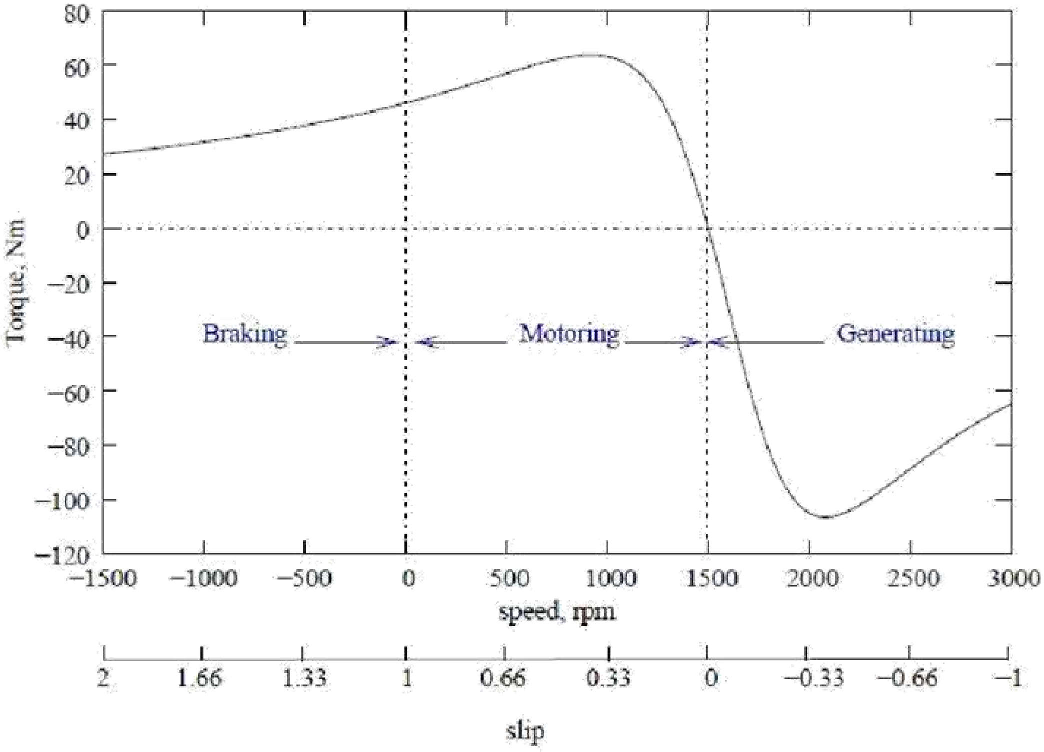


Fig: 3.19

3.13.2 Effect of Rotor Resistance on Speed Torque Characteristic

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

-

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

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

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

- The negative sign being valid for negative slip.

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

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

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

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

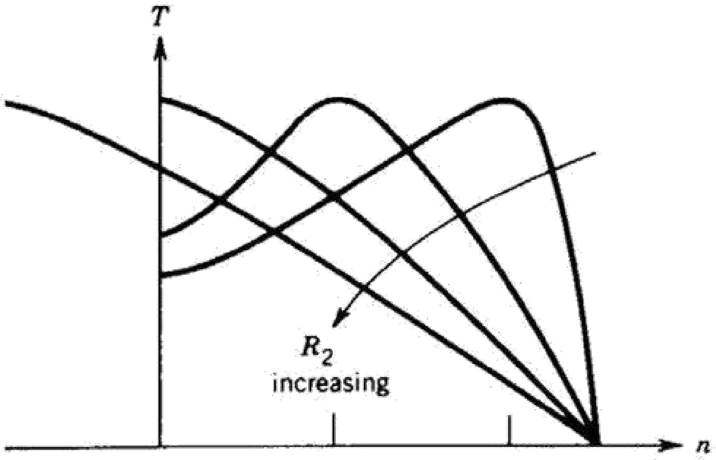


Fig: 3.20

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

3.13.3 Operating Point and Stable & Unstable region of Operation

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

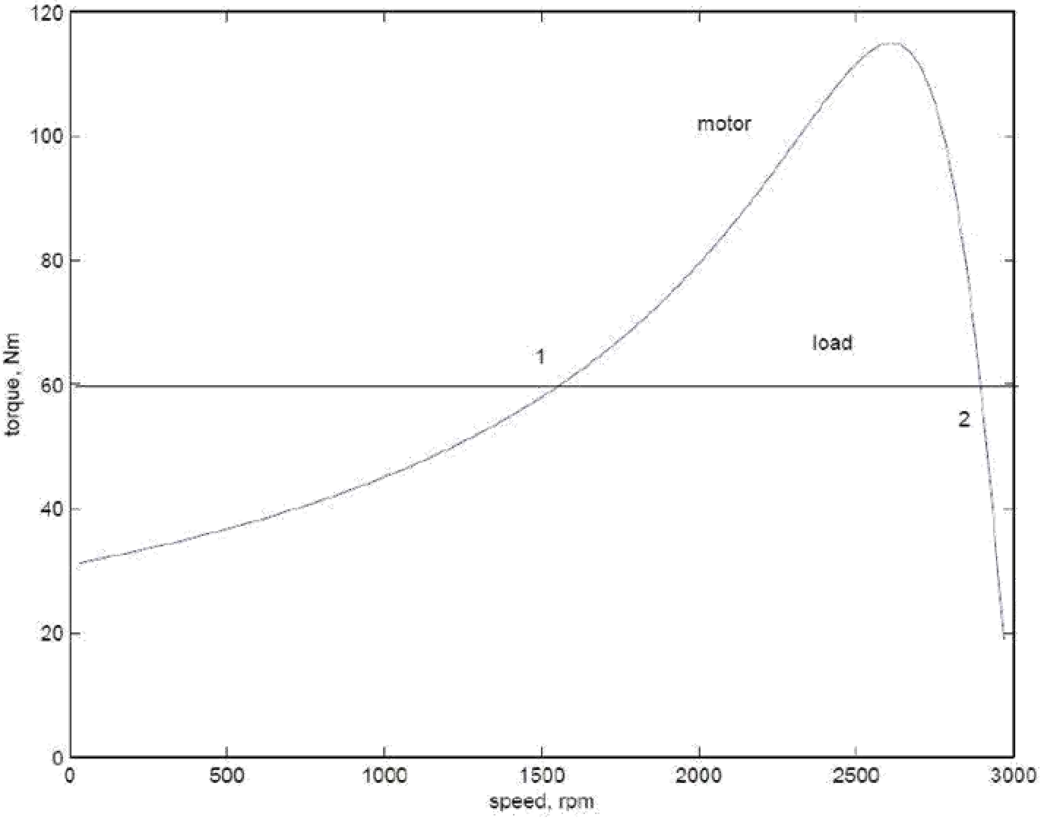


Fig: 3.21

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

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

Let us consider the point 2. If this point shifts to 2′, the slip is now higher (speed is lower) and the positive difference in torque will accelerate the machine. This behaviour will tend to bring the operating point towards 2 once again. In other words, disturbances at point 2 will not cause a runaway effect. Similar arguments may be given for the case where the load characteristic shifts down. Therefore we conclude that point 2 is a stable operating point.

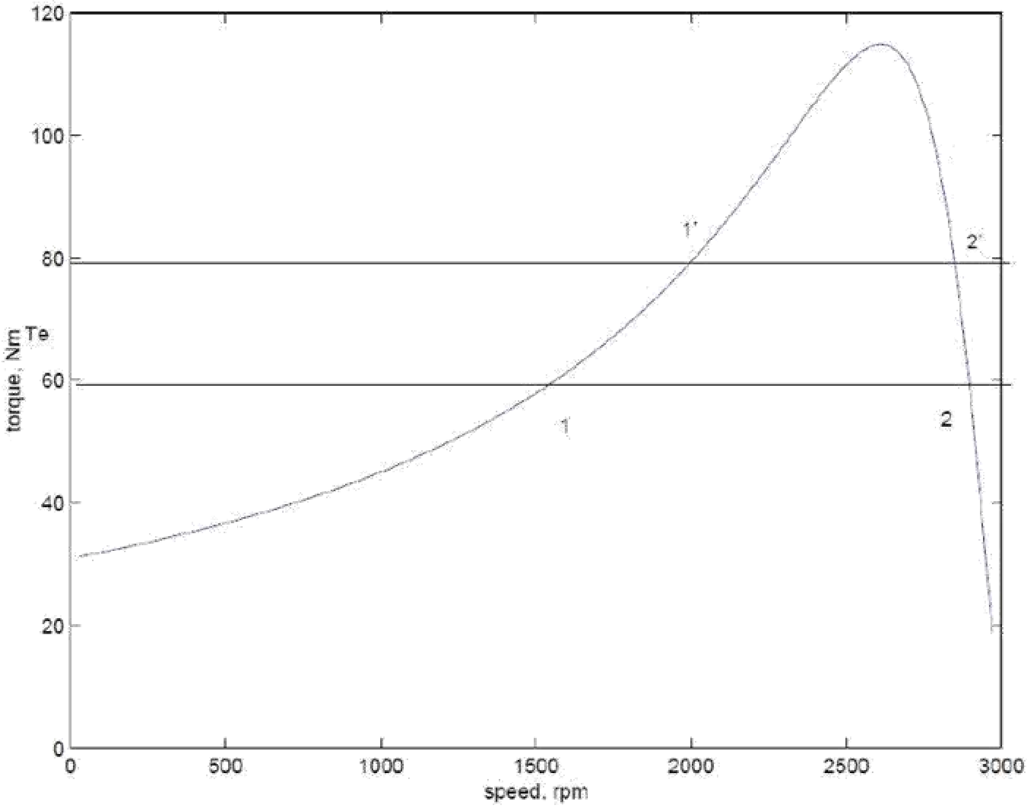


Fig: 3.22

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

3.14 Operation with Unbalanced Supply Voltage on Polyphase Induction Motors

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

Unbalance Defined

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

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

Example:

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

Effect on performance-

General

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

Temperature rise and load carrying capacity

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

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

Torques

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

Full-load speed

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

Currents

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

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

UNIT-IV

STARTING AND SPEED CONTROL OF THREE PHASE INDUCTION MOTOR

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

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

Methods of Starting Three Phase Induction Motors

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

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

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

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

(i) Direct-on-line starting

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

(ii) Stator resistance starting

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

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

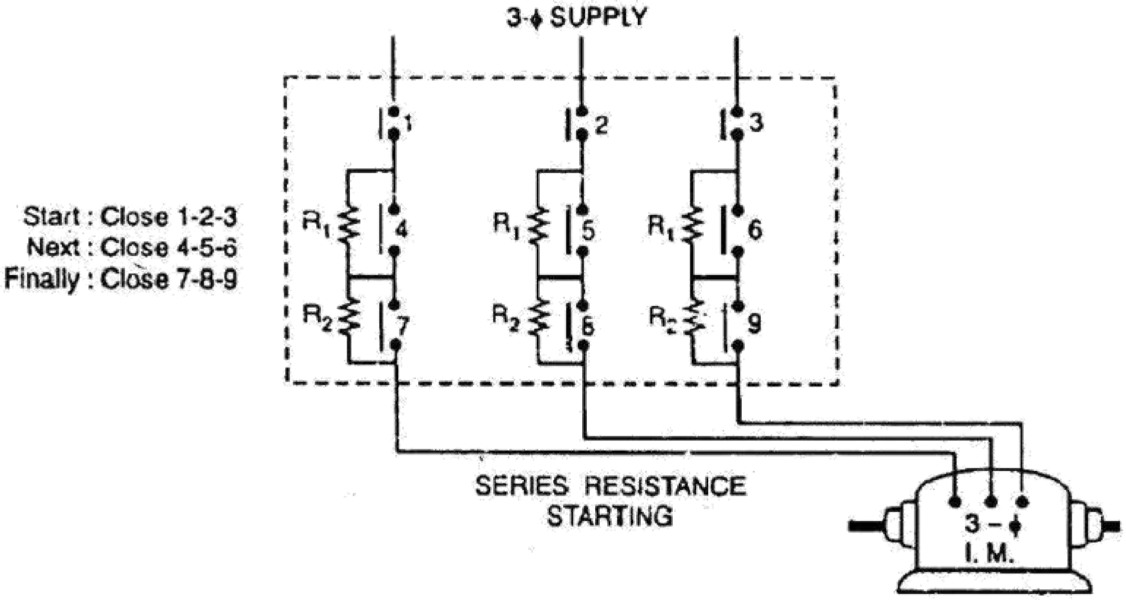


Fig: 3.23

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

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

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

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

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

(iii) Autotransformer starting

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

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

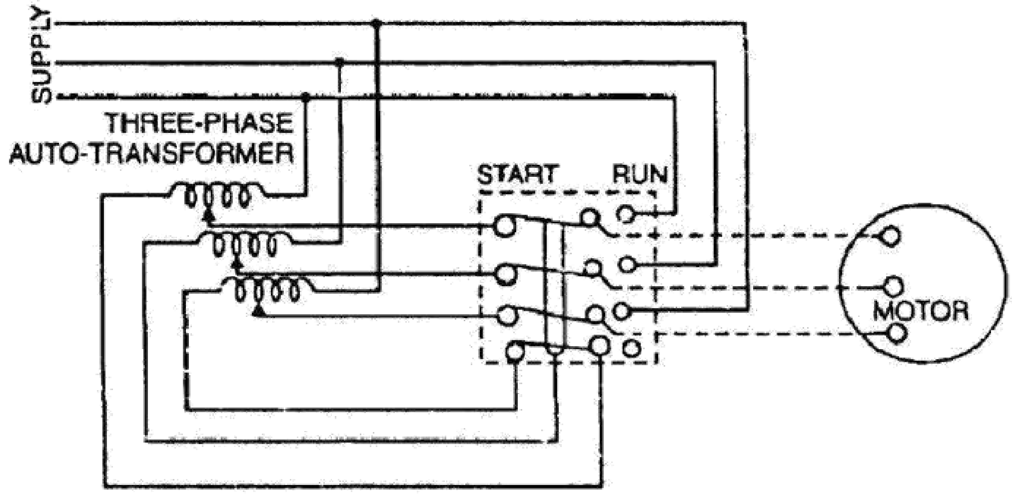


Fig: 3.24

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

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

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

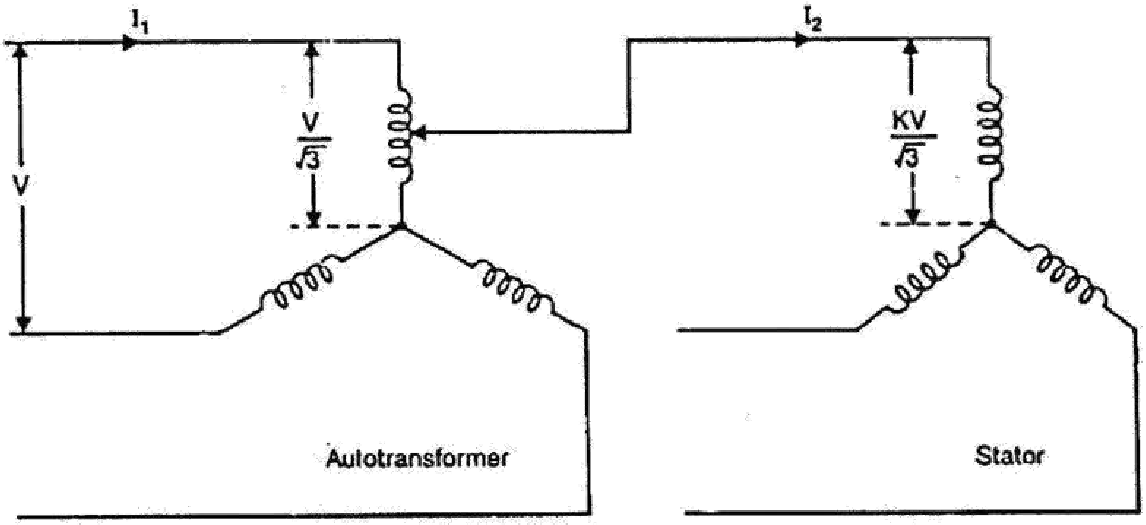


Fig: 3.25

The current taken from the supply or by autotransformer is $I_1 = KI_2 = K_2I_{sc}$. Note that motor current is K times, the supply line current is K_2 times and the starting torque is K_2 times the value it would have been on direct-on-line starting.

(iv) Star-delta starting

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

The six leads of the stator windings are connected to the changeover switch as shown. At the instant of starting, the changeover switch is thrown to "Start" position which connects the stator

−

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

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

(b) The reduction in voltage is fixed.

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

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

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

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

In star starting, we have,

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

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

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

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

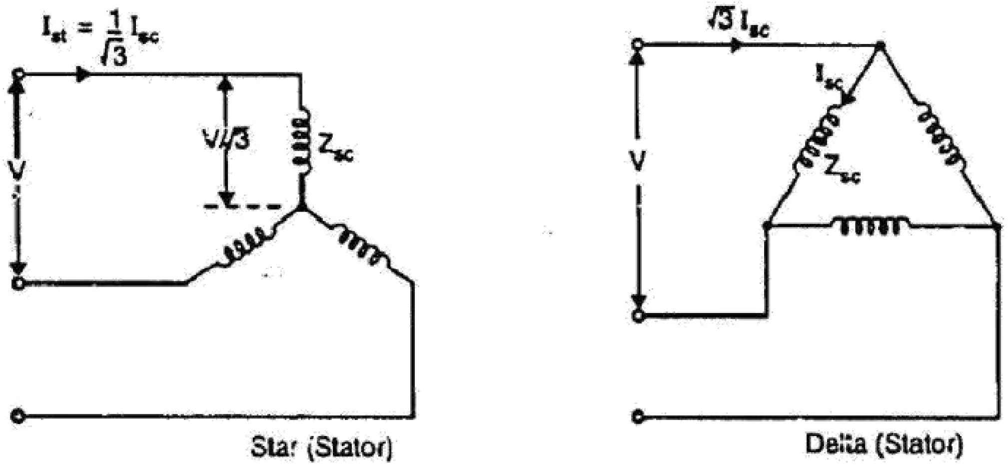


Fig: 3.26

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

Starting of Slip-Ring Induction Motors

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

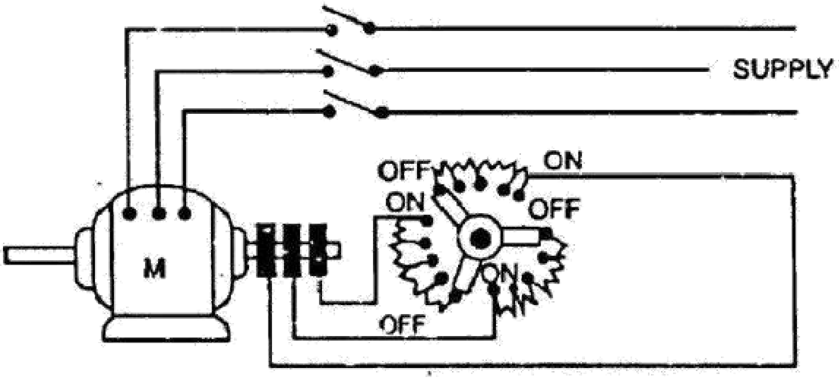


Fig: 3.27

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

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

Speed control of Three Phase Induction Motors

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

Speed control by changing applied voltage

From the torque equation of the induction machine we can see that the torque depends on the square of the applied voltage. The variation of speed torque curves with respect to the applied �

voltage is shown in Fig:. 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 *SS* range for stable operation remains the same.

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

Fig: 3.28 also shows a load torque characteristic — one that is typical of a fan type of load. In a fan (blower) type of load, the variation of torque with speed is such that $TT \propto \omega\omega_2$. Here one can

see that it may be possible to run the motor to lower speeds within the range n_S to

(1 ˆs) n_S. Further, since the load torque at zero speed is zero, the machine can start even at reduced voltages. This will not be possible with constant torque type of loads.

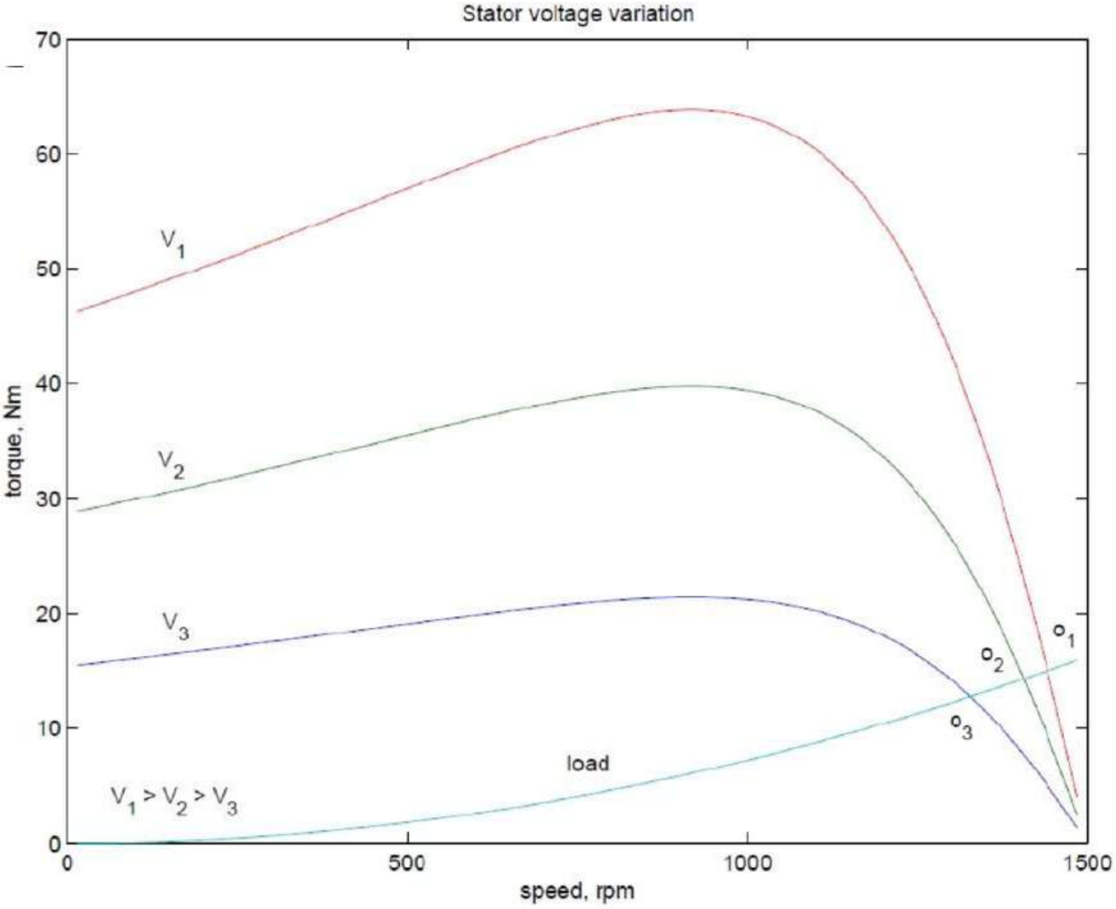


Fig:

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

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

Rotor resistance control

The expression for the torque of the induction machine is dependent on the rotor resistance. Further the maximum value is independent of the rotor resistance. The slip at maximum torque is dependent on the rotor resistance. Therefore, we may expect that if the rotor resistance is changed, the maximum torque point shifts to higher slip values, while retaining a constant torque. Fig: 3.29 shows a family of torque-speed characteristic obtained by changing the rotor resistance.

Note that while the maximum torque and synchronous speed remain constant, the slip at which maximum torque occurs increases with increase in rotor resistance, and so does the starting torque. Whether the load is of constant torque type or fan-type, it is evident that the speed control range is more with this method. Further, rotor resistance control could also be used as a means of generating high starting torque.

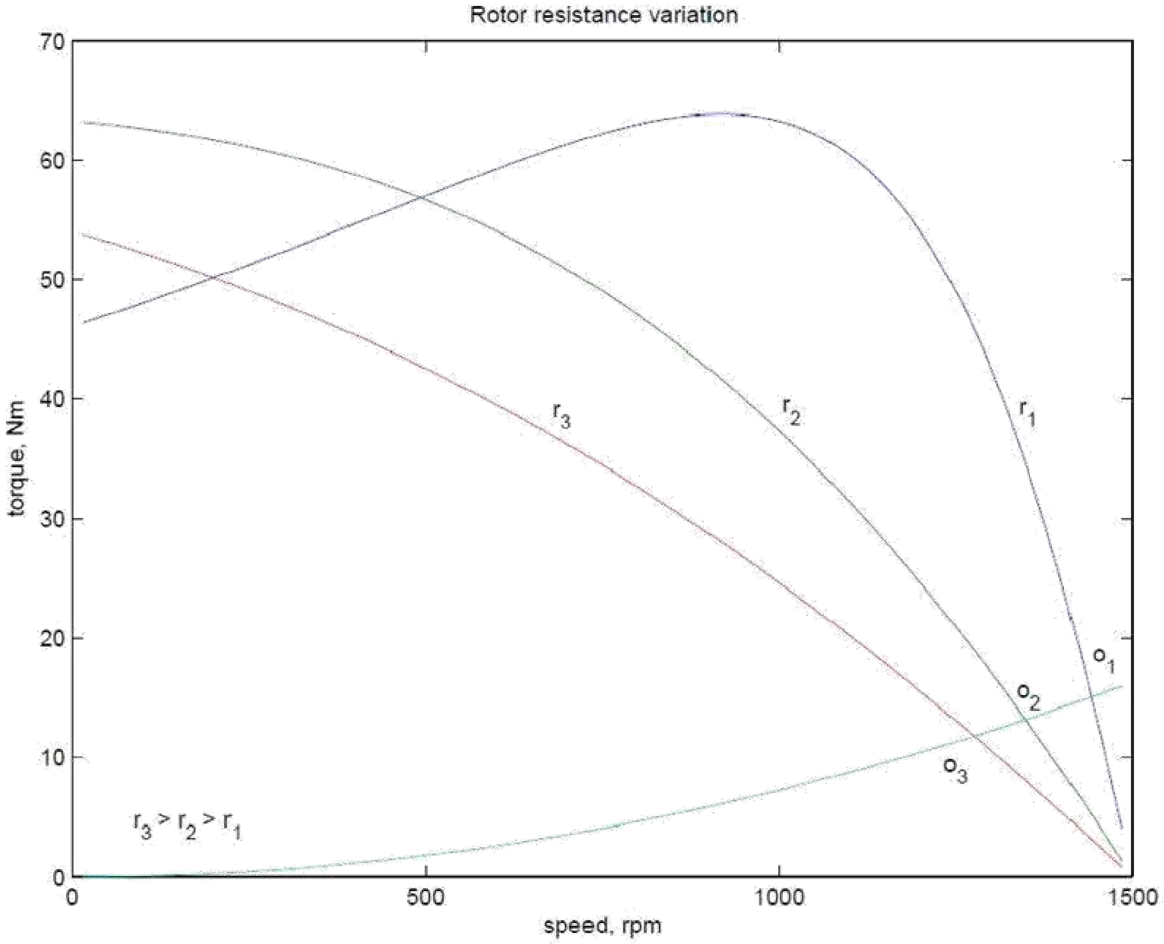


Fig:

For all its advantages, the scheme has two serious drawbacks. Firstly, in order to vary the rotor resistance, it is necessary to connect external variable resistors (winding resistance itself cannot be changed). This, therefore necessitates a slip-ring machine, since only in that case rotor terminals are available outside. For cage rotor machines, there are no rotor terminals. Secondly, the method is not very efficient since the additional resistance and operation at high slips entails dissipation.

The resistors connected to the slip-ring brushes should have good power dissipation capability. Water based rheostats may be used for this. A 'solid-state' alternative to a rheostat is a chopper controlled resistance where the duty ratio control of the chopper presents a variable resistance load to the rotor of the induction machine.

Cascade control

The power drawn from the rotor terminals could be spent more usefully. Apart from using the heat generated in meaning full ways, the slip ring output could be connected to another induction machine. The stator of the second machine would carry slip frequency currents of the first machine which would generate some useful mechanical power. A still better option would be to mechanically couple the shafts of the two machines together. This sort of a connection is called cascade connection and it gives some measure of speed control.

Let the frequency of supply given to the first machine be f_1, its number poles be p_1, and its slip of operation be S_1. Let f_2, p_2 and S_2 be the corresponding quantities for the second machine. The frequency of currents flowing in the rotor of the first machine and hence in the stator of the second machine is $S_1 f_1$. Therefore $f_2 = S_1 f_1$. Since the machines are coupled at the shaft, the speed of the rotor is common for both. Hence, if n is the speed of the rotor in radians,

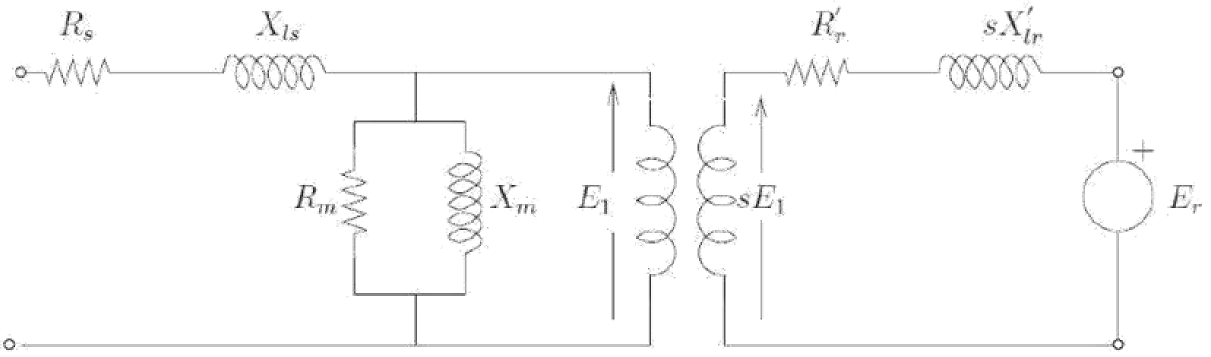
$$n = \frac{f_1}{p_1}(1 - s_1) = \pm\frac{s_1 f_1}{p_2}(1 - s_2).$$

Note that while giving the rotor output of the first machine to the stator of the second, the resultant stator mmf of the second machine may set up an air-gap flux which rotates in the same direction as that of the rotor, or opposes it. This results in values for speed as -

$$n = \frac{f_1}{p_1 + p_2} \quad or \quad n = \frac{f_1}{p_1 - p_2} \quad (s_2\ negligible)$$

The latter expression is for the case where the second machine is connected in opposite phase sequence to the first. The cascade connected system can therefore run at two possible speeds.

Speed control through rotor terminals can be considered in a much more general way. Consider the induction machine equivalent circuit of Fig: 3.30, where the rotor circuit has been terminated with a voltage source E_r.



Fig; 3.30

If the rotor terminals are shorted, it behaves like a normal induction machine. This is equivalent to saying that across the rotor terminals a voltage source of zero magnitude is connected. Different situations could then be considered if this voltage source E_r had a non-zero magnitude. Let the power consumed by that source be P_r. Then considering the rotor side circuit power dissipation per phase

$$sE_1 I_2' \cos \phi_2 = I_2' R_2' + P_r.$$

Clearly now, the value of s can be changed by the value of P_r. for $P_r = 0$, the machine is like a normal machine with a short circuited rotor. As P_r becomes positive, for all other circuit conditions remaining constant, *s* increases or in the other words, speed reduces. As P_r becomes negative, the right hand side of the equation and hence the slip decreases. The physical interpretation is that we now have an active source connected on the rotor side which is able to supply part of the rotor copper losses. When Pr = I'_{22} R_2 the entire copper loss is supplied by the external source. The RHS and hence the slip is zero. This corresponds to operation at synchronous speed. In general the circuitry connected to the rotor may not be a simple resistor or a machine but a power electronic circuit which can process this power requirement. This circuit may drive a machine or recover power back to the mains. Such circuits are called static Kramer drives.

Pole changing method

Sometimes induction machines have a special stator winding capable of being externally connected to form two different number of pole numbers. Since the synchronous speed of the induction machine is given by $n_s = f_s/p$ (in rev. /s) where p is the number of pole pairs, this would correspond to changing the synchronous speed. With the slip now corresponding to the new synchronous speed, the operating speed is changed. This method of speed control is a stepped variation and generally restricted to two steps.

If the changes in stator winding connections are made so that the air gap flux remains constant, then at any winding connection, the same maximum torque is achievable. Such winding arrangements are therefore referred to as constant-torque connections. If however such connection changes result in air gap flux changes that are inversely proportional to the synchronous speeds, then such connections are called constant-horsepower type.

The following figure serves to illustrate the basic principle. Consider a magnetic pole structure consisting of four pole faces A, B, C, D as shown in Fig: 3.31.

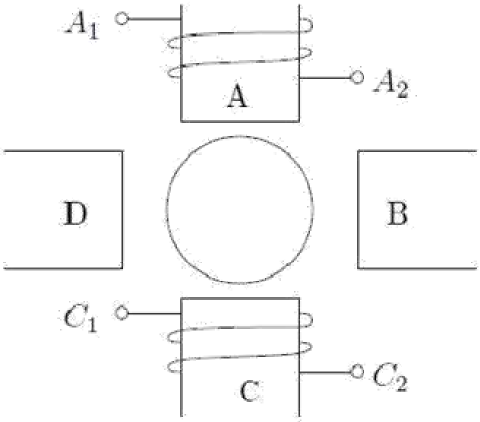


Fig: 3.31

Coils are wound on A & C in the directions shown. The two coils on A & C may be connected in series in two different ways — A2 may be connected to C1 or C2. A1 with the

Other terminal at C then form the terminals of the overall combination. Thus two connections result as shown in Fig: 3.32 (a) & (b).

Now, for a given direction of current flow at terminal A1, say into terminal A1, the flux directions within the poles are shown in the figures. In case (a), the flux lines are out of the pole A (seen from the rotor) for and into pole C, thus establishing a two-pole structure. In case (b) however, the flux lines are out of the poles in A & C. The flux lines will be then have to complete the circuit by flowing into the pole structures on the sides. If, when seen from the rotor, the pole emanating flux lines is considered as North Pole and the pole into which they enter is termed as south, then the pole configurations produced by these connections is a two-pole arrangement in Fig: 3.32(a) and a four-pole arrangement in Fig: 3.32 (b).

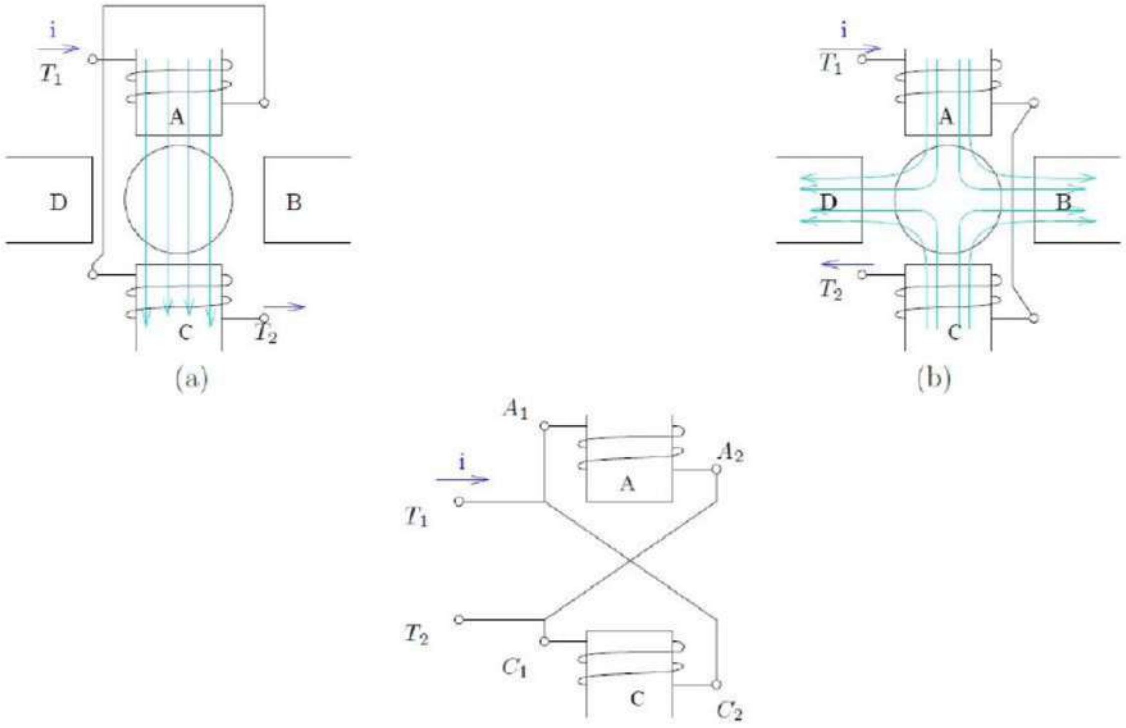


Fig: 3.32

Thus by changing the terminal connections we get either a two pole air-gap field or a four-pole field. In an induction machine this would correspond to a synchronous speed reduction in half from case (a) to case (b). Further note that irrespective of the connection, the applied voltage is balanced by the series addition of induced emf s in two coils. Therefore the air-gap flux in both cases is the same. Cases (a) and (b) therefore form a pair of constant torque connections.

Consider, on the other hand a connection as shown in the Fig: 3.32 (c). The terminals T1 and T2 are where the input excitation is given. Note that current direction in the coils now resembles that of case (b), and hence this would result in a four-pole structure. However, in Fig: 3.32 (c), there is only one coil induced emf to balance the applied voltage. Therefore flux in case (c) would therefore be halved compared to that of case (b) or case (a), for that matter). Cases (a) and (c) therefore form a pair of constant horse-power connections.

It is important to note that in generating a different pole numbers, the current through one coil (out of two, coil C in this case) is reversed. In the case of a three phase machine, the following example serves to explain this. Let the machine have coils connected as shown [C1 C6] as shown in Fig:

The current directions shown in C1 & C2 correspond to the case where T1, T2, T3 are supplied with three phase excitation and Ta, Tb &Tc are shorted to each other (STAR point). The applied voltage must be balanced by induced emf in one coil only (C1 & C2 are parallel). If however the excitation is given to Ta, Tb &Tc with T1, T2, T3 open, then current through one of the coils (C1 & C2) would reverse. Thus the effective number of poles would increase, thereby bringing down the speed. The other coils also face similar conditions.

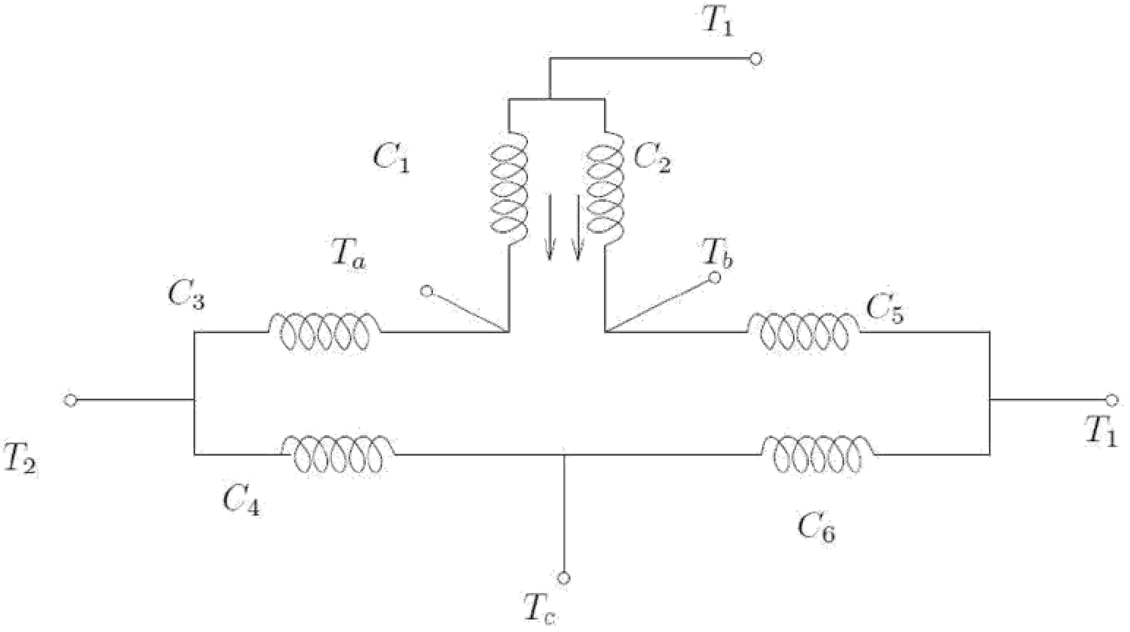


Fig: 3.33

Stator frequency control

The expression for the synchronous speed indicates that by changing the stator frequency also it can be changed. This can be achieved by using power electronic circuits called inverters which convert dc to ac of desired frequency. Depending on the type of control scheme of the inverter, the ac generated may be variable-frequency-fixed-amplitude or variable-frequency-variable-amplitude type. Power electronic control achieves smooth variation of voltage and frequency of the ac output. This when fed to the machine is capable of running at a controlled speed. However, consider the equation for the induced emf in the induction machine. frequency. Where, N is the number of the turns per phase, $\varphi\varphi_{mm}$is the peak flux in the air gap and $f$is the

$$V = 4.44N\phi_m f$$

Note that in order to reduce the speed, frequency has to be reduced. If the frequency is reduced while the voltage is kept constant, thereby requiring the amplitude of induced emf to remain the same, flux has to increase. This is not advisable since the machine likely to enter deep saturation. If this is to be avoided, then flux level must be maintained constant which implies that voltage must be reduced along with frequency. The ratio is held constant in order to maintain the flux level for maximum torque capability.

Actually, it is the voltage across the magnetizing branch of the exact equivalent circuit that must be maintained constant, for it is that which determines the induced emf. Under conditions where the stator voltage drop is negligible compared the applied voltage. In this mode of operation, the voltage across the magnetizing inductance in the 'exact' equivalent circuit reduces in amplitude with reduction in frequency and so does the inductive reactance. This implies that the current through the inductance and the flux in the machine remains constant. The speed torque characteristics at any frequency may be estimated as before. There is one curve for every excitation frequency considered corresponding to every value of synchronous speed. The curves are shown below. It may be seen that the maximum torque remains constant.

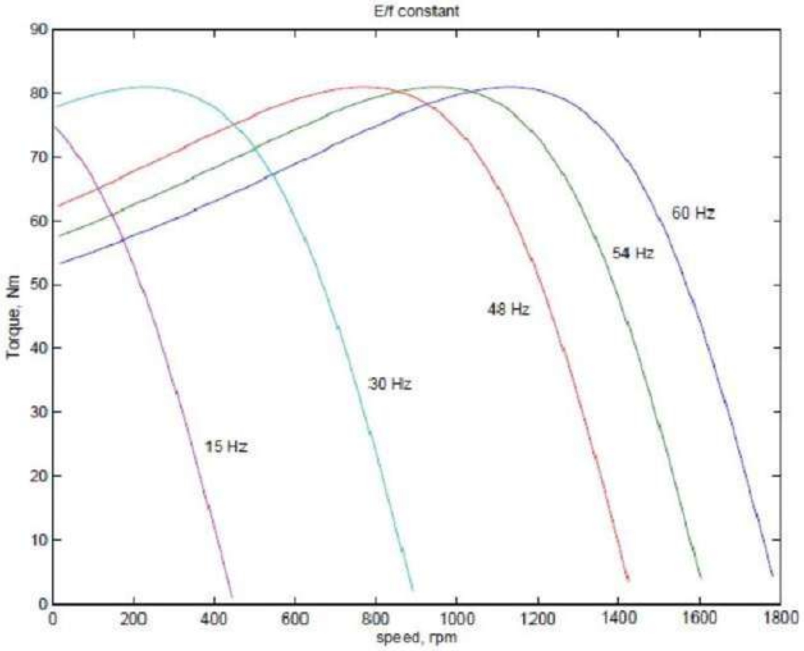


Fig:

and f is the frequency of excitation, then E =*kf, where k* is the constant of proportionality. If = 2π, the developed torque is given by This may be seen mathematically as follows. If E is the voltage across the magnetizing branch

$$T_{E/f} = \frac{k^2 f^2}{\left(\frac{R'_r}{s}\right)^2 + (\omega L'_{lr})^2} \frac{R'_r}{s\omega}$$

If this equation is differentiated with respect to *s* and equated to zero to find the slip at maximum into above equation, torque ˆs, we get ˆs = ±R′r/(ωωL′lr). The maximum torque is obtained by substituting this value of frequency. This means that the maximum torque always occurs at a speed lower than It shows that this maximum value is independent of the frequency. Further *ωω* is independent

$$\hat{T}_{E/f} = \frac{k^2}{8\pi^2 L'_{lr}}$$

synchronous speed by a fixed difference, independent of frequency. The overall effect is an *ss* apparent shift of the torque-speed characteristic as shown in Fig:

Though this is the aim, E is an internal voltage which is not accessible. It is only the terminal voltage V which we have access to and can control. For a fixed V, E changes with operating slip (rotor branch impedance changes) and further due to the stator impedance drop. Thus if we approximate E/*f* as V/*f*, the resulting torque-speed characteristic shown in Fig: is far from desirable.

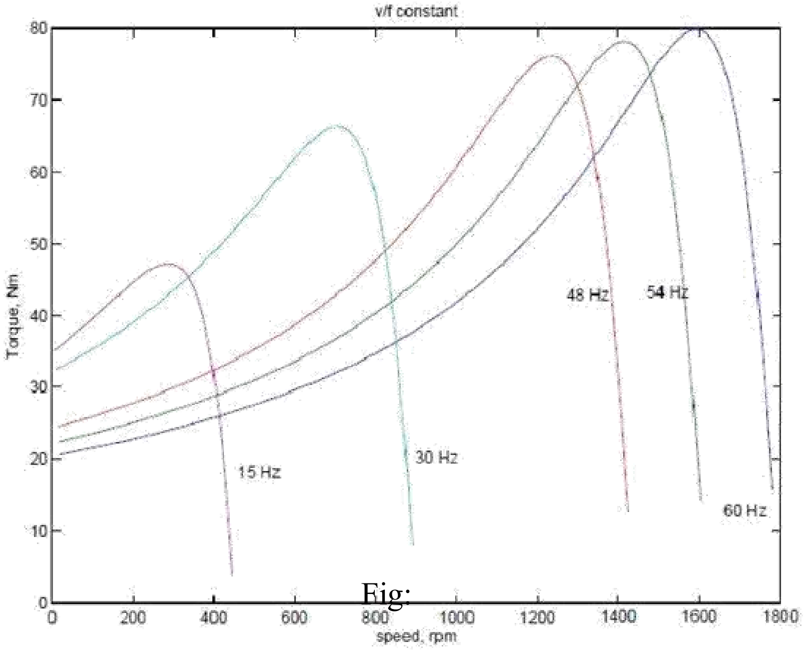


Fig:

At low frequencies and hence low voltages the curves show a considerable reduction in peak torque. At low frequencies (and hence at low voltages) the drop across the stator impedance prevents sufficient voltage availability. Therefore, in order to maintain sufficient torque at low frequencies, a voltage more than proportional needs to be given at low speeds. Another component of compensation that needs to be given is due to operating slip. With these two components, therefore, the ratio of applied voltage to frequency is not a constant but is a curve such as that shown in Fig:

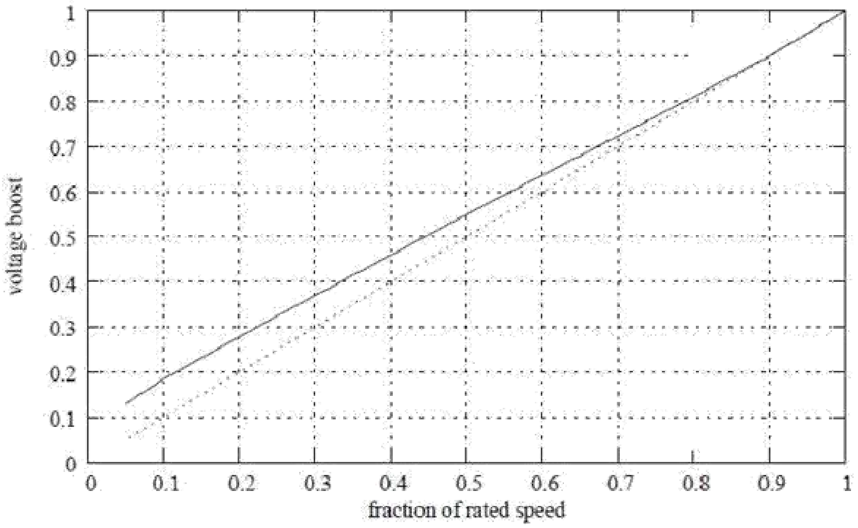


Fig:

With this kind of control, it is possible to get a good starting torque and steady state performance. However, under dynamic conditions, this control is insufficient. Advanced control techniques such as field- oriented control (vector control) or direct torque control (DTC) are necessary.

Power Stages in an Induction Motor

The input electric power fed to the stator of the motor is converted into mechanical power at the shaft of the motor. The various losses during the energy conversion are:

1. Fixed losses

(i) Stator iron loss

(ii) Friction and windage loss

The rotor iron loss is negligible because the frequency of rotor currents under normal running condition is small.

2. Variable losses

(i) Stator copper loss

(ii) Rotor copper loss

Fig: 3.37 shows how electric power fed to the stator of an induction motor suffers losses and finally converted into mechanical power.

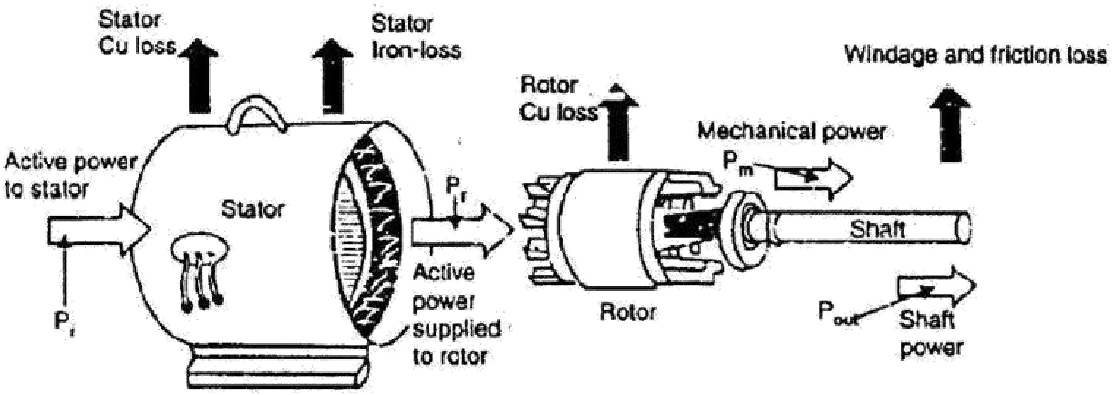


Fig:

The following points may be noted from the above diagram:

(i) Stator input, Pi = Stator output + Stator losses

= Stator output + Stator Iron loss + Stator Cu loss

(ii) Rotor input, Pr = Stator output

It is because stator output is entirely transferred to the rotor through air-gap by electromagnetic induction.

(iii) Mechanical power available, Pm = Pr - Rotor Cu loss

This mechanical power available is the gross rotor output and will produce a gross torque T_g.

(iv) Mechanical power at shaft, Pout = Pm - Friction and windage loss

Mechanical power available at the shaft produces a shaft torque T_{sh}.

Clearly, Pm - Pout = Friction and windage loss.

Double Cage Induction Motor

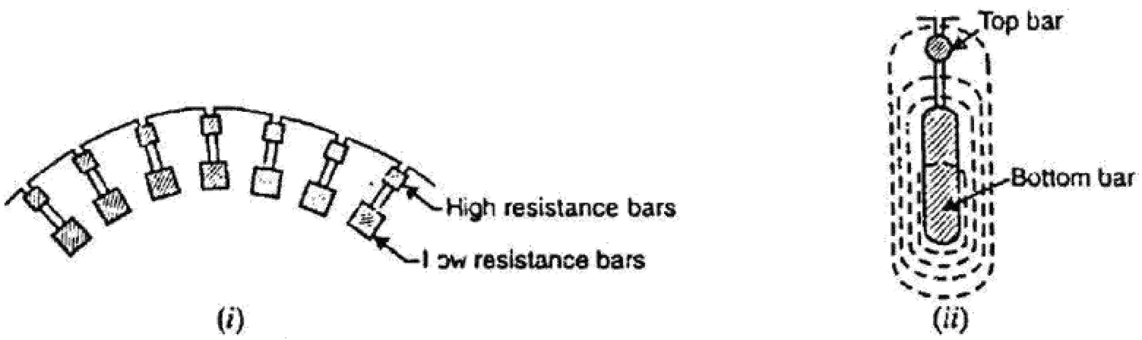
One of the advantages of the slip-ring motor is that resistance may be inserted in the rotor circuit to obtain high starting torque (at low starting current) and then cut out to obtain optimum running conditions. However, such a procedure cannot be adopted for a squirrel cage motor because its cage is permanently short-circuited. In order to provide high starting torque at low starting current, double-cage construction is used.

Construction

As the name suggests, the rotor of this motor has two squirrel-cage windings located one above the other as shown in Fig: 3.38(i).

The outer winding consists of bars of smaller cross-section short-circuited by end rings. Therefore, the resistance of this winding is high. Since the outer winding has relatively open slots and a poorer flux path around its bars [See Fig: 3.38(ii)], it has a low inductance. Thus the resistance of the outer squirrel-cage winding is high and its inductance is low.

The inner winding consists of bars of greater cross-section short-circuited by end rings. Therefore, the resistance of this winding is low. Since the bars of the inner winding are thoroughly buried in iron, it has a high inductance [See Fig: (ii)].Thus the resistance of the inner squirrel cage winding is low and its inductance is high.



(i) (ii)

Fig: 3.38

Working

When a rotating magnetic field sweeps across the two windings, equal e.m.f.s are induced in each.

(i) At starting, the rotor frequency is the same as that of the line (i.e., 50 Hz), making the reactance of the lower winding much higher than that of the upper winding. Because of the high reactance of the lower winding, nearly all the rotor current flows in the high-resistance outer cage winding. This provides the good starting characteristics of a high-resistance cage winding. Thus the outer winding gives high starting torque at low starting current.

(ii) As the motor accelerates, the rotor frequency decreases, thereby lowering the reactance of the inner winding, allowing it to carry a larger proportion of the total rotor current At the normal operating speed of the motor, the rotor frequency is so low (2 to 3 Hz) that nearly all the rotor current flows in the low-resistance inner cage winding. This results in good operating efficiency and speed regulation.

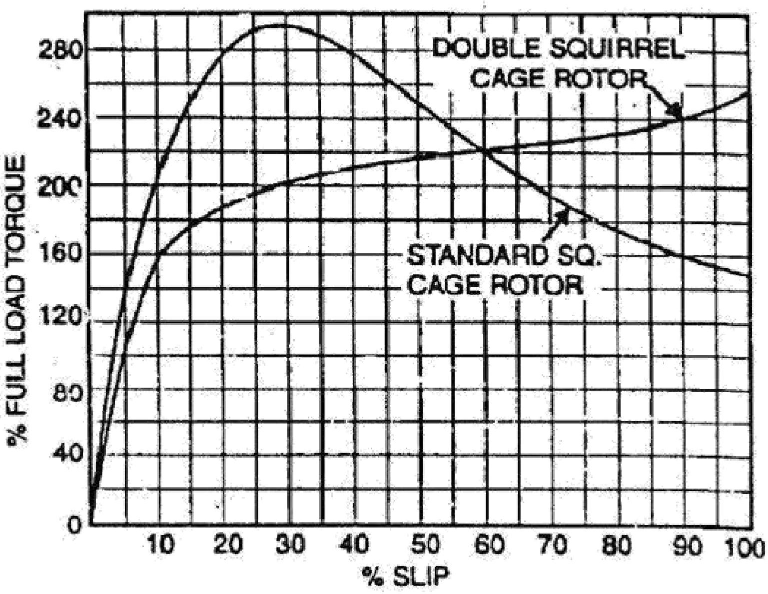


Fig:

Fig: 3.39 shows the operating characteristics of double squirrel-cage motor. The starting torque of this motor ranges from 200 to 250 percent of full-load torque with a starting current of 4 to 6 times the full-load value. It is classed as a high-torque, low starting current motor.

Cogging and Crawling of Induction Motor

Crawling of induction motor

Sometimes, squirrel cage induction motors exhibits a tendency to run at very slow speeds (as low as one-seventh of their synchronous speed). This phenomenon is called as crawling of an induction motor.

This action is due to the fact that, flux wave produced by a stator winding is not purely sine wave. Instead, it is a complex wave consisting a fundamental wave and odd harmonics like 3rd, 5th, 7th etc. The fundamental wave revolves synchronously at synchronous speed Ns whereas 3rd, 5th, 7th harmonics may rotate in forward or backward direction at Ns/3, Ns/5, Ns/7 speeds respectively. Hence, harmonic torques are also developed in addition with fundamental torque.

3rd harmonics are absent in a balanced 3-phase system. Hence 3rdd harmonics do not produce rotating field and torque. The total motor torque now consist three components as: (i) the fundamental torque with synchronous speed Ns, (ii) 5th harmonic torque with synchronous speed

Ns/5, (iv) 7th harmonic torque with synchronous speed Ns/7 (provided that higher harmonics are neglected).

Now, 5th harmonic currents will have phase difference of

5 x 120 = 600° =2 x 360 - 120 = -120°.

Hence the revolving speed set up will be in reverse direction with speed Ns/5. The small amount of 5th harmonic torque produces breaking action and can be neglected.

The 7th harmonic currents will have phase difference of

7 x 120 = 840° = 2 x 360 +120 = + 120°.

Hence they will set up rotating field in forward direction with synchronous speed equal to Ns/7. If we neglect all the higher harmonics, the resultant torque will be equal to sum of fundamental torque and 7th harmonic torque. 7th harmonic torque reaches its maximum positive value just before1/7th of Ns. If the mechanical load on the shaft involves constant load torque, the torque developed by the motor may fall below this load torque. In this case, motor will not accelerate up to its normal speed, but it will run at a speed which is nearly 1/7th of its normal speed as shown in Fig: *This phenomenon is called as crawling of induction motors*.

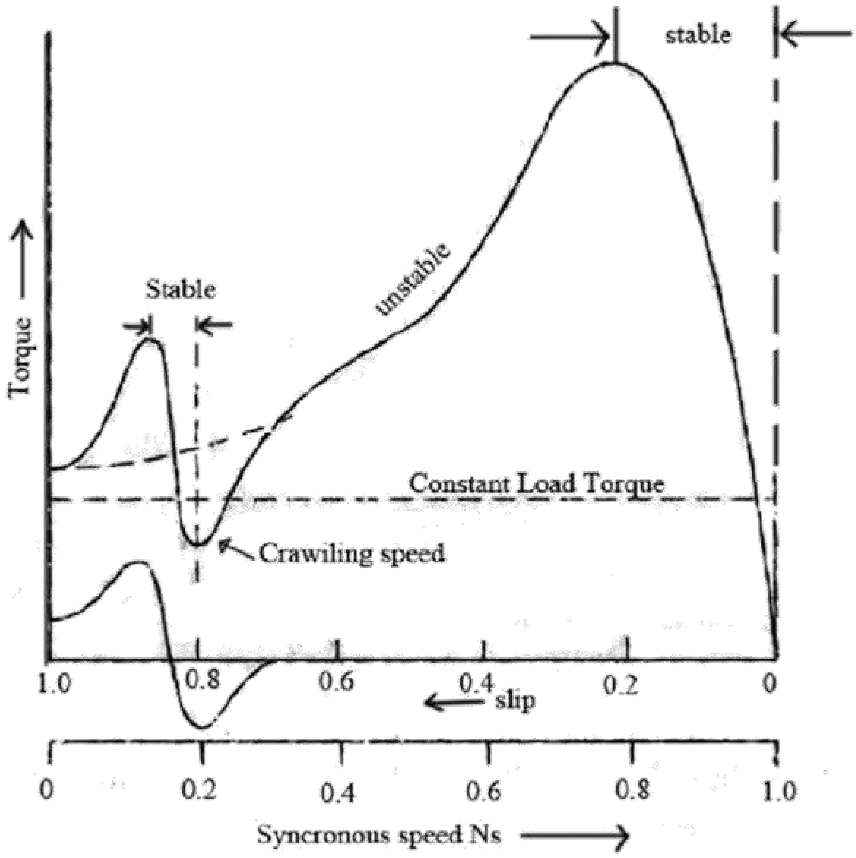


Fig:

Cogging (Magnetic Locking or Teeth Locking) of induction motor

Sometimes, the rotor of a squirrel cage induction motor refuses to start at all, particularly if the supply voltage is low. This happens especially when number of rotor teeth is equal to number of stator teeth, because of magnetic locking between the stator teeth and the rotor teeth. When the rotor teeth and stator teeth face each other, the reluctance of the magnetic path is minimum that is why the rotor tends to remain fixed. This phenomenon is called cogging or magnetic locking of induction motor.

Induction Generator

When a squirrel cage induction motor is energized from a three phase power system and is mechanically driven above its synchronous speed it will deliver power to the system. An induction generator receives its excitation (magnetizing current) from the system to which it is connected. It consumes rather than supplies reactive power (KVAR) and supplies only real power (KW) to the system. The KVAR required by the induction generator plus the KVAR requirements of all other loads on the system must be supplied from synchronous generators or static capacitors on the system.

Operating as a generator at a given percentage slip above synchronous speed, the torque, current, efficiency and power factor will not differ greatly from that when operating as a motor. The same slip below synchronous speed, the shaft torque and electric power flow is reversed. Typical speed torque characteristic of induction generator is shown in Fig:

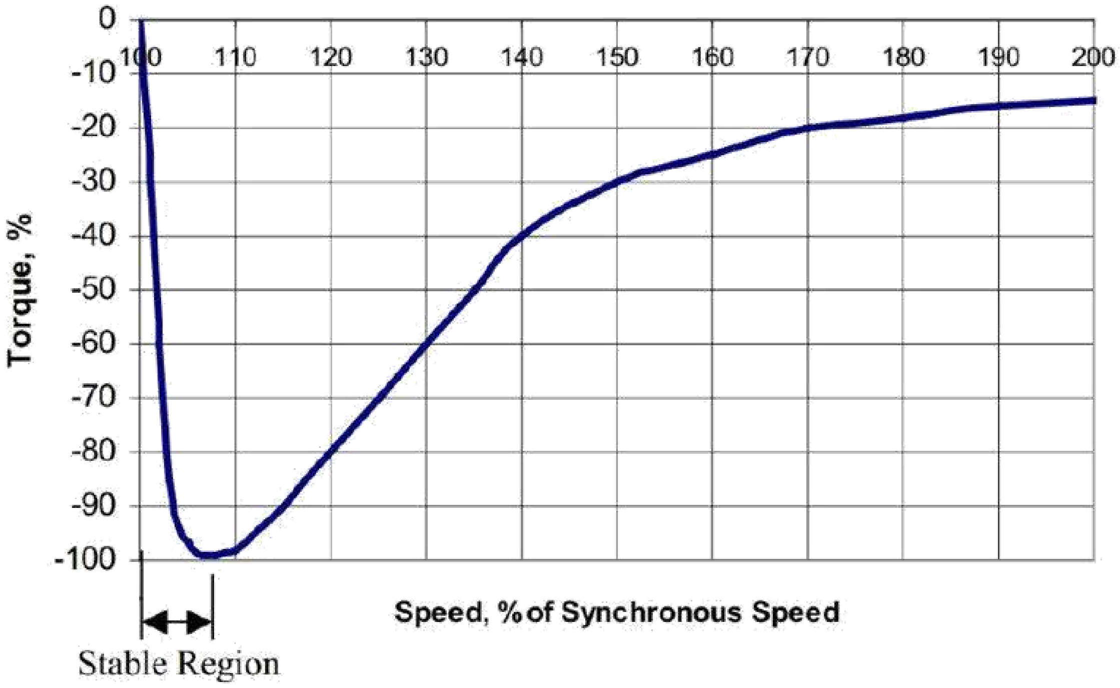


Fig:

Now for example, a 3600 RPM squirrel cage induction motor which delivers full load output at 3550 RPM as a motor will deliver full rated power as a generator at 3650 RPM. If the half-load motor speed is 3570 RPM, the output as a generator will be one-half of rated value when driven at 3630 RPM, etc. Since the induction generator is actually an induction motor being driven by a prime mover, it has several advantages.

1. It is less expensive and more readily available than a synchronous generator.
2. It does not require a DC field excitation voltage.
3. It automatically synchronizes with the power system, so its controls are simpler and less expensive.

The principal disadvantages of an induction generator are listed below

1. It is not suitable for separate, isolated operation
2. It consumes rather than supplies magnetizing KVAR
3. It cannot contribute to the maintenance of system voltage levels (this is left entirely to the synchronous generators or capacitors)
4. In general it has a lower efficiency.

Induction Generator Application

As energy costs so high, energy recovery became an important part of the economics of most industrial processes. The induction generator is ideal for such applications because it requires very little in the way of control system or maintenance.

Because of their simplicity and small size per kilowatt of output power, induction generators are also favoured very strongly for small windmills. Many commercial windmills are designed to operate in parallel with large power systems, supplying a fraction of the customer's total power needs. In such operation, the power system can be relied on for voltage & frequency control, and static capacitors can be used for power-factor correction.

Induction Motor Braking Regenerative Plugging Dynamic Braking of Induction Motor

Under Digital Electronics

Regenerative Braking of Induction Motor • Plugging Braking • Dynamic Braking

Induction motors are used at various places. Speed control of induction motors is quite difficult and that's why their use was restricted and DC motors had to be used as their speed regulation was possible. But when induction motor drives were invented and implemented, they were given preference because of many advantages over DC motors. Whenever controlling of motors is done, braking is the most important term, so as with induction motors. **Induction motor braking** can be done by different methods, which are

i. **Regenerative braking of induction motor**

ii. **plugging Braking of induction motor**

iii. **Dynamic braking of induction motor** is further categorized as

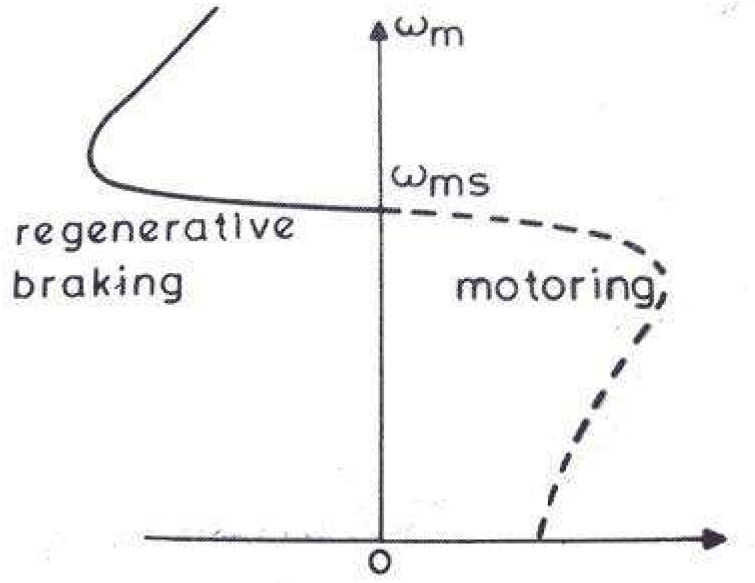
a) AC dynamic breaking

b) Self excited braking using capacitors c) DC dynamic braking

d) Zero Sequence braking

Regenerative Braking of Induction Motor

We know the power (input) of an induction motor is given as.



Regenerative braking

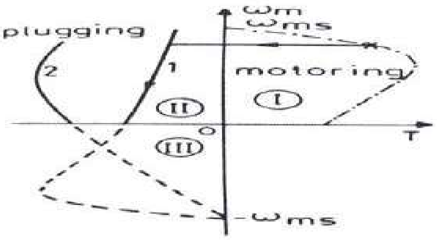
$P_{in} = 3VI_S\cos\phi_S$

Here, φ_S the phase angle between stator phase voltage V and the stator phase current I_S. Now, for motoring operation $\varphi_S < 90°$ and for braking operation $\varphi_S > 90°$. When the speed of the motor is more than the synchronous speed, relative speed between the motor conductors and air gap rotating field reverses, as a result the phase angle because greater than 90° and the power flow reverse and thus regenerative braking takes place. The nature of the speed torque curves are shown in the figure beside. It the source frequency is fixed then the **regenerative braking of induction motor** can only take place if the speed of the motor is greater than synchronous speed, but with a variable frequency source **regenerative braking of induction motor** can occur for speeds lower than synchronous speed. The main advantage of this kind of braking can be said that the generated power is use fully employed and the main disadvantage of this type of braking is that for fixed frequency sources, braking cannot happen below synchronous speeds.

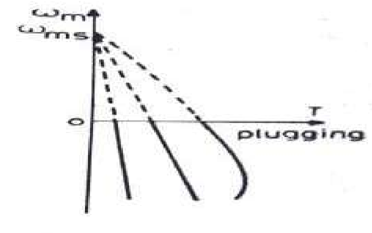
Plugging Braking of Induction Motor

Plugging **induction motor braking** is done by reversing the phase sequence of the motor. **Plugging braking of induction motor** is done by interchanging connections of any two phases of stator with respect of supply terminals. And with that the operation of motoring shifts to **plugging braking**. During plugging the slip is (2 - s), if the original slip of the running motor is s, then it can be shown in the following way.

$$S_n = \frac{-\omega_{ms} - \omega m}{-\omega_{ms}} = 2 - s$$



(a) 1: natural characteristic
2: with external resistance in rotor



(b) Plugging in IV quadrant with large external resistance in rotor

UNIT-V SINGLE PHASE INDUCTION MOTOR AND SPECIAL MACHINES

Single Phase Induction Motors

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

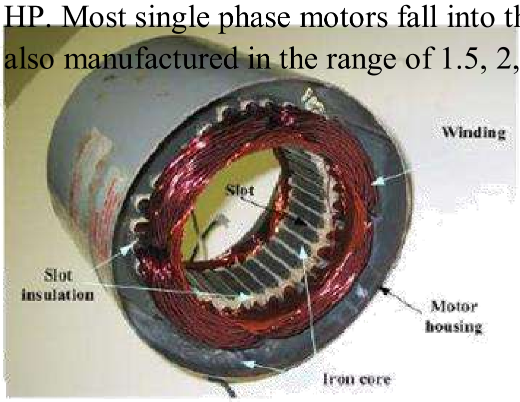


Fig: (a) Stator

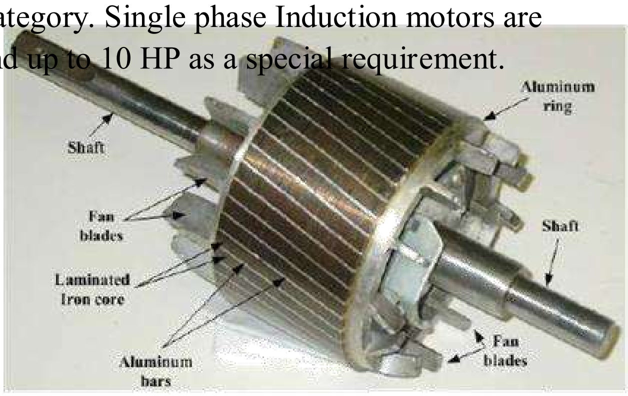


Fig: (b) Squirrel cage rotor

Theory of Operation

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

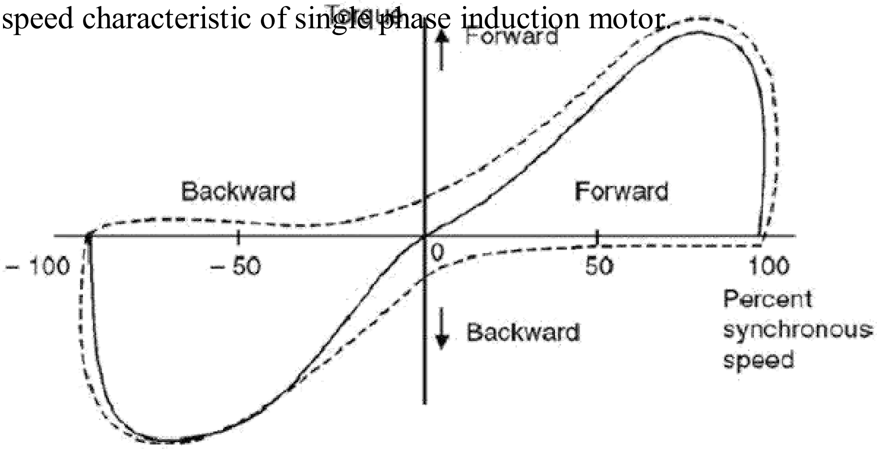


Fig: (a)

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

Double Revolving Field Theory of Single Phase Induction Motor

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

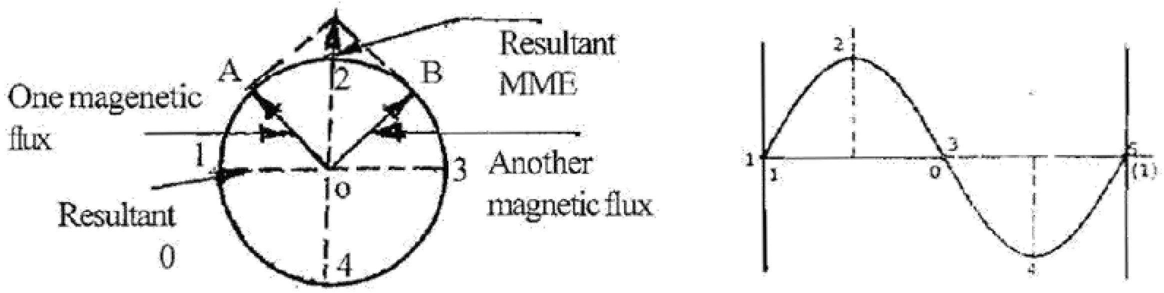


Fig: (b)

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

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

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

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

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

EQUIVALENT CIRCUIT OF SINGLE PHASE INDUCTION MOTOR

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

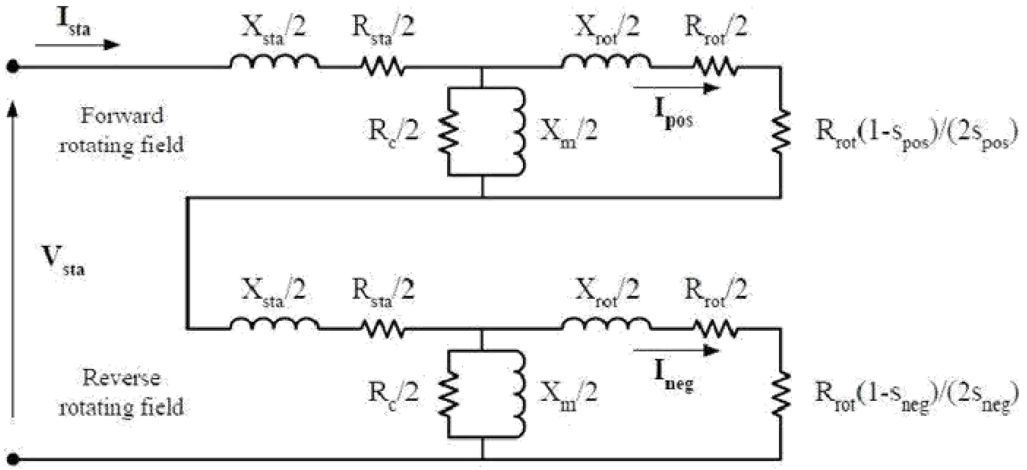


Fig:

Determination of Equivalent Circuit Parameters of Single Phase Induction motor

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

1- The DC Test:

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

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

Then, the AC resistance is given by:

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

2-The Blocked Rotor Test:

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

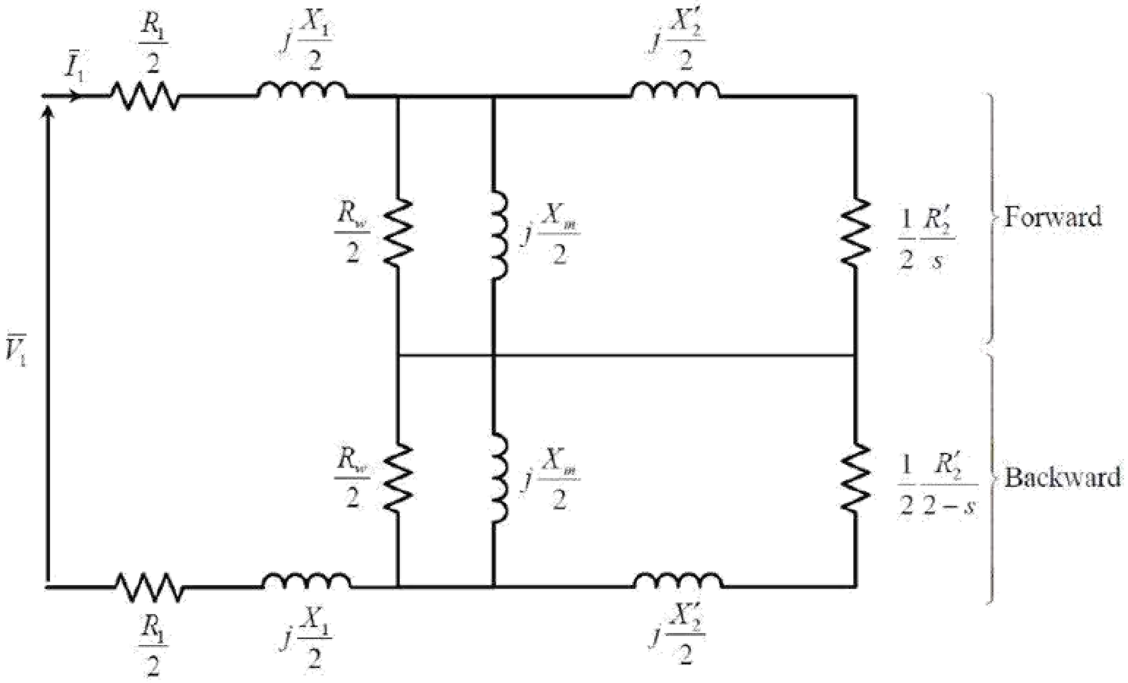


Fig: Equivalent circuit of single phase induction motor.

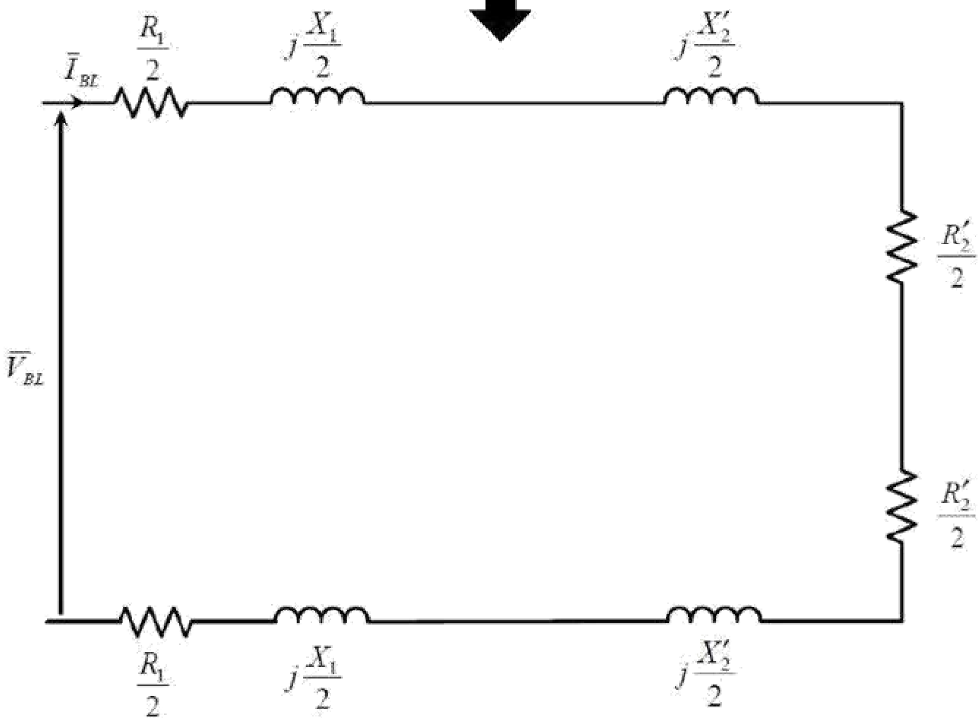


Fig: (a) Approximate equivalent circuit of the single phase induction motor at standstill.

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

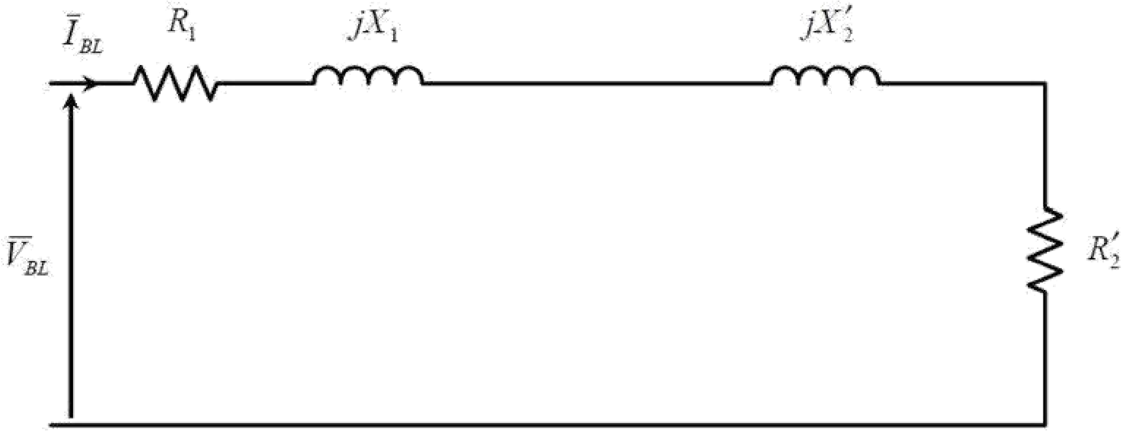
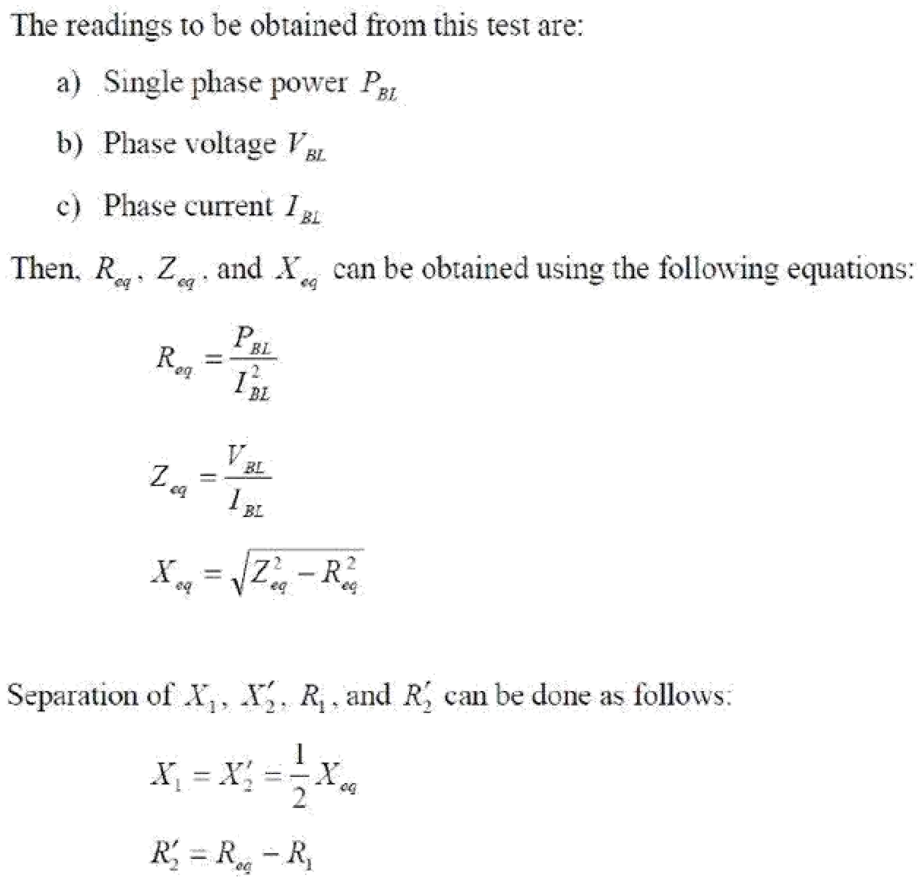


Fig: (b) Rearranged approximate equivalent circuit of the single phase induction motor at standstill.



The readings to be obtained from this test are:

a) Single phase power P_{BL}
b) Phase voltage V_{BL}
c) Phase current I_{BL}

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

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

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

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

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

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

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

3-The No Load Test:

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

The readings to be obtained from this test are:

d) Single phase power P_{NL}

e) Phase voltage V_{NL}

f) Phase current I_{NL}

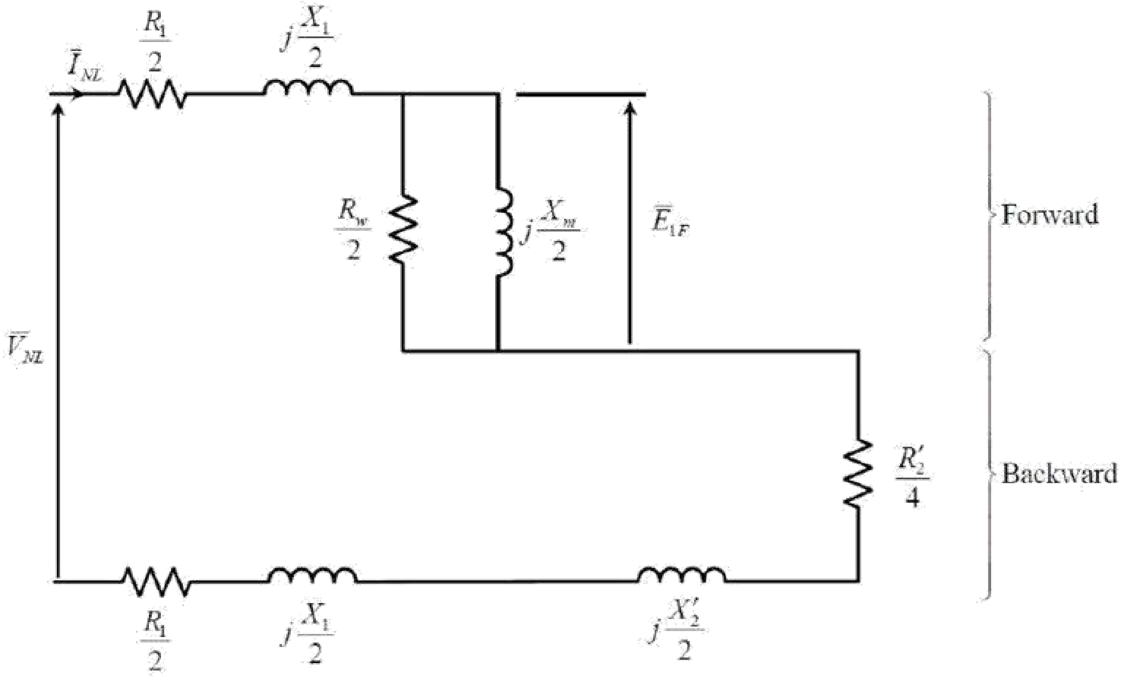


Fig: (a) Approximate equivalent circuit of the single phase induction motor at no load.

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

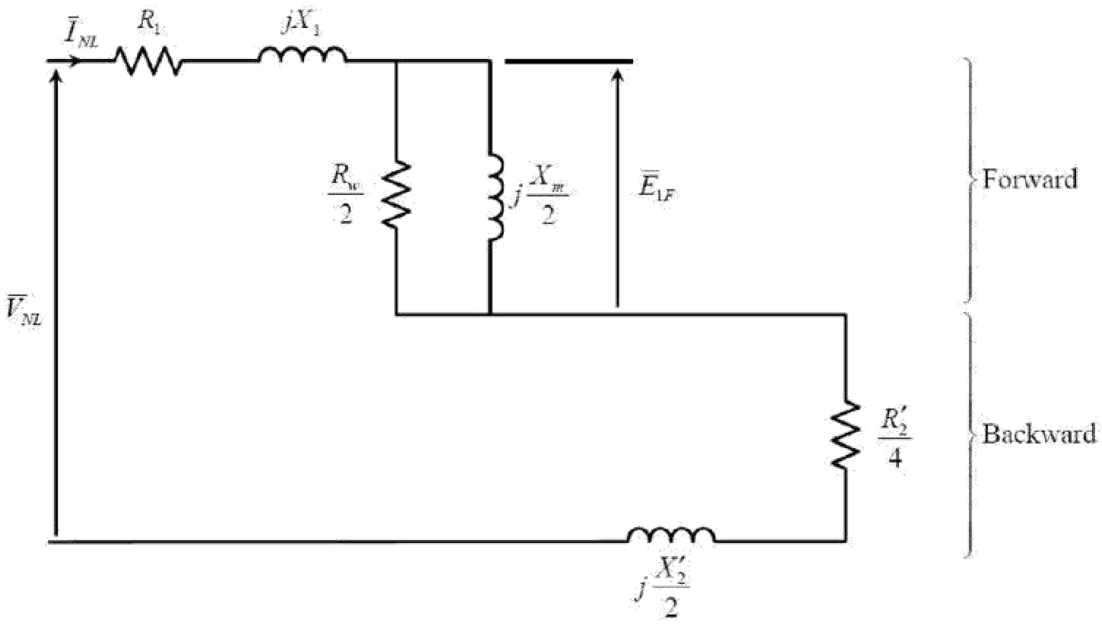


Fig: (b) Rearranged approximate equivalent circuit of the single phase induction motor at no load

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

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

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

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

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

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

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

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

Methods of Starting

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

(1) Split phase starting.

(2) Repulsion starting.

(3) Shaded pole starting.

PRINCIPLE OF SPLIT PHASE INDUCTION MOTOR

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

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

Working of Split Phase Motor

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

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

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

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

TYPES OF SPLIT-PHASE INDUCTION MOTORS

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

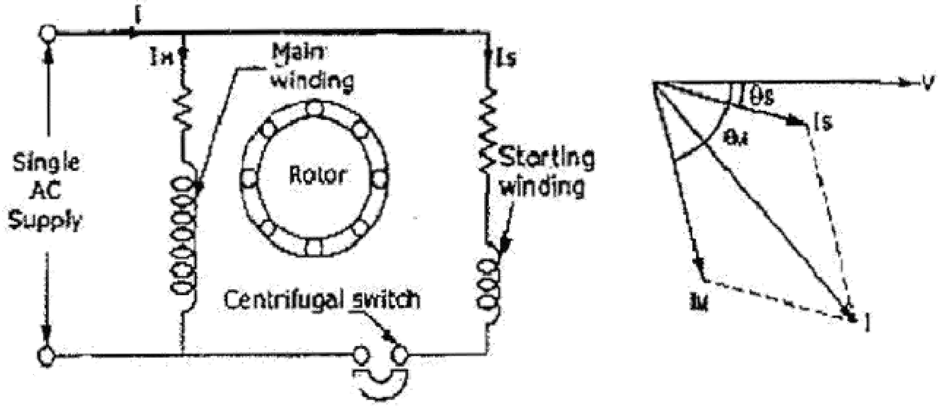
1. RESISTANCE-START, INDUCTION-RUN MOTORS

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

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

CONSTRUCTION AND WORKING

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



a)Schamatic diagram

b)Vector diagram

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

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

CHARACTERISTICS

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

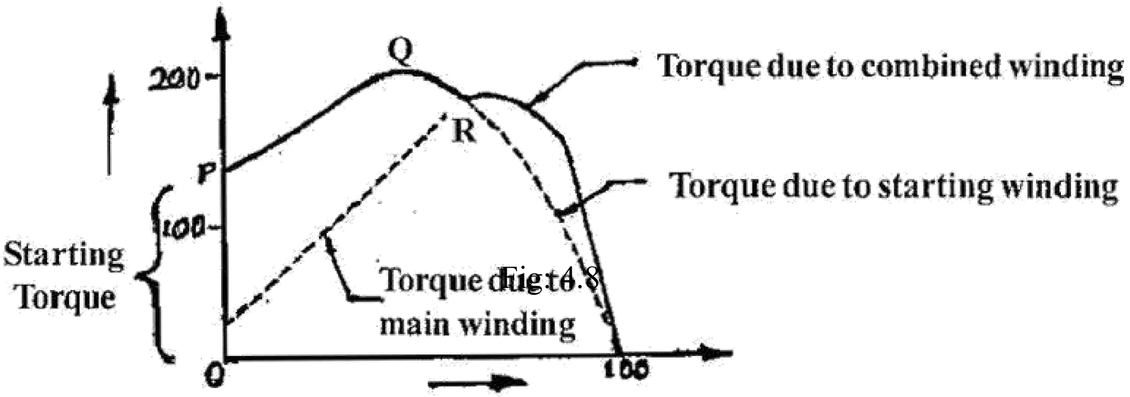


Fig: 4.8

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

APPLICATIONS

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

2. CAPACITOR-START, INDUCTION-RUN MOTOR

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

CONSTRUCTION AND WORKING

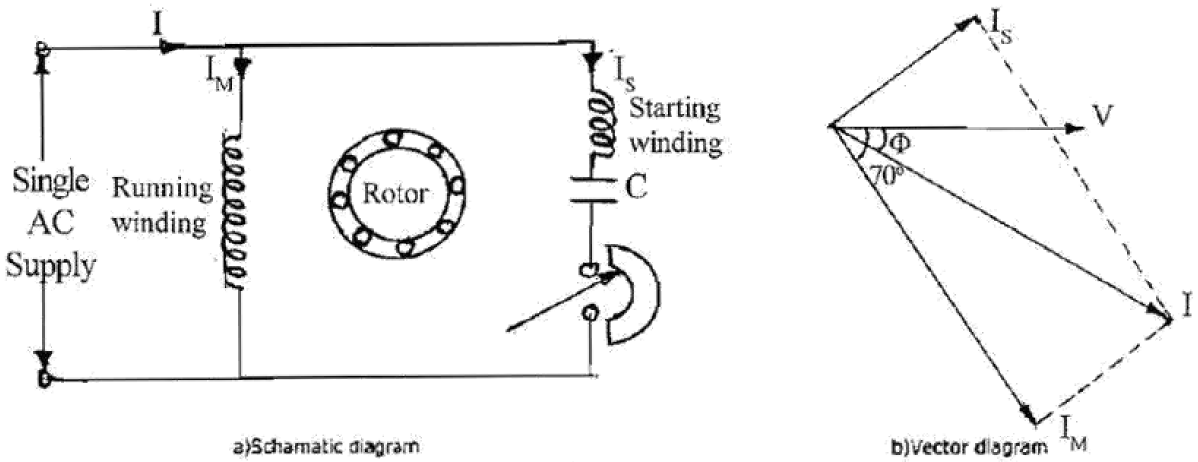
Fig: (a) shows the schematic diagram of a capacitor-start, induction-run motor. As shown, the main winding is directly connected across the main supply whereas the starting winding is connected across the main supply through a capacitor and centrifugal switch.

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

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

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

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



a)Schamatic diagram

b)Vector diagram

Fig:

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

CHARACTERISTICS

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

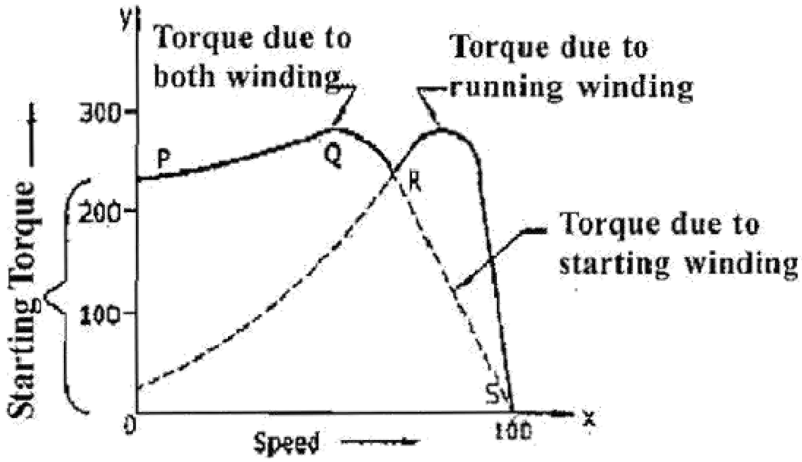


Fig: 4.10

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

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

APPLICATIONS

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

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

3. CAPACITOR-START, CAPACITOR-RUN MOTORS

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

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

CONSTRUCTION AND WORKING

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

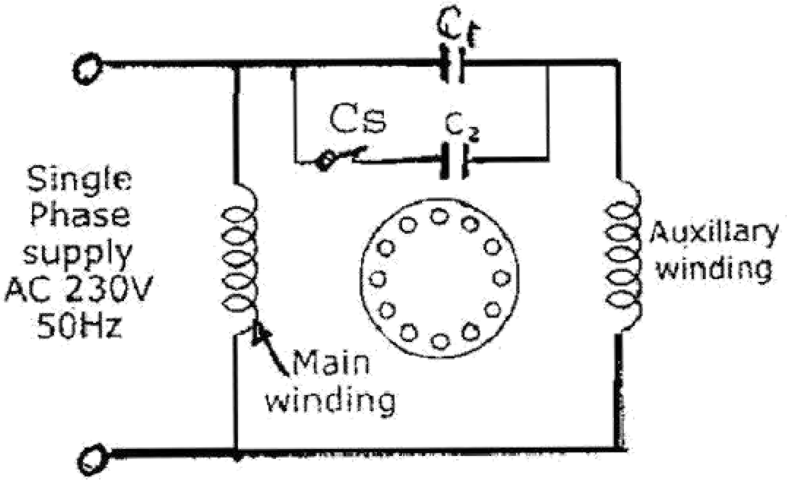


Fig:

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

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

CHARACTERISTICS

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

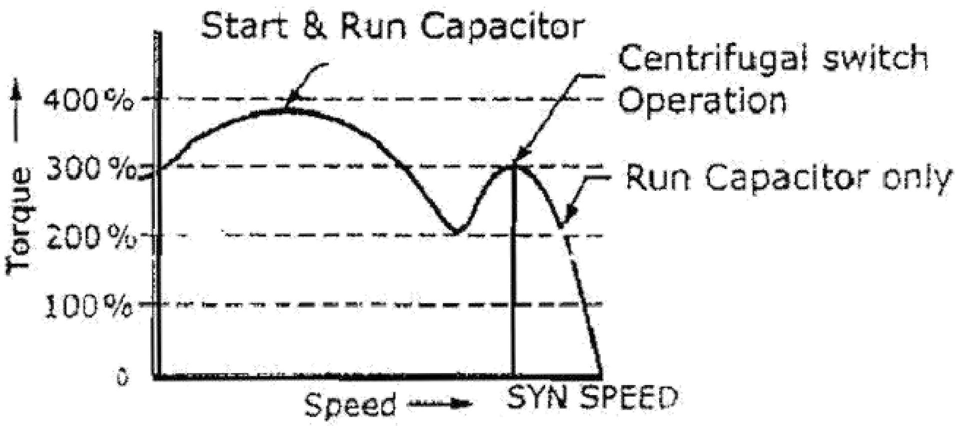


Fig:

This motor has the following advantages:

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

APPLICATIONS

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

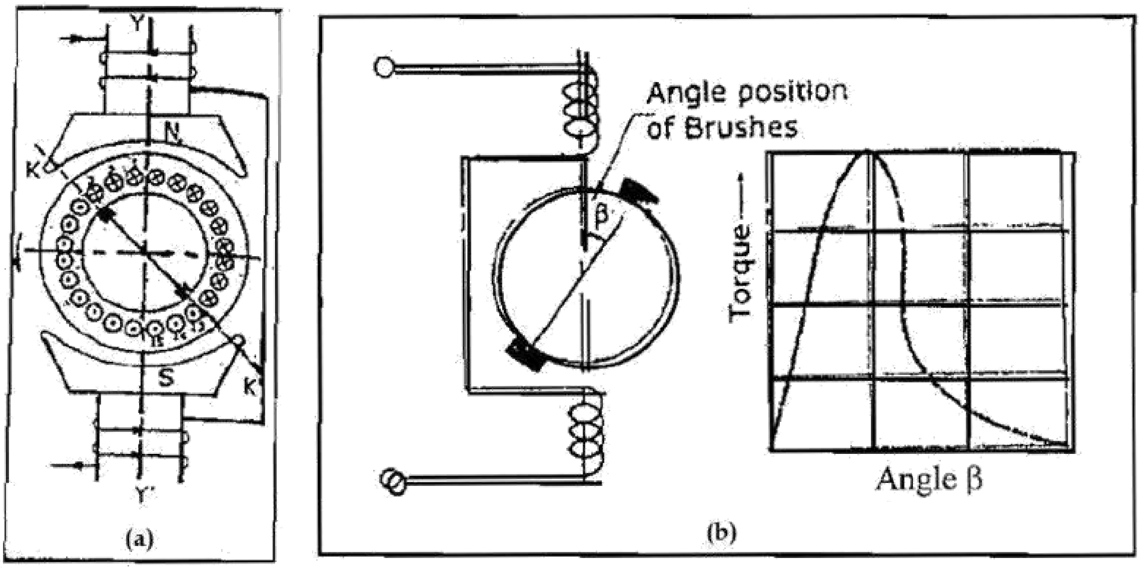
REPULSION STARTING

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

CONSTRUCTION AND WORKING

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

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



(a)

(b)

Fig:

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

CHARACTERISTICS

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

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

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

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

SHAPED POLE STARTING

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

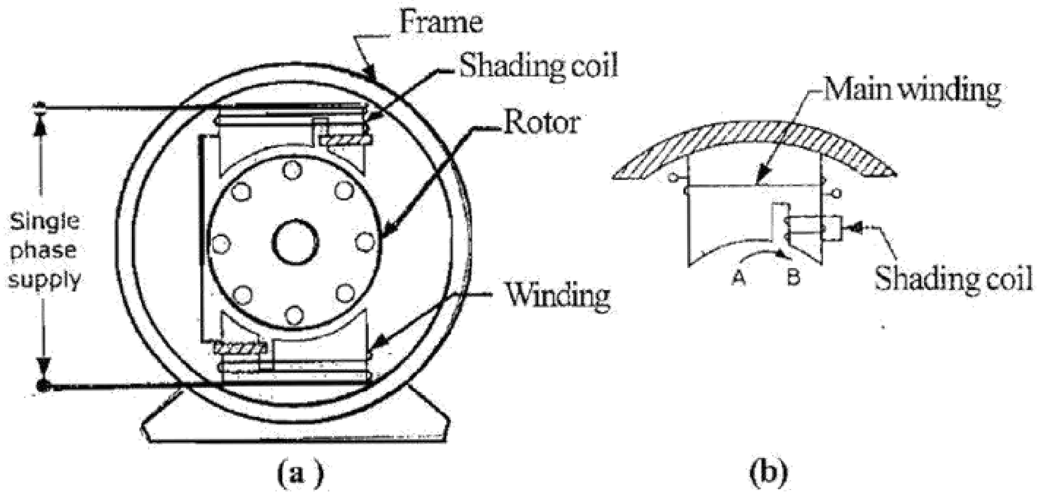


Fig:

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

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

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

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

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

THE MAGNETIC FLUX SHIFTING

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

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

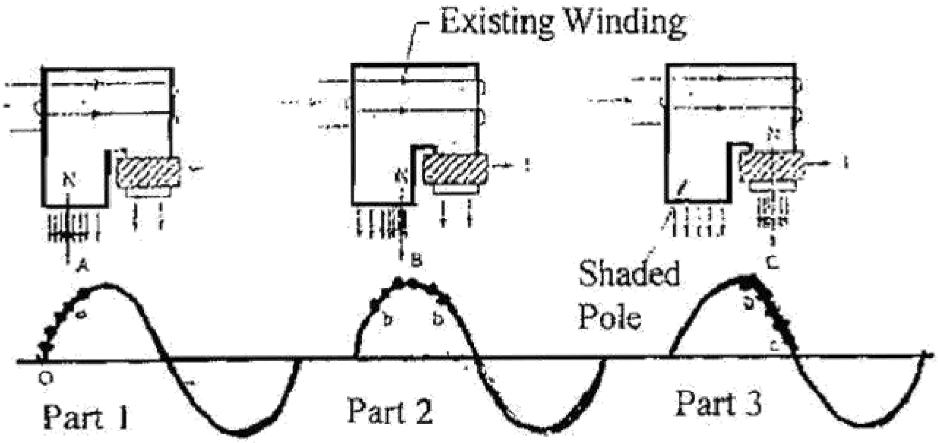


Fig: Shifting of magnetic flux

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

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

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

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

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

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

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

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

a. The double set of shading coils method

b. The double set of exciting winding method.

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

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

APPLICATIONS

- Record players
- Fans
- Hair driers.

Single Phase Series Motor

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

Operation

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

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

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

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

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

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

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

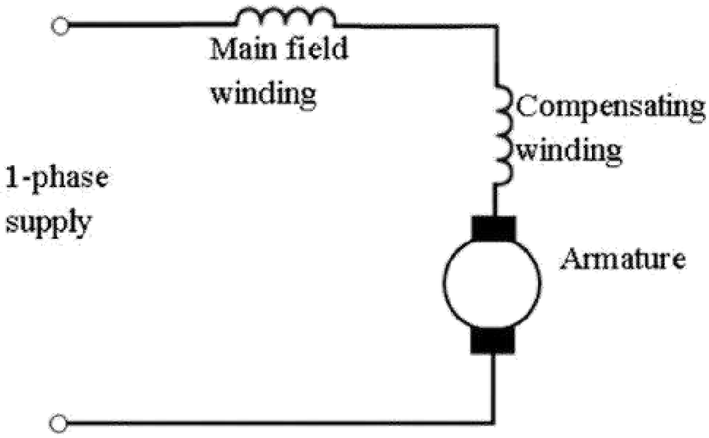


Fig: 4.16

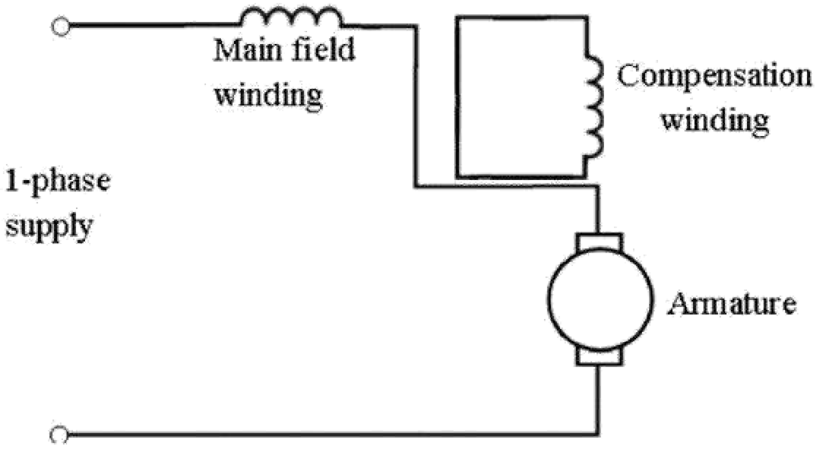


Fig:

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

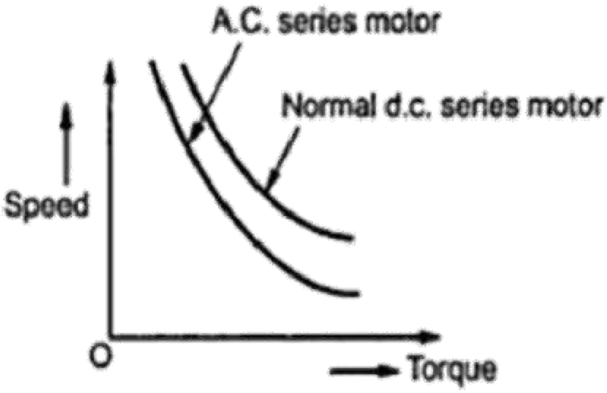


Fig: 4.18

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

4.4.2 Phasor Diagram of A.C Series Motor

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

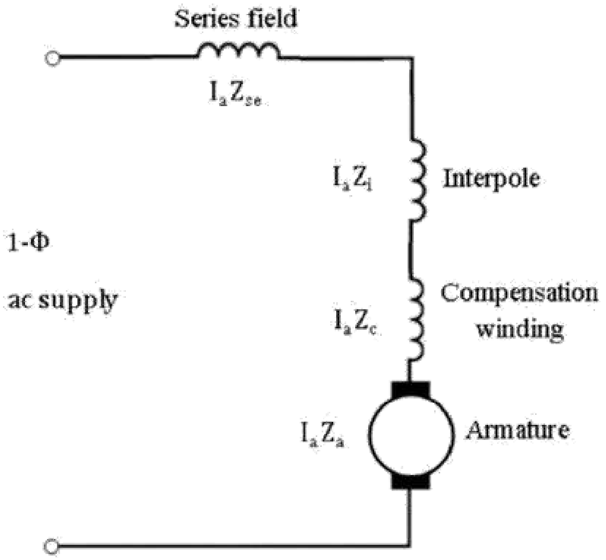


Fig:

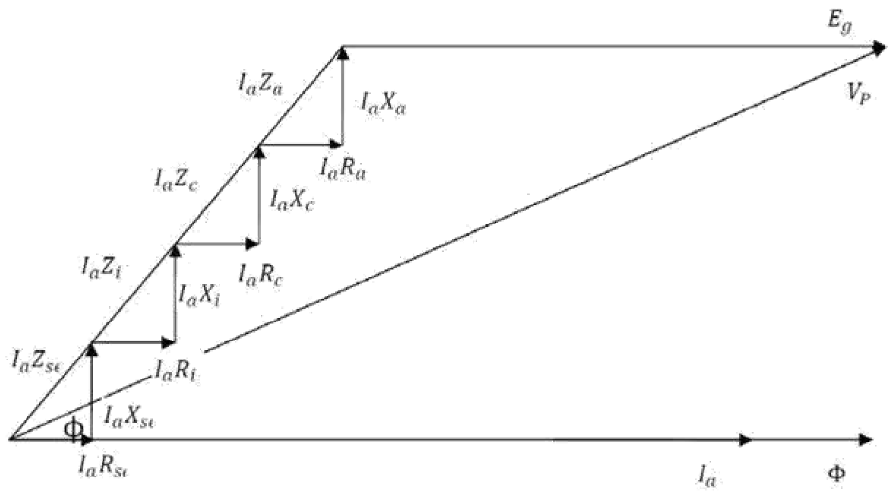


Fig:

The resistance I_aR_{se}, I_aR_i, I_aR_c and I_aR_a drops are due to resistances of series field, interpole winding, compensating winding and of armature respectively are in phase with armature current I_a. The reactance drops I_aX_{se}, I_aX_i, I_aX_c and I_aX_a are due to reactance of series field, interpole winding, compensating winding and of armature respectively lead current I_a by 90_0. The generated armature counter emf is E_g. The terminal phase voltage V_P is equal to the phasor sum of E_g and all the impedance drops in series.

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

The power factor angle between V_P and $I_a$is .

4.4.3 Applications

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

Schrage Motor

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

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

Construction and Operation

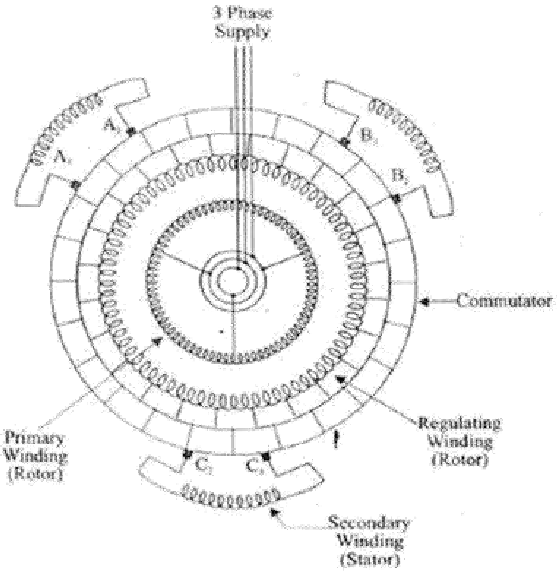


Fig:

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

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

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

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

Brushes A_1, B_1& C_1 move together and are 120_0 apart.

Brushes A_2, B_2& C_2 also move together and are 120_0 apart.

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

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

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

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

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

Speed Control

Speed of Schrage Motor can be obtained above and below Synchronous speed by changing the Brush position i.e. changing "θ" (' ' - Brush separation angle).

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

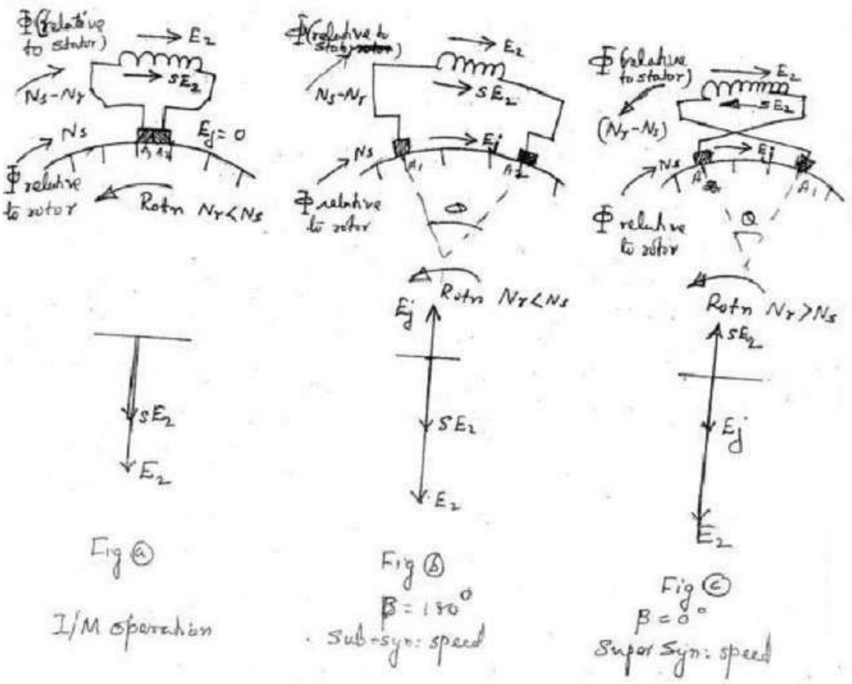


Fig: (a) ,(b) & (c)

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

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

"β is the angle between E_2 and Ej. β=180^0 and so here also $N_r < N_s$.

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

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

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

Power Factor Improvement

This can be obtained by changing the phase angle of the injected voltage into the secondary winding. In this case one set of brushes is advanced more rapidly than the other set. Now the twocentre lines do not coincide, have an angle ' 'ρbetween them. ('ρ" - Brush shift angle).

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

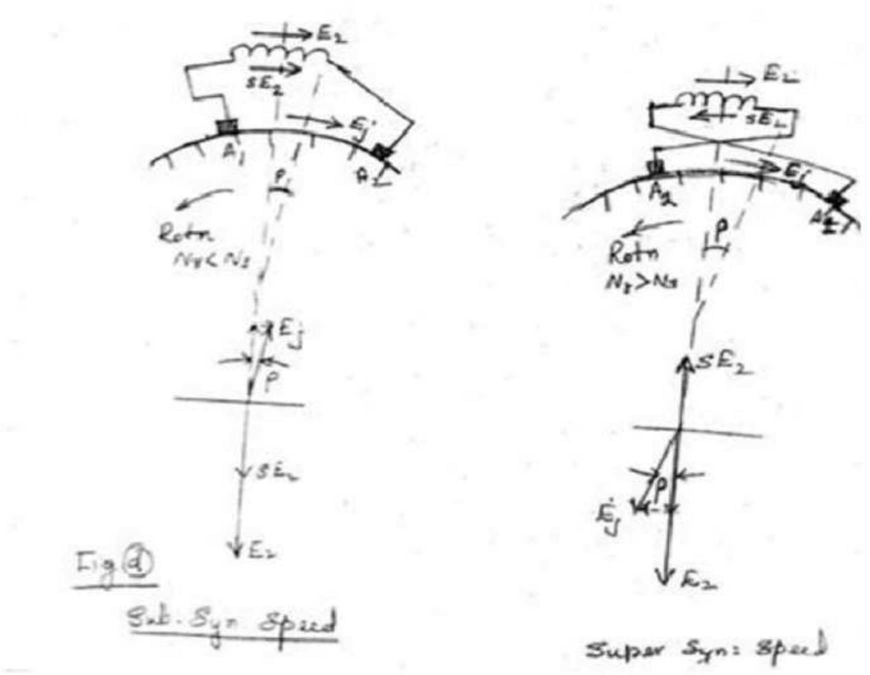


Fig: (d) & (e)

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

Both p.f. and speed can be controlled by varyingθ ' &ρ' '.

Thus 'Ej Cosρand 'Ej Sinρ' effect the speed and p.f. respectively. Fig: 4.23 show Variation of no load speed with Brush Separation.

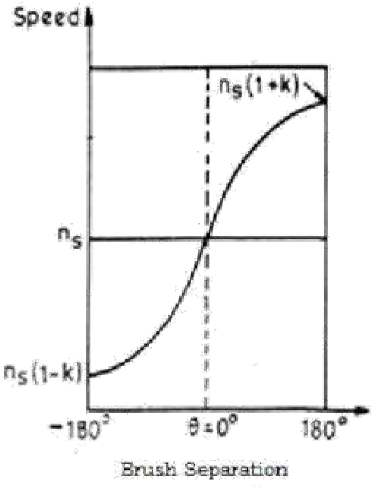


Fig:

Speed Torque Characteristics

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

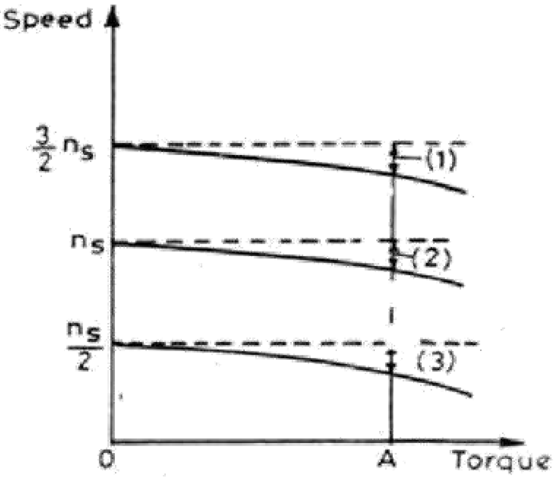


Fig:

Advantages & Shortcomings

Advantages:

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

(iii) High efficiency at all speeds except N_S

Shortcomings:

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

Applications

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

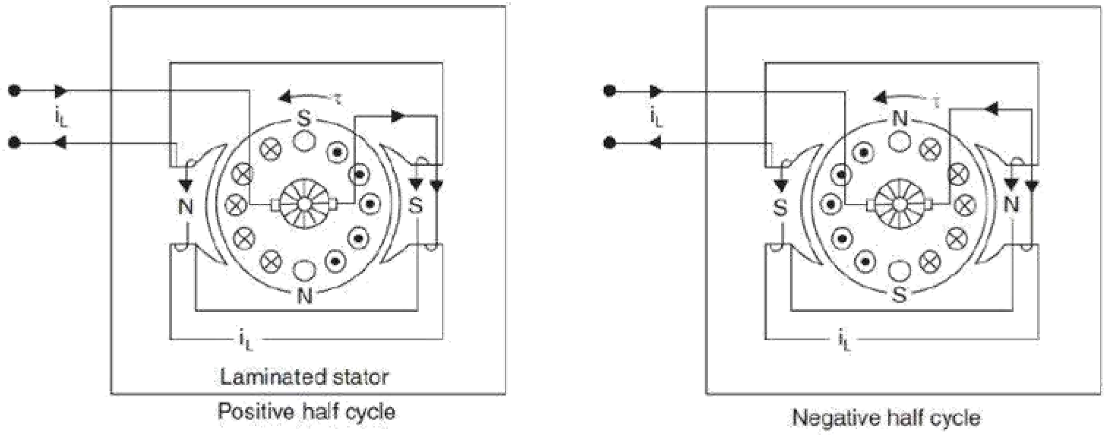
Universal Motors

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

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

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

Fig:



(a) (b)

Fig:

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

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

Operation

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

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

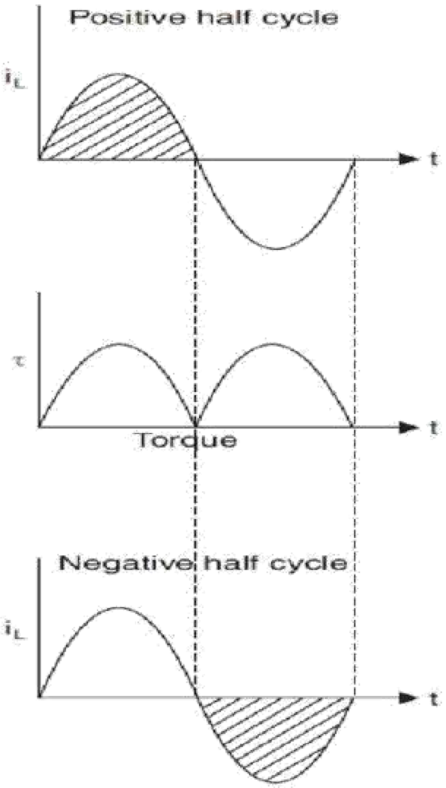


Fig: 4.26

Characteristic

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

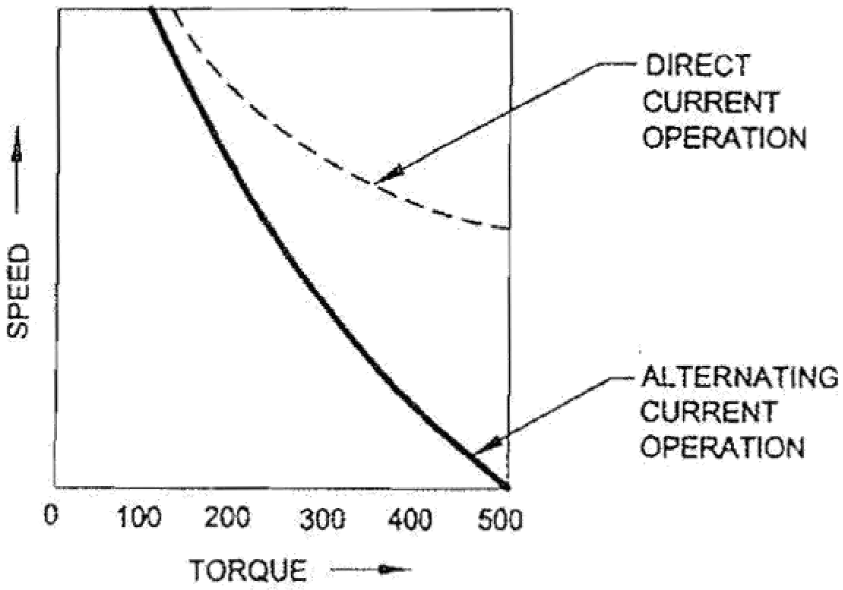


Fig: 4.27

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

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

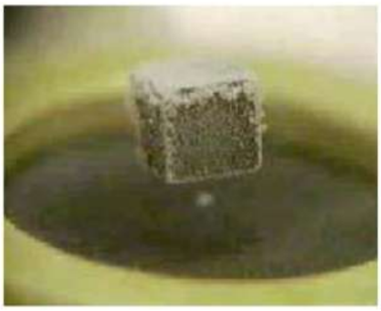
Applications

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

Magnetic Levitation

Magnetic fields are actively excluded from superconductors (Meissner effect). If a small magnet is brought near a superconductor, it will be repelled becaused induced supercurrents will produce mirror images of each pole. If a small permanent magnet is placed above a superconductor, it can be levitated by this repulsive force. Levitation currents in the superconductor produce effective magnetic poles that repel and support the magnet. The black ceramic material in the illustrations is a sample of the yttrium based superconductor.

By tapping with a sharp instrument, the suspended magnet can be caused to oscillate or rotate. This motion is found to be damped, and will come to rest in a few seconds.



A stepper motor is an electromechanical device which converts electrical pulses into discrete mechanical movements. The shaft or spindle of a stepper motor rotates in discrete step increments when electrical command pulses are applied to it in the proper sequence. The motors rotation has several direct relationships to these applied input pulses. The sequence of the applied pulses is directly related to the direction of motor shafts rotation. The speed of the motor shafts rotation is directly related to the frequency of the input pulses and the length of rotation is directly related to the number of input pulses applied.

Stepper Motor Advantages and Disadvantages

Advantages

1. The rotation angle of the motor is proportional to the input pulse.
2. The motor has full torque at standstill (if the windings are energized)
3. Precise positioning and repeatability of movement since good stepper motors have an accuracy of 3 – 5% of a step and this error is non cumulative from one step to the next.
4. Excellent response to starting/ stopping/reversing.
5. Very reliable since there are no contact brushes in the motor. Therefore the life of the motor is simply dependant on the life of the bearing.
6. The motors response to digital input pulses provides open-loop control, making the motor simpler and less costly to control.
7. It is possible to achieve very low speed synchronous rotation with a load that is directly coupled to the shaft.
8. A wide range of rotational speeds can be realized as the speed is proportional to the frequency of the input pulses.

Disadvantages

1. Resonances can occur if not properly controlled.
2. Not easy to operate at extremely high speeds.

Glossary

Accelerating Time: The time required for a motor to reach full speed from standstill (zero speed) position.

AC Contactor: An alternating current (ac) contactor is designed for the specific purpose of establishing or interrupting an AC power circuit.

Accelerating Torque: The torque developed from standstill (zero speed) to full speed at nameplate voltage. Sometimes the term "Net Accelerating Torque" is used to mean the excess motor torque capability over the torque for the attached load.

Adjustable Speed: The concept of varying the speed of applications.

Adjustable Speed Drive: A unit comprised of a motor, drive controller and operator's controls (either manual or automatic). Is also used to refer to the inverter which is a device used to convert standard sine wave power form into a simulated form for varying speed ranges on the driven equipment.

Adjustable Speed Motor: A motor that can be varied in speed over a range, but a motor that is essentially constant speed at any one set speed within that range.

Aerator Motors: A specific duty motor used pump air into a sludge type environment. The large air/liquid interface area provides excellent gas transfer and enables the sludge to be broken down and recycled into the environment.

Air Filter: Filter made from polyurethane (vertical), zinc or stainless steel (horizontal) medium to trap air-borne particles which may clog the operations of a weather protected II (WPII) motor.

Air Gap: The space between the rotating and stationary member in an electric motor.

Air Pressure Differential Switch: For use with air filters on weather protected II (WPII) enclosed motors. This switch will send alarm when a concentration of particles causes a pressure drop in the air flowing through the filter and into the motor. This feature allows the air filter to be used until its maximum capacity is reached.

ALLGUARD® Protection: Similar to CORRO-DUTY® treatment on motors, ALLGUARD protects the gearbox from corrosive atmospheres.

Alternating Current: The commonly available electric power supplied by an AC generator and distributed in one, two, and three phase form.

Altitude: The height of the motor in reference to sea level. Standard altitude is 3300 feet, or 1000 meters. Sometimes written as 3300 FASL (feet above sea level).

Ambient Temperature (Amb.): Ambient Temperature is the temperature of the medium, such as air, water or earth, into which the heat of the equipment is dissipated.

For self-ventilated equipment, the ambient temperature is the average temperature of the air in the immediate neighborhood of the equipment.

For air or gas cooled equipment with forced ventilation, or secondary water cooling, the ambient temperature is taken as that of the in coming air or cooling gas.

For self-ventilated enclosed (including oil immersed) equipment, considered as a complete unit, the ambient temperature is the average temperature of the air outside of the enclosure in the immediate neighborhood of the equipment.

Most motors are designed to operate in an ambient not over 40°C (104°F).

Note: A rating of 40°C Ambient is not the same as a rating of 40°C Rise; see Temperature Rise.

Ampere: The rate of flow of charge in a conductor of one coulomb per second.

Ampere Turn: The magnetomotive force produced by a current of one ampere in a coil of one turn.

Angular Contact Bearing: A specialized thrust bearing used on high-thrust vertical motors. The special angular design reduces friction and wear while supporting the rotating parts.

Angular Velocity: Angular displacement per unit time, measured in degrees/time or radians/time.

Anti-Friction Bearings: A bearing using balls or rollers as the supporting device between hardened races.

Antihunt: Antihunt is the means of reducing or suppressing the oscillation of a system.

Antiplug Protection: The effect of a control function, or a device that operates to prevent application of counter torque, by the motor until the motor speed has been reduced to an acceptable value.

Arctic Duty: Specific duty motors designed to withstand severely cold temperatures and environments. These motors will withstand ambient temperatures to -70° F.

Armature: The laminated iron core with wire wound around it in which electromotive force is produced by magnetic induction in a motor or generator: usually the rotor of a DC motor or the stator of an AC motor.

Armature Control: Abbreviated term for armature voltage control of a DC motor, which describes the usual method of changing the speed of a DC motor by controlling the magnitude of applied armature voltage.

Armature Current: Armature current is the DC current required by a DC motor to product torque and drive a load. The maximum safe, continuous current is stamped on the motor nameplate. This can only be exceeded for initial acceleration, and for short periods of time. Armature current is proportional to the amount of torque being produced, therefore it rises and falls as the torque demand rises and falls.

Armature Reaction: The current that flows in the armature winding of a D.C. motor tends to produce magnetic flux in addition to that produced by the field current. This effect, which reduces the torque capacity, is called armature reaction and can effect the commutation and the magnitude of the motor's generated voltage.

Armature Voltage Feedback: Armature voltage can be used as the speed feedback signal to an electronic speed regulator. This voltage is almost directly proportional to motor speed, assuming a constant motor field and ignoring IR drop. Armature voltage feedback is used where the expense of a tachometer generator for speed feedback is not justified and a regulation accuracy of 2-5% is adequate.

Asynchronous Motor: Also called non-synchronous motor, is an AC motor which does not run at synchronous speed. The ordinary induction motor is an asynchronous motor - single or polyphase.

Automotive Duty: Specific duty motors designed to meet the needs of the auto industry which include all cast iron construction, special ambient and temperature rise, and special drains and breathers. (See reference manual for actual automotive duty motor specification.)

Auxiliary Contacts: Auxiliary contacts of a switching device are contacts in addition to the main circuit contacts and operate with the movement of the latter.

Axial Centering Force: The magnetic force on the rotor resulting from its axial displacement from magnetic center.

Axis: A principal direction along which movement of the tool or workpiece occurs. The term "axis" also refers to one of the reference lines of a coordinate system.

Bandwidth: Generally, this is the frequency range of a system input over which the system will respond satisfactorily to a command.

Base Speed: Base speed is the manufacturer's nameplate rating where the motor will develop rated HP at rated load and voltage. With DC drives, it is commonly the point where full armature voltage is applied with full rated field excitation. With AC systems, it is commonly the point where 60 Hz is applied to the induction motor.

Bases - Slide Rails: A two piece mounting system for motors which enable the motor to be mounted and leveled to the needed heights.

Bases - Sole Plates: A one piece mounting system for motors which enable the motor to be raised and lowered to the required height.

Bearing, (Ball): A "ball" shaped component that is used to reduce friction and wear while supporting rotating elements. For a motor, this type of bearing provides a relatively rigid support for the output shaft.

Used where higher load capacity is required or ball bearing is preference. Common means used to keep out dirt:

Shields – Metal rings with close running clearance on one side (single-shielded) or both sides (double shielded) of bearing.

Seals – Similar to shields, except have rubber lips that press against inner race, more effectively excluding dirt, etc.

Bearing, (Roller): A special bearing system with cylindrical rollers capable of handling belted load applications that are too large for standard ball bearings.

Bearing, Sleeve (Slv.): A bearing that is made of a sleeve bushing, not a ball or roller bearing. In fractional hp motors, sleeve bearings are used on motors with low to moderate radial and axial loads.

Bearing, Unit: Motors are constructed with a long, single sleeve bearing. For fan duty only. All-position mounting unless otherwise stated.

Bearing Life: The expected endurance of motor bearings under specified load conditions. Bearing life is normally stated in terms of hours or years. Commonly referred to in motor specifications as B10 life or L10 life; both are used interchangeably.

Bipolar Transistor: Ordinary NPN or PNP transistor with emitter, base and collector are called bipolar since they operate through the collector are called bipolar since they operate through the flow of both holes and elections. Unipolar devices, such as FET transistors, operate through the flow of minority carries only, i.e. election flow.

Braking: Braking provides a means of stopping an AC or DC motor and can be accomplished in several ways:

1. **Dynamic Braking (DC Drives)** - Slows the motor by applying a resistive load across the armature leads after disconnection from the DC supply. This must be done while the motor field is energized. The motor then acts as a generator until the energy of the rotating armature is dissipated. This is not a holding brake.

   Dynamic Braking (AC Drives) - Since AC motors do not have separate field excitation, dynamic braking is accomplished by continuing to excite the motor from the drive. This causes a regenerative current to the drive's DC intermediate bus circuit. The dynamic brake resistors are then placed across the DC bus to dissipate the power returned. The brake resistor is usually switched by a transistor or other power switch controlled by the drive.
2. **Regenerative Braking** - This is similar to dynamic braking, but it is accomplished electronically. The generated power is returned to the line through the power converter. It may also be just dissipated as losses in the converter (within its limitations).
3. **Motor Mounted or Separately Mounted Brake** - This is a positive action, mechanical, friction device. Normal configuration is such that when the power is removed, the brake is set. This can be used as a holding brake. (Note: A separately mounted brake is one which is located on some part of the mechanical drive train other than the motor..)

Braking Torque: The torque required to bring a motor down from running speed to a standstill. The term is also used to describe the torque developed by a motor during dynamic braking conditions.

Breakaway Torque: The torque required to start a machine from standstill.

Breakdown Torque: The maximum torque which a motor will develop with rated voltage applied at rated frequency, without an abrupt drop in speed.

Bridge Rectifier: A full wave rectifier that conducts current in only one direction of the input current. AC applied to the input results in approximate DC at the output.

Bridge Rectifier (Diode, SCR): A diode bridge rectifier is a non-controlled full wave rectifier that produces a constant, rectifier DC voltage. An SCR bridge rectifier is a full wave rectifier with an output that can be controlled by switching on the gate control element.

Brush: A brush is a conductor, usually composed of some element of carbon, serving to maintain an electrical connection between stationary and moving parts of a machine (commutator of a DC motor). The brush is mounted in a springloaded holder and positioned tangent to the commutator segments against which it "brushes." Pairs of brushes are equally spaced around the circumference of the commutator.

Buss Connections: An option on titan conduit boxes. Used to add up to three standoff insulators.

C-Face (Motor Mounting): This type of motor mounting is used to close couple pumps and similar applications where the mounting holes in the face are threaded to receive bolts from the pump. Normally, the C-Face is used where a pump or similar item is to be overhung on the motor. This type of mounting is a NEMA standard design and available with or without feet.

C-Flange: A type of mounting used to connect motors/gearmotors to driven equipment with dimensions defined by NEMA. This type of mounting is used to close couple pumps and similar applications where the mounting holes in the face are threaded to receive bolts from the driven equipment.

Capacitance: The value in microfarads of a capacitor or condenser.

Capacitor: A device which, when connected in an alternating current circuit, causes the current to lead the voltage in time phase. The peak of the current wave is reached ahead of the voltage wave. This is the result of the successive storage and discharge of electric energy.

Two kinds of capacitors are normally used in AC induction motors. A start capacitor is connected in series with the auxiliary circuit. It can only stay energized for a short period of time. Therefore it is only energized when the motor is started and it is removed from the circuit after the motor reaches operating speed. The run capacitor can stay energized continuously. Therefore, it stays in the circuit even after the motor reaches operation speed and used in PSC and the running circuit of capacitor-start capacitor-run motors.

Capacitor value and voltage rating are essential to the proper motor operation. Always use the correct capacitor as specified by the motor manufacturer to insure maximum performance and life and safe operation of the motor.

Cascade Drive System: Two or more drives connected to a master speed setting potentiometer. The master speed setting potentiometer sets the speed of the master drive. Each of the slave drives has a potentiometer of trimming the speed reference from the master speed setting potentiometer.

CEMF: Abbreviation for counter electromotive force, which is the product of a motor armature rotating in a magnetic field. This generating action takes place whenever a motor is rotating. Under stable motoring conditions the generated voltage (CEMF) is equal to the voltage supplied to the motor minus small losses. However, the polarity of the CEMF is opposite to that of the power being supplied to the armature.

Center Distance: The measured distance from the center of a pinion to the center of its mating gear.

Centrifugal Cutout Switch: A centrifugally operated automatic mechanism used in conjunction with single phase induction motors. Centrifugal cutout switch will open or disconnect the starting winding when the rotor has reached a predetermined speed, and re-connect it when the motor speed falls below it. Without such a device, the starting winding would be susceptible to rapid overheating and subsequent burnout.

Closed Loop: Closed loop refers to a regulator circuit in which the actual value of the controlled variable (e.g., speed) is sensed and a signal proportional to this value (feedback signal) is compared with a signal proportional to the desired value (reference signal). The difference between these signals (error signal) causes the actual value to change in the direction that will reduce the difference in signals to zero.

Code Letter: A code letter is a letter which appears on the nameplate of alternating-current motors to show their locked-rotor KVA per horsepower.

Cogging: A term used to describe non-uniform angular velocity. It refers to rotation occurring in jerks or increments rather than smooth motion. When an armature coil enters the magnetic field produced by the field coils, it tends to speed up and slow down when leaving it. This effect becomes apparent at low speeds. The fewer the number of coils, the more noticeable it can be.

Commutation (DC Motors): Reversing the current in an armature coil when the coil (ends) move from one side of the brush to the other side of the same brush. This completes the connection between the armature winding and the external circuit.

Commutation (Inverter): The process by which forward current is interrupted or transferred from one switching device to the other. In most circuits where power is supplied from an AC source, turn-on control is adequate and turn-off occurs naturally when the AC cycle causes the polarity across a given device to reverse.

Commutator: A cylindrical device mounted on the armature shaft and consisting of a number of wedge-shaped copper segments arranged around the shaft (insulated from it and each other). The motor brushes ride on the periphery of the commutator and electrically connect and switch the armature coils to the power source.

Comparator: A device that compares one signal to another, usually the process signal compared to the set point or command signal.

Computerized Numerical Control (CNC): A numerical control system where a computer is used to perform some or all of the basic numerical control functions on a machine tool.

Conduit Box: Metal box on motor where motor leads terminate.

Constant Horsepower: A multi-speed wound motor where all the windings are of the same horsepower.

Constant Horsepower Range: In VFD applications, a range of motor operation where the motor speed is controlled by field weakening. In this range, motor torque decreases as speed increases. Since horsepower is speed times torque (divided by a constant), the value of horsepower developed by the motor in this range is constant.

Constant Torque: A multi-speed motor wound so that the horsepower varies directly as the speed.

Constant Torque Range: In VFD applications, a speed range in which the motor is capable of delivering a constant torque, subject to cooling limitations of the motor.

Constant Voltage Range (AC Drives): The range of motor operation where the drive's output voltage is held constant as output frequency is varied. This speed range produces motor performance similar to a DC drive's constant horsepower range.

Constant Volts Per Hertz (V/HZ): This relationship exists in AC drives where the output voltage is varied directly proportional to frequency. This type of operation is required to allow the motor to produce constant rated torque as speed is varied.

Control Circuit: The control circuit of a control apparatus or system is the circuit which carries the electric signals directing the performance of the controller, but does not carry the main circuit power.

Control Device: A control device is an individual device used to control functions.

Control Transformer: A control transformer is a voltage transformer utilized to supply voltage suitable for the operation of control devices.

Counter Electromotive Force: (CEMF) The induced voltage in motor armature, caused by conductors moving through or "cutting" field magnetic flux. This induced voltage opposes the armature current and tends to reduce it.

Conductor: Any material which tends to make the flow of electric current relatively easy (copper, aluminum, etc.).

Contactor: A two-state (On-Off) device for repeatedly establishing an interrupting an electric power circuit. Interruption is obtained by introducing a gap or a very large impedance.

Contactor Reversing: A method of reversing motor rotation by the use of two separate contactors, one of which produces rotation in one direction and the other produces rotation in the opposite direction. The contactors are electrically (and mechanically) interlocked so that both cannot be energized at the same time.

Continuous Duty: A motor that can continue to operate within the insulation temperature limits after it has reached normal operating temperature.

Continuous Rating: The maximum constant load that can be carried continuously without exceeding established temperature rise limitations under prescribed conditions of load and within the limitations of established standards.

Control Transformer: A control transformer is a voltage transformer utilized to supply voltage suitable for the operation of control devices.

Converter: The process of changing AC to DC and back to AC again. This is accomplished through the use of a diode rectifier or thyristor rectifier circuit. The term "converter" may also refer to the process such that is found in an adjustable frequency drive, consists of a rectifier, a DC intermediate circuit, an inverter and a control unit.

Copper Bar Rotor: Specialized rotor construction used on high inertia applications that require high slip or torques. Centrifugal cast end rings are fully brazed to each rotor bar. Rotor bars are swagged preventing inslot movement and tight bar constructions. Heavy finger plates tightly hold the rotor cove together controlling internal stress and maintaining dimension stability under all loads.

CORRO-DUTY ®: U.S. MOTORS® brand motor product created for withstanding corrosive environments.

Coupling: A means for which the driven load is connected to the driver (motor). Couplings are divided into 2 halves with one placed on the motor shaft and the other on the driven equipment. The 2 halves are then bolted together.

Coupling Angle: The mechanical degree relationship between the rotor and the rotating electrical field in a motor. While present in both synchronous and non-synchronous A.C. motors, it is usually of concern in synchronous applications. At no load, the rotor poles line up exactly with the field poles and the coupling angle is considered to be zero. When a load is applied, the lines of force coupling the rotor with the stator field are stretched, causing the rotor to fall behind the field. The mechanical angle by which the rotor lags behind the field is called the coupling angle. The coupling angle will continue to increase with load until it reaches the "pull-out" point. The maximum angle which is possible prior to pull-out is dependent on motor type and rotor design.

Critical Speed: All rotating masses have a so-called critical speed (RPM) where abnormal vibrations occur. Induction motors (rotors), generally run well above this speed, but occasionally in redesigning -- the critical speed may occur at or near the operating speed -- and intolerable situation.

Crusher Duty: Specific-duty motor design including special rotor, larger shaft (if needed), increased locked rotor and breakdown torques, end turn bracing and lock washers, and minimized stress riser.

Current Limit: An electronic method of limiting the maximum current available to the motor. This is adjustable so that the motor's maximum current can be controlled. It can also be preset as a protective device to protect both the motor and controller from extended overloads.

Current Limit Acceleration: A system of control in which acceleration is so governed that the motor current does not exceed an adjustable maximum value.

Current Limiting Fuse: A fuse that, when it is melted by a current within its specified current limiting range, abruptly introduces a high impedance to reduce the current magnitude and duration.

Current Relay: A current relay functions at a predetermined value of current. It may be an overcurrent relay, an undercurrent relay or a combination of both.

Current Transformers: Option available on titan motors to maintain the same magnitude of current flowing in and out of each phase of the motor winding. A breakdown in the insulation system alters this balance resulting in measurable "difference" when the current flowing in and out of each circuit is compared for symmetry. Any dissimilarity within an individual circuit is knows as "differential current" which can be detected with current transformers that provide differential protection.

D-Flange (Mounting): A type of motor mounting used when the motor is to be built as part of the machine. The mounting holds of the flange are not threaded. The bolts protrude through the flange from the motor side. Normally, D-flange motors are supplied without feet since the motor is mounted directly to the driven machine.

Damping: Damping is the reduction in amplitude of an oscillation in the system.

Dead Band: The range of values through which a system input can be changed without causing a corresponding change in system output.

Deceleration Time: The time required to stop a motor - whether - free running or with some braking means.

Definite Purpose Motor: A definite purpose motor is any motor design, listed and offered in standard ratings with standard operating characteristics and mechanical construction, for use under service conditions other than usual or for use on particular type of application (NEMA). An example would a vertical holloshaft motor.

Deviation: Difference between an instantaneous value of a controlled variable and the desired value of the controlled variable corresponding to the set point. Also called an error.

di/dt: The rate of change in current versus a rate of change in time. Line reactors and isolation transformers can be used to provide the impedance necessary to reduce the harmful effects that unlimited current sources can have on phase controlled rectifiers (SCR's).

Dimension Drawing: A dimension drawing or outline drawing (base plan or floor plan) is one which shows the physical space and mounting requirements of a piece of equipment. It may also indicate ventilation requirements and space provided for connections or the location to which connections are to be made.

Diode: A device that passes current in one direction, but blocks current in the reversed direction.

DC Contactor: A contactor specifically designed to establish or interrupt a direct current power circuit.

DC Motor - Compound Wound: Type of DC motor having both shunt and series field connections. This motor has good speed regulation and starting torque.

DC Motor - Permanent Magnet: Type of DC motor where the field poles and the armature poles are electromagnets. The only current used by the motor is that of the armature. Has high starting torque, good speed regulation and a definite maximum speed.

DC Motor - Series Wound: Type of DC motor which has its field winding connected in series with the armature. This motor has very high starting torque, but has a tendency to ‘run-away’ when lightly loaded or unloaded, and has poor speed regulation.

DC Motor - Shunt Wound: Type of DC motor which has its armature winding and field winding done in parallel circuits. This motor has very good speed regulation.

Distributed Pole: A motor has distributed poles when its stator or field windings are distributed in adjacent slots located within the arc of the pole.

Drain/Breather: A hole located in the lowest spot of the motor used to drain oil/grease when re-lubricating the motor.

Drift: Drift is the deviation from the initial set speed with no load change over a specific time period. Normally, the drive must be operated for a specified warm-up time at a specified ambient temperature before drift specifications apply. Drift is normally caused by random changes in operating characteristics of various controller components.

Drip Cover: A metal piece shaped like a pizza pan attached to the top of a motor mounted vertically shaft down to protect liquid from entering into the motor.

Drive Controller (Also variable speed drive): An electronic device that can control the speed, torque, horsepower and direction of an AC or DC motor.

Dual Voltage: A connection method with enough leads in the terminal box to permit simple reconnection to either of two voltages.

Duty Cycle: The relationship between the operating and rest time. A motor which can continue to operate within the temperature limits of its insulation system, after it has reached normal operating (equilibrium) temperature is considered to have a continuous duty (CONT.) rating. One which never reaches equilibrium temperature, but is permitted to cool down between operations is operating under intermittent duty (INT.) conditions.

dv/dt: The rate of change in voltage versus a rate of change in time. When a motor is operated under VFD power a high value of dv/dt will indicate voltage spikes and/or line disturbances.

Dwell: The time spent in one state before moving to the next. In motion control applications, for example, a dwell time may be programmed to allow for a tool change or part clamping operation.

Dynamic Braking: This is caused by current being applied to the windings after the power is shut off. This is accomplished by either excitation (D.C. motors) or by separate excitation, A.C. motors. It is seldomly used to hold a load, but it can be used as a retarding force to prevent over-running.

Dynamic Unbalance: A noise producing condition caused by non-symmetrical weight distribution of a rotating member. The lack of a uniform wire spacing in a wound armature or casting voids in a rotor or fan assembly can cause relatively high degrees of unbalance.

Eddy Current: Localized currents induced in an iron core by alternating magnetic flux. These currents translate into losses (heat) and their minimization is an important factor in lamination design.

Eddy Current Brake: A unit consisting of a rotating member keyed to a straight through, double extension shaft and a field coil assembly. The brake rotor rotates at the speed of the prime mover until the field coil is energized. Rotation of the rotor is slowed by controlling the current in the field coil.

Eddy Current Clutch: A device that permits connection between a motor and a load by electrical (magnetic) means - no physical contact is involved. This method is also used for speed control (by clutch "slippage").

Eddy Current Drive: A unit consisting of a driving member which is the drum assembly, the driven member which is the rotor assembly, and a magnetic member which is the field coil assembly. The driven member is driven by a constant speed AC motor. Control of the eddy current drive is obtained by controlling the current in the field coil.

Efficiency: The efficiency of a motor is the ratio of mechanical output to electrical input. It represents the effectiveness with which the motor converts electrical energy into mechanical energy at the output shaft. The higher the efficiency, the better the conversion process and the lower the operating costs.

Electrical Coupling: When two coils are so situated that some of the flux set up by either coil links some of the turns of the other, they are said to be electrically coupled.

Electrical Degree: A unit of measurement of time as applied to alternating current. One complete cycle = 360 electrical degrees. One cycle in a rotating electric machine is accomplished when the rotating field moves from one pole to the next pole of the same polarity. There are 360 electrical degrees in this time period. Therefore, in a two pole machine there are 360 degrees in one revolution, and the electrical and mechanical degrees are equal. In a machine with more than two poles, the number of electrical degrees per revolution is obtained by multiplying the number of pairs of poles by 360.

Electrical Time Constant: The ratio of electrical inductance to armature resistance.

Electromotive Force: (EMF) A synonym for voltage, usually restricted to generated voltage. In DC adjustable speed drives, voltage applied to the motor armature from a power supply is the EMF and the voltage generated by the motor is the counter-electromotive force, or CMEF.

Electronic DC Motor Controller: An electronic direct current motor controller is a phase-controlled rectifying system using semi-conductors for power conversion to supply the armature circuit or the armature and shunt field circuits of a direct current motor to provide adjustable speed, adjustable and compensated speed, or adjustable and regulated speed characteristics.

Enable: To allow an action or acceptance of data by applying an appropriate signal to the appropriate input.

Encapsulated Winding: A motor which has its winding structure completely coated with an insulating resin (such as epoxy). This construction type is designed for exposure to more severe atmospheric conditions than the normal varnished winding.

Enclosure: Enclosure refers to the housing in which the controller is mounted. Enclosures are available in designs for various environmental conditions.

Defines the motor construction according to environmental protection and method of cooling. Types include:

> **Open**: A motor that has openings, which permit passage of external cooling air over and around the windings. Usually used indoors, in fairly clean locations.
>
> **Dripproof/Open Dripproof (DP/ODP):** Horizontal motor term indicating a machine in which the ventilating openings are so constructed that successful operation is not interfered with when drops of liquid, or solid particles, strike, or enter, the enclosure at any angle from 0 to 15° downward from the vertical.
>
> **Dripproof Guard (DPG):** An open dripproof machine in which all openings giving direct access to live metal or rotating parts (except smooth rotating surfaces) are limited in size by the structural parts, or by the screens, baffles, grilles, expanded metal, or other means to prevent accidental contact with hazardous parts. Openings giving direct access to such live or rotating parts shall not permit the passage of a cylindrical rod 0.75 inch in diameter.
>
> **Explosionproof (XP):** Previous designation for Hazardous Location. A machine designed to withstand an explosion of a specified vapor, gas, or dust, inside the motor casing and prevent the ignition outside the motor by sparks, flashing, or explosion.
>
> **Pipe Ventilated:** Similar to an open dripproof motor except that openings for admission of ventilating air are so arranged that inlet ducts or pipes can be connected to them. Air may be circulated by means integral with the machine or by means external to the machine (separately or forced ventilated).
>
> **Separately Ventilated (DC Motors):** A motor which has a blower attached, or some other cooling equipment, to move air across the unit and keep it below the limiting temperature rise.

Splash Proof (DC Motor): An open machine in which the ventilating openings are so constructed that successful operation is not interfered with when drops of liquid or solid particles strike or enter the enclosure at any angle not greater than 100° downward from the vertical.

Totally Enclosed Air Over (TEAO): A machine which does not utilize a fan for cooling, but is used in situations where air is being blown over the motor frame for cooling, such as a fan application. When quoting this motor, air velocity in feet per minute must be specified.

Totally Enclosed Air-to-Air Machine (TEAAC): A totally enclosed machine which is cooled by circulating the internal air through a heat exchanger which, in turn, is cooled by circulating external air. It is provided with an air-to-air heat exchanger for cooling the internal air, a fan (or fans), integral with the rotor shaft or separate, for circulating the internal air and a separate fan for circulating the external air.

Totally Enclosed Fan Cooled (TEFC): A machine which has an enclosure which does not allow for free exchange of air, but still breathes air. A fan is attached to the shaft that pushes air over the frame during operation to help in the cooling process.

Totally Enclosed Non-Ventilated (TENV): A totally enclosed machine which does not have means for cooling built into the design. This design requires external cooling provision supplied by an outside source.

Totally Enclosed Water Cooled (TEWC): A totally enclosed machine which is cooled by circulating water and with the water or water conductors come in direct contact with the machine parts.

Totally Enclosed Water-to-Air Cooled (TEWAC): A totally enclosed machine which is cooled by circulating air which, in turn, is cooled by circulating water. These motors are provided with a water-cooled heat exchanger for cooling the internal and a fan(s), integral with the rotor shaft separate, for circulating the internal air. (Design not offered in U.S. MOTORS® brand product line.)

Washdown Duty: A machine designed specifically for the food processing industry and other applications that are routinely exposed to washdown, chemicals, humidity, and other severe environments.

Weather Protected I (WPI): A vertical or large horizontal machine which has ventilating passages constructed to minimize the entrance of rain, snow, airborne particles and prevent passage of a 0.75 inch diameter cylindrical rod.

Weather Protected II (WPII): A machine which has the protection of a weather protected I machine plus the normal path of the ventilating air which enters the electric parts of the machine so arranged so that there are at least 3 abrupt changes in direction, none of which is less than 90° . In addition, an area of low velocity not exceed 600 feet per minute shall be provided in the intake air path to minimize the possibility of moisture or dirt being carried into the electric parts of the machine.

Enclosure, Controller NEMA Type 1: A general purpose enclosure of either a ventilated or non-ventilated variety. It is used for most indoor applications and is intended to protect against dust, light, indirect splashing and accidental human contact with the electrical circuit.

Enclosure, Controller NEMA Type 4: A watertight enclosure, required whenever the unit is subjected to a great amount of water from any angle. It is normally used in areas that are repeatedly hosed down. This enclosure is not designed to be submerges.

Enclosure, Controller NEMA Type 7: An enclosure designed for a hazardous location , Class I (air), Group D, per the National Electrical Code. This hazardous environment is one in which flammable gases or vapor may be present in the air in quantities sufficient to produce explosive or ignitable mixtures. This hazardous location enclosure shall be of such substantial construction that it will withstand the internal pressures resulting from explosions without bursting, permanently distorting, or loosening its joints.

Enclosure, Controller NEMA Type 9: An enclosure designed for hazardous locations, Class II, Groups F and G, per the National Electrical Code. The atmosphere in which this controller must operate will contain carbon black, coal or coke dust, flour, starch, or grain dust.

Enclosure, Controller NEMA Type 12: Designed for industrial use. The enclosure is intended for use in applications where it is desirable to exclude such materials as cooling oil, seepage, dust, lint, fibers, and filings. This is normally a non-ventilated enclosure with an oil resistant, synthetic gasket between the case and the cover. The cover is hinged to swing horizontally and is held in place with suitable fasteners which require the use of a tool.

Encoder: An electromechanical transducer that produces a serial or parallel digital indication of mechanical angle or displacement. Essentially, an encoder provides high resolution feedback data related to shaft position and is used with other circuitry to indicate velocity and direction. The encoder produces discrete electrical pulses during each increment of shaft rotation.

End Bells: Also called end shields, cover plates, etc., used to support bearings or to cover the windings. On small motors the end bell is a complete cover, with a few openings for cooling. On large motors, when the bearings are not part of the end shield, a perforated cover may leave the rotor exposed, and only the stator windings are protected.

Endshield: That part of the motor housing which supports the bearing and acts as a protective guard to the electrical and rotating parts inside the motor. This part is frequently called the "end bracket" or "end bell".

Equilibrium Torque: The torque required by a load that will not cause a motor to become unstable. High 20% "buffer" between load and rated allowable load.

Excitation Current: A term usually applied to the current in the shunt field of a motor resulting from voltage applied across the field.

Fan: In totally enclosed, fan cooled motor enclosures (TEFC), the cooling device used to keep the temperature rise below a specified value.

Fan Cover Guard: In totally enclosed, fan cooled motor enclosures (TEFC), the fan cover guard covers the fan assembly to keep out solid objects while allowing air to enter the fan chamber for cooling purposes.

Farad: A unit of measurement for electrical capacitance. A capacitor has a capacitance of one farad when a potential difference of one volt will charge it with one coulomb of electricity.

Fault Current: A current which results from the loss of insulation between conductors or between a conductor and ground.

FDE (From Drive End): A way to view the motor. From drive end refers to looking at the motor from the shaft end.

Feedback: As it generally relates to motors (gear-motors) and controls, feedback refers to the voltage information received by a feedback circuit. Depending on a pre-determined potentiometer setting, a motor control can correct the voltage to deliver appropriate speed and/or torque.

Ferromagnetic: A material with high magnetic permeability (imposes little resistance to orientation in the presence of a magnetic field). Such materials as iron, steel, and nickel are ferromagnetic substances.

Field: A term commonly used to describe the stationary (stator) member of a D.C. motor. The field provides the magnetic field with which the mechanically rotating (armature) member interacts.

Field Control: Method of controlling DC motor speed by varying the field current in the shunt field windings.

Field Economy: A circuit design feature of a DC motor shunt field supply that reduces the supply voltage output after a predetermined period of time. On may field supplies, this means 50% reduction in output voltage 2 to 3 minutes after machine shutdown (idle). A field economy circuit serves to reduce standby power consumption and prolong the insulation life of the motor field windings.

Field Forcing: Temporarily over-exciting a motor shunt field to overcome the L/R time constant, increase the rate of flux change and rapidly reverse the direction of shunt motor field current.

Field Range: The range of motor speed from base speed to the maximum rated speed.

Field Reversing: One method for producing regeneration. It is accomplished by changing the direction of current through the motor field, which reverses the polarity of the motor CEMF to account for generator action.

Field Weakening: The introduction of resistance in series with the shunt wound field of a motor to reduce the voltage and current which weakens the strength of the magnetic filed and thereby increase the motor speed.

Filter: A device that passes a signal or a range of signals and eliminates all others.

Flux: The magnetic field which is established around an energized conductor or permanent magnet. The field is represented by flux lines creating a flux pattern between opposite poles. The density of the flux lines is a measure of the strength of the magnetic field.

FODE (From Opposite Drive End): A way to view the motor. From opposite drive end refers to looking at the motor from opposite the shaft end.

Follower Drive: A drive in which the referenced input and operation are direct functions of another drive, called the master drive.

Four-Quadrant Operation: The four combinations of forward and reverse rotation and forward and reverse torque of which a regenerative drive is capable:

1. Forward rotation/forward torque (motoring)
2. Forward rotation/reverse torque (regeneration)
3. Reverse rotation/reverse torque (motoring)
4. Reverse rotation/forward torque (regeneration)

Force: The tendency to change the motion or position of an object with a push or pull. Force is measured in ounces or pounds.

Form Factor: A figure of merit which indicates how much rectified current departs from pure (non-pulsating) D.C. A large departure from unity form factor (pure D.C.) increases the heating effect of the motor and reduces brush life. Mathematically form factor is the ratio of the root-mean-square (rms) value of the current to the average (av) current of Irms/Iav.

Form Wound Coils: Coils wound in form and shaped ready to insert into the slot of a motor.

Fractional Horsepower Motor: A motor with a continuous rating of less than one horsepower.

Frame: The main motor housing. Can be constructed of aluminum, steel, or cast iron.

Frame Size: Usually refers to the NEMA system of standardized motor mounting dimensions, which facilitates interchangeability. The physical size of a motor, usually consisting of NEMA defined "D" and "F" dimensions at a minimum. The "D" dimension is the distance in quarter inches from the center of the motor shaft to the bottom of the mounting feet. The "F" dimension relates to the distance between the centers of the mounting feet holes.

Frequency: The rate at which alternating current reverses its direction of flow. Measured in hertz (Hz); 1 Hz = 1 cycle per second.

Full-Load Amps (FLA): Line current (amperage) drawn by a motor when operating at rated HP and voltage. Shown on motor nameplate. Important for proper wire size selection, motor starter heater selection, and over current protection.

Full Load Current: The current drawn from the line when the motor is operating at full load torque and full load speed at rated frequency and voltage.

Full Load Speed: The speed that the output shaft of the drive motor attains with rated load connected and with the drive's controller adjusted to deliver rated output at rated speed. This will always be less than the synchronous speed and will vary depending on the rating and characteristics of the particular motor. For example, four pole 60 Hz fractional horsepower motors have a synchronous speed of 1800 RPM, a nominal full load speed (as shown on the nameplate) of 1725 RPM, and an actual full load speed ranging from 1715 to 1745 RPM.

Full Load Torque: The full-load torque of a motor is the torque necessary to produce its rated horsepower at full-load speed in pounds at a 1-foot radius, it is equal to the horsepower times 5252 divided by the full-load speed.

Full Pitch: The full pitch value is obtained by dividing the number of slots by the number of poles.

Full Wave Rectification: Full wave rectification passes the positive half and inverts the negative half cycle of the input sinusoid so that the output contains two half sine pulses for each input cycle.

Gain: The ratio of system output signal to system input signal.

Gate: The control element an SCR (silicon controlled rectifier) commonly referred to as a thyristor. When a small positive voltage is applied to the gate momentarily, the SCR will conduit current (when the anode is positive with respect to the cathode of the SCR). Current conduction will continue even after the gate signal is removed.

Gear Ratio: In gearboxes and gearmotors, the gear ratio is derived by dividing the input speed by the output speed.

Gear Types - Inline Reducer: A gearbox in which the input and output shafts are in a straight line.

Gear Types - Parallel Shaft: A gear box in which the input and output shafts run in parallel to each other.

Gear Types - Planetary: A specialized speed reducer in which the self-aligning gear train floats to evenly distribute all internal loads. This design is used for demanding high shock load applications.

Gear Types - Right Angle: A gear box in which the input and output shafts run at right angles to each other.

Gear Types - Worms: A type of gear box in which the gear teeth mesh with a threaded shaft called the worm when operating.

Gears - Bevel: Gears which are made in a beveled shape.

Gears - Helical: Gears which are made in a helical shape.

Gears - Herringbone: Gears which are made in a herringbone shape.

General Purpose Motors: Motors as defined by NEMA which have certain operating characteristics that make them applicable for operation of many type of driven equipment.

Generator Action of an Induction Motor: An induction (squirrel cage) motor acts as a generator in 2 different ways:

1. Generally the rotor acquires some residual magnetism (especially if DC current is applied to the stator for dynamic braking). In this case the rotor causes generator action in the stator for several seconds. That is, with the line switch quickly opened, a voltage remains across the motor terminals from 1/2 second to several seconds, diminishing with the decrease in motor speed.
2. An induction motor driven above its rated speed delivers leading power factor current back into the line -- it must derive its exciting current from the line. This is a very simple form of generation of power and for certain power systems is an almost ideal method of increasing line capacity.

GTO: Gate turn-off or gate turn-on power semiconductor device.

Guide Bearing: A bearing on vertical motors which acts as the guide in shaft alignment.

Half Wave Rectification: In the rectifying process, half wave rectification passes only one-half of each incoming sinusoid, and does not pass the opposite half cycle. The output contains a single half sine pulse for each input cycle. A single rectifier provides half wave rectification.

Hazardous Location Motor: A totally enclosed motor designed to withstand an internal explosion of specified gases or vapors and not allow the internal flame or explosion to escape. (Previously referred to as Explosionproof)

Hazardous Location Divisions: The first classification of hazardous location motors as developed by the National Electrical Code (NEC). Divisions divide the motor environment into areas where the danger of explosion is always present (division 1) and areas where only under certain conditions is the danger of explosion present (division 2).

Hazardous Location Groups: The third classification of hazardous location motors as developed by the National Electrical Code (NEC). Groups divide the motor classes even further by grouping together similar liquids, vapors, dusts, and flyings.

Hazardous Location Labels: In electric motors the hazardous location label describes whether the motor is good for liquids only, or for liquids, vapors, dusts, and flyings.

Head: A measurement of pressure, usually in feet of water. A 30 foot head is the pressure equivalent to the pressure found at the base of the column of water 30 feet high.

Heater Coil (Thermal Overload Relay): A heater coil is a part of a thermal overload relay that is intended to produce heat when conducting current. Heater coils are sometimes referred to as heaters, thermal units, current elements or heater elements.

Heat Loss: Losses due to resistance take the form of heat which has to be dissipated into the air or surrounding cooling medium. Heat loss is also referred to as I2R loss because the current squared, multiplied by the resistance will yield the heat loss value (in watts).

Heat Loss at Full Load: The total heat loss at full load of a motor usually given in Kilowatts. This value is needed to determine total power requirements when a number of motors are supplied by a power source, or more often when the motor or motors are in an enclosed area, to fine the cooling needed.

Heat Loss From Starting: A necessary figure to answer two questions: (1) If the motor is started often will the accumulated heat damage the winding, and (2) Does additional cooling have to be added to overcome this accumulated heat from starting.

Hertz (Hz): Frequency, in cycles per second, of AC power; usually 60 Hz in the USA and 50 Hz overseas.

High Potential Test: A test which consists of the application of a voltage higher than rated between the winding and the frame or between two or more windings for the purpose of determining the adequacy against breakdown of insulating materials and spacings under normal conditions. It is not a test of the conductor insulation in any one winding.

Horsepower: 33,000 foot pounds of work per minute or 550 foot pounds per second.

Hot Spot Allowance: An insulation system is only as good as its weakest link. Thus it is necessary to locate the hottest part of the machine as this limiting temperature determines the motor life. The difference in degrees of temperature between the readily accessible points and the true "hot-spot" is called the hot spot allowance.

Hunting: Undesirable fluctuations in motor speed that can occur after a step change in speed reference (either acceleration or deceleration) or load.

Hysteresis Loss: The resistance offered by materials to becoming magnetized results in energy being expended and corresponding loss. Hysteresis loss in a magnetic circuit is the energy expended to magnetize and demagnetize the core.

Index of Protection Code: A European definition describing motor enclosures. Common ones are IP55 - totally enclosed fan cooled, and IP23 - weather protected I. See charge in enclosure for the complete listing.

Inductance: The characteristic of coil or wire to cause the current to lag the voltage in time phase. The current reaches its peak after the voltage does.

Induction Motor: An alternating current motor in which the primary winding on one member (usually the stator) is connected to the power source. A secondary winding on the other member (usually the rotor) carries the induced current. There is no physical electrical connection to the secondary winding; its current is induced.

Inertia: A measure of a body's resistance to changes in velocity, whether the body is at rest or moving at a constant speed. The velocity can be either lineal or rotational. The moment of inertia (WK^2) is the product of the weight (W) of an object and the square of the radius of gyration (K^2). The radius of gyration is a measure of how the mass of the object is distributed about the axis of rotation. WK^2 is usually expressed in units of lb. ft.^{2}.

Inertial Load: A load (flywheel, fan, etc.) which tends to cause the motor shaft to continue to rotate after the power has been removed (stored kinetic energy). If this continued rotation cannot be tolerated, some mechanical or electrical braking means must normally be applied.

Inline Thrust Motor: A specialized vertical solid shaft motor which can handle thrust values up to 2000 pounds (depending on the horsepower and speed) and the thrust can be either up or down thrust.

Instability: The state or property of a system where there is an output but no corresponding input.

Insulation (Ins.): In motors, usually classified by maximum allowable operating temperatures as defined by U.L.:

Class A - 105°C (221°F)

Class B - 130°C (266°F)

Class F - 155°C (311°F)

Class H - 180°C (356°F)

Insulator: A material which tends to resist the flow of electric current (paper, glass, etc.).

Integral Horsepower Motor: In terms of HP, a motor built in a frame having a continuous rating of one horsepower or more. An integral horsepower motor is in the 1 to 500 horsepower range.

Interconnection Diagram: An interconnection diagram is a diagram which shows only the external connections between controllers and associated machinery and equipment.

Intermittent Duty: A motor that never reaches equilibrium temperature, but is permitted to cool down between operations. For example, a crane, hoist, or machine tool bar is often rated for 15 or 30 duty.

Interrupting Capacity: The interrupting capacity is the maximum value of current that a contact assembly is required to successfully interrupt at a specified voltage for a limited number of operations under specified conditions.

Inverter: A term commonly used for an AC adjustable frequency drive. An inverter is also a term used to describe a particular section of an AC drive. This section uses the DC voltage from a previous circuit stage (intermediate DC circuit) to produce an AC current or voltage having the desired frequency.

IR Compensation: A way to compensate for the voltage drop across resistance of the AC or DC motor circuit and the resultant reduction in speed. This compensation also provides a way to improve the speed regulation characteristics of the motor, especially at low speeds. Drives that use a tachometer generator for speed feedback do not require an IR compensation circuit because the tachometer will inherently compensate for the loss in speed.

Isolation Transformer: A transformer that electrically separates the drive from the AC power line. An isolation transformer provides the following functions:

1. In DC motor applications, it guards against inadvertent grounding of power plant lines through grounds in the DC motor armature circuit.
2. Enhances protection of semiconductors from line voltage transients.
3. Reduces disturbances from other solid state control equipment such as drives without isolation transformers, time clock systems and electronic counters.

Jogging: A means of accomplishing momentary motor movement by repetitive closure of a circuit using a push-button or contact elements.

Kinetic Energy: The energy of motion possessed by a body.

Leads: The wires exiting out of the motor terminal box used to connect the motor and/or accessories to the power supply.

Line Voltage: Voltage supplied by the power company or voltage supplied as input to the device.

Linear Acceleration/Deceleration (LAD): A Circuit that controls the rate at which the motor is allowed to accelerate to a set speed or decelerate to zero speed. On most drives, this circuit is adjustable and can be set to accommodate a particular application.

Linearity: The measure of the maximum deviation between the actual speed and the set speed, expressed as a percentage of set speed.

Locked-Rotor Current: The steady-state current taken from the line with the rotor locked and with rated voltage (and rated frequency in the case of alternating-current motors) applied to the motor.

Locked-Rotor Torque: (Static Torque) The locked-rotor torque of a motor is the minimum torque which it will develop at rest for all angular positions of the rotor, with rated voltage applied at rated frequency.

Long Shaft Motor: NEMA standard MG-1 defines shaft length as the dimension AH, or the distance from the face, flange or base of the machine to the end of the shaft. In a standard type "T" frame the NEMA standard shaft extension (long shaft) is supplied. It is normally used where overhung loads from pulleys, shieves and sprockets are encountered.

Magnetic Polarity: It is a fundamental principle of winding that adjacent poles must be wound to give opposite magnetic polarity. This does not mean that the coils actually have to be wound in this direction before being placed into the stator. It does mean that the winding must be connected so that, if the current proceeds through one pole in a clockwise direction, it must proceed through the next pole in a counterclockwise direction. This principle is used to determine the correctness of connection diagrams.

Marine Duty Motor: A specialized motor designed for use onboard ships. Motors are designed per IEEE 45 motor specification.

Master Drive: A drive that sets the reference for one or more follower drives.

Mechanical Degree: The popular physical understanding of degrees (360 degrees = 1 revolution).

Megohm Meter: A device used to measure an insulation system's resistance. This is usually measured in megohms and tested by passing a high voltage at low current through the motor windings and measuring the resistance of the various insulation systems.

Modular Construction: The major circuit elements are mounted in replaceable modules which can readily be removed and replaced. Equipment can be serviced without delay.

Module: A unit of circuit elements usually packaged so it can be readily replaced.

Motor Constant: The ratio of motor torque to motors input current (motor torque per amp).

Mounting (Mtg.): – Basic types:

1. Bolted – Motor is attached to frame with removable bolts.
2. Rigid – Motor solidly fastened to equipment through metal base that is welded, bolted, or cast into the metal shell or clamped to the end shield hubs.

3. Cradle/Resilient (Res.) – Motor shell isolated from base by vibration absorbing material, such as rubber rings on the end shields, to reduce transmission of vibration to the driven equipment.
4. Face or Flange – Shaft end has a flat mounting surface, machined to standard dimensions, with holes to allow easy, secure mounting to driven equipment. Commonly used on pumps, oil burners and gear reducers.
5. Stud – Motor has bolts extending from front or rear, by which it is mounted. Often used on small, direct-drive fans and blowers.
6. Yoke – Tabs or ears are welded to motor shell, to allow bolting motor to a fan column or bracket.

Multi Motor Operation: A system in which one controller operates two or more motor simultaneously, maintaining a constant ratio between the speeds of the motors.

Multi Speed Motor: An induction motor that can obtain tow, three, or four discrete (fixed) speeds by the selection of various stator winding configurations.

Mush Wound Coils: Also called random wound coils -- Where the turns are wound without definite placement, or, at random. Most small motors up to 25 HP are mush wound although motors up to 150 HP have been successfully wound without formed coils. The limit is not the horsepower, but did the manufacturer allow enough slot space for the wasteful, random wound coil.

National Electrical Code (NEC): The recommendation of the National Fire Protection Association and is revised every 3 years. The NEC determines the divisions, classes, groups, and temperature codes of hazardous location motors.

National Electrical Manufacturers Association (NEMA): A non-profit organization organized and supported by manufacturers of electrical equipment and supplies. Some of the standards NEMA specifies are horsepower ratings, speeds, frame sizes and dimensions, and torques and enclosures.

NEC: The National Electrical Code is the recommendation of the National Fire Protection Association and is revised every three years. City or state regulations may differ from these code regulations and take precedence over NEC rules.

Negative Feedback: A condition where feedback is subtractive to the input reference signal. Negative feedback forms the basis for automatic control systems.

Negative Torque: A torque developed in opposition to the normal torque of the motor. This may occur at starting (common to 2 pole motors) or at some speed below nameplate RPM. This causes "cusps" or "saddles" in the graphed torque curves.

NEMA Design A Motors: Classification of motors by NEMA used on machines such as fans, blowers, pumps and compressors, requiring relatively low starting torque followed by increasing torque with increasing speed up to the full-load speed and torque. Design A motors are differentiated from design B motors by a higher locked-rotor current.

NEMA Design B Motors: Classification of motors by NEMA used on machines such as fans, blowers, pumps and compressors, requiring relatively low starting torque followed by increasing torque with increasing speed up to the full-load speed and torque. This is the most popular motor design.

NEMA Design C Motors: Classification of motors by NEMA used on machines such as reciprocating air compressors and conveyors, requiring relatively high starting torque that is normally greater than the torque required at full-load speed.

NEMA Design D Motors: Classification of motors by NEMA used on machines that impose pulsating loads or require frequent starting of the motor, such as punch press, oil well pumping, and hoist applications. Design D motors are not offered by as part of the U.S. MOTORS® brand product line.

NFPA: National Fire Protection Association. The group that prepares and published the National Electric Code, Hazardous Chemicals, and numerous other such publications.

No Load: The state of a machine rotating at normal speed under rated conditions, but when no output is required from it.

Non-Reverse Ratchet: A feature on vertical motors for use in deep well applications where water lubricated pump bearings are installed. These ratchets stop the shaft from spinning once the power is discontinued and the pump water column is receding. U.S. MOTORS® brand products use a ball-type non-reverse ratchet which has extended life over pin types as used by other vertical motor manufacturers.

Off Delay: Off delay signifies that the timing period of a time delay relay is initiated upon de-energizing of its coil.

Offset: The steady state deviation of a controlled variable from a fixed setpoint.

Oil Mist Lubrication: A centralized lubricating system in which the energy of compressed gas, usually air taken from the plant supply, is used to atomize oil. Oil is then conveyed by the air in a low pressure distribution system to multiple point of lubricant application.

On Delay: On delay signifies that the timing period of a time delay relay is initiated upon energization of its coil.

Open Circuit: An open circuit in a motor is a defect which causes an interruption in the path through which the electric current normally flows.

Open Loop: A control system that lacks feedback.

Operating Overload: Operating overload is the overcurrent to which an electric apparatus is subjected in the course of the normal operating conditions that it may encounter. For example, those currents in excess of running current which occur for a short time as a motor is started or jogged are considered normal operating overloads for a control apparatus.

Op Amp: An operational amplifier is usually a high gain DC amplifier that is designed to be used with external circuit elements to perform a specified computing operation.

Open Machine (Motors): A machine having ventilating openings which permit passage of external cooling air over and around the windings of the machine.

1. **Drip-proof Machine -** is an open type machine in which the ventilating openings are so constructed that successful operations is not interfered with when drops of liquid or solid particles strike or enter the enclosure at any angle from 0 to 15 degrees downward from vertical.
2. **Splash-proof -** is an open machine in which the ventilating openings are so constructed that successful operation is not interfered with when drops of liquid or solid particles strike or enter the enclosure at any angle not greater than 100 degrees downward from the vertical.
3. **Semiguarded** - is an open machine in which part of the ventilating openings in the machine, normally in the top half, are guarded as in the case of a "guarded machine," while the other parts are left open.
4. **Guarded Machine (NEMA Standard)** - is an open machine in which all openings giving direct access to live metal or rotating parts (except smooth rotating surfaces) are limited in size by the structural parts or by the screens, baffles, grilles, expanded metal or other means to prevent accidental contact with hazardous parts. Openings giving direct access to such live or rotating parts shall not permit the passage of a cylindrical rod 0.75 inch in diameter.
5. **Drip-proof Guarded Machine -** is a drip-proof machine whose ventilating openings are guarded in accordance with the definition of a guarded machine.

6. **Open Externally Ventilated Machine -** is one which is ventilated by means of a separate motor driven blower mounted on the machine enclosure. This machine is sometimes known as a blower-ventilated or a force-ventilated machine.
7. **Open Pipe Ventilated Machine -** is basically an open machine except that openings for admission of ventilating air so arranged that inlet ducts or pipes can be connected to them. Air may be circulated by means integral with the machine or by means external to the machine (separately or forced ventilated).
8. **Weather Protected Machine -** is an open enclosure divided into two types:
    1. Type 1 enclosures have ventilating passages constructed to minimize the entrance of rain, snow, airborne particles and prevent passage of a 0.75 in. diameter cylindrical rod.
    2. Type 2 enclosures provide additional protection through the design of their intake and exhaust ventilating passages. The passages are so arranged that wind and airborne particles blown into the machine can be discharged without entering directly into the electrical parts of the machine. Additional baffling is provided to minimize the possibility of moisture or dirt being carried inside the machine.

Operating Service Deviation: A means of specifying the speed regulating performance of a drive's a controller, generally in percent of base speed. Operating Deviation defines speed change due to load change and typically assumes:

1. A change from one steady state load value to another (not transient).
2. A 95% maximum load change.

Service Deviation defines speed change due to changes in ambient conditions greater than these typical variations:

Condition	**Change**
AC Line Voltage	+10%, -5%
AC Line Frequency	+3%, -3%
Ambient Temperature	15°C.

Output Torque, Gear: A calculation of the input torque multiplied by the gear ratio and the gear efficiency.

Overcurrent Relay: An overcurrent relay operates when the current through the relay, during its operating period, is equal to or greater than its setting.

Overhung Load: A load which tends to impose a radial force (perpendicular to the shaft axis) on a motor or gear-motor output shaft.

Overshoot: The amount that a controlled variable exceeds a desired value after a change of input.

Overspeed: Any speed above the rated (nameplate) speed. Can be caused by a load overhauling (crane and elevator motors), or intentional as on induction generators.

Part Winding Starting: Originally and still defined by NEMA as a motor that has one half its windings energized first, then the other half is paralleled with the first half for full on. Now used as the name for tow thirds start and double delta starting.

Partial Motor: A motor sold with rotor and stator only -- NO end bells -- and no containing frame. Also called a "shell type" motor.

Permeability: Is the measurement of the ease with which a material can be magnetized and how much better than air it is as a path for magnetic fields (permeability of 1).

Phase: Phase is a term, which indicates the space relationships of windings, and changing values of the recurring cycles of A.C. voltages and currents. Due to the positioning (or the phase relationship) of the windings, the various voltages and currents will not be similar in all aspects at any given instant. Each winding will lead or lag another, in position. Each voltage will lead or lag another voltage, in time. Each current will lead or lag another current, in time.

Phase, Single: Available in these types:

1. Shaded Pole – Low starting torque. Usually used in direct-drive fans and blowers.
2. Permanent Split Capacitor (PSC) – Performance and applications similar to shaded pole but more efficient, with lower line current and higher horsepower capabilities.
3. Split-Phase Start, Induction Run (or simply Split-Phase) – Moderate starting torque, high breakdown torque. Used on easystarting equipment such as belt-driven fans and blowers, grinders, centrifugal pumps, gear motors, etc.
4. Split-Phase Start, Capacitor Run – Same performance as induction run, except higher efficiency.
5. Capacitor Start, Induction Run (or Capacitor Start) – High starting and breakdown torque, medium starting current. Used on hard-starting applications: compressors, positive displacement pumps, farm equipment, etc.
6. Capacitor Start, Capacitor Run – Similar to capacitor start, induction run, except have higher efficiency. Generally used in higher HP single-phase ratings.

Phase, Three: Operate on three-phase power only. High starting and breakdown torque, high efficiency, medium starting current, simple, rugged design, long life. For industrial uses.

Phase Control: The process of varying the point within the cycle at which forward conduction is permitted to begin.

Pickup Voltage or Current: The pickup voltage or current of a magnetically operated device is the voltage or current at which the device operates.

Piggyback Mounting: A mounting configuration where the motor is mounted to the top of the gearbox and then the motor shaft is connected to the gearbox input shaft by belts.

Plain Bearing: A term used for a non-ball or roller bearing, i.e., a sleeve bearing.

Plate Bearing: A specialized vertical motor bearing which has practically unlimited life factor if the thrust capacity is properly selected, lubricated, cooled and not overloaded. Vibration, cavitation and heat can severely affect the life of this type bearing. Construction of this bearing calls for a solid plate runner and segmental pivoted shoes with the runner riding on a film of oil between it and the bearing shoes. Operation at higher loads than designed for, or higher temperatures, may break down the film of oil and destroy the bearing.

Plugging: Plugging refers to a type of motor braking provided by reversing either voltage polarity or phase sequence so that the motor develops a counter-torque which exerts a retarding force to brake the motor.

Plug Reversal: Reconnecting a motor’s windings to reverse its direction of rotation while running. Although it is an effective dynamic braking means in many applications, plugging is more severe than other methods and should be used with caution.

Polarities: Terms, (Positive, Negative: North and South) which indicate the direction of current and flux flow in electrical and magnetic circuits at any given instant.

Polarization Index: A term used to indicate the insulation value to ground of a winding. Actually the index determines the moisture content of a winding.

Pole: A definite group of coils connected in series that will show a uniform polarity with DC current applied. This can also be only one coil. This also applies to AC current rotating equipment.

Position Transducer: An electronic device (e.g., encoder or resolver) that measures actual position and converts this measurement into a feedback signal convenient for transmission. This signal may then be used as an input to programmable controller which controls the parameters of the positioning system.

Positive Feedback: Positive Feedback is a condition where the feedback is additive to the input signal.

Potentiometer: A three terminal rheostat, or a resistor with one or more adjustable sliding contacts, that function as an adjustable voltage divider.

Power: Work done per unit of time. Measured in horsepower or watts (1 HP = 33,000 ft. lb./min. = 746 watts).

Power Factor: A measurement of the time phase difference between the voltage and current in an A.C. circuit. It is represented by the cosine of the angle of this phase difference. For an angle of 0 degrees, the power factor is 100% and the volt/amperes of the circuit are equal to the watts.

Power Factor Correction Capacitor: A device used to raise the power factor on motors to avoid penalties from utilities for low power factors. This is because induction electrical equipment takes more power from the electrical supply system than is necessary to produce the work required. A properly sized capacitor will offset most of the lagging current of a motor and raise its power factor to about 95%.

Power Supply: The voltage of the supply line, which can be single phase or three phase.

Preset Speed: Preset speed refers to one or more fixed speeds at which the drive will operate.

Printed Circuit Board: A board for mounting of separately manufactured components which has the connections made by printed circuitry.

Prony Brake: A simple mechanical device, normally a wooden piece with an adjustable leather strap used to test torque output. The prony brake-loads the motor and a spring scale attached to it gives a relatively accurate measurement of torque.

Pull-Out Torque: The pull-out torque of a synchronous motor is the maximum sustained torque which the motor will develop at synchronous speed with rated voltage applied at rated frequency and with normal excitation.

Pull Up Torque: The minimum torque developed during the period of acceleration from locked-rotor to the speed at which breakdown torque occurs. It is usually expressed as a percentage of full-load torque.

Pulse: A pulse is a signal of relatively short duration.

Pulse Width Modulating Inverter (PWM): A type of AC adjustable frequency drive that accomplishes frequency and voltage control at the output section (inverter) of the drive. The drive’s DC bus voltage is always a constant amplitude and by "chopping" (pulse width modulating), the average voltage is controlled.

Push-Button: A push-button is a switch of relatively short duration

PWM: A type of AC adjustable frequency drive that accomplishes frequency and voltage control at the output section (inverter) of the drive. The drive's DC bus voltage is always a constant amplitude and by "chopping" (pulse width modulating), the average voltage is controlled.

QS 9000: Automotive Duty Quality Specification

Radial Magnetic Pull: The magnetic force on the rotor resulting from its radial (air gap) displacement from magnetic center.

Random Wound Coils: Also called mush wound coils -- where the turns are wound without definite placement, or, at random.

Reactance: The opposition to the flow of current made by an induction coil or a capacitor.

Reactance (Inductive): The characteristic of a coil, when connected to alternating current, which causes the current to lag the voltage in time phase. The current wave reaches its peak later than the voltage wave reaches its peak.

Rectification: Designates the process by which electric energy is transferred from an alternating current (AC) to a direct current (DC) circuit.

Rectifier: An electronic circuit which converts alternating current into direct current.

Reed Critical Frequency: Rotational elements generate natural resonance frequencies which is a function of shaft stiffness, mounting, and environment conditions (i.e., vibration from equipment nearby). Vertical motors are affected more by this condition because of mounting at one end with the other end free to move. Under normal operating conditions with the motor operating at rated speed, the resonant frequencies is not a concern. However, inverter applications changes the base speed which affects the motor harmonics and will give an unstable resonance or vibration condition. To correct for potential operation in a critical speed zone, pump manufacturers can make their discharge heads either stiff or loose.

Regeneration: The characteristic of a motor to act as a generator when the CEMF is larger than the drive's applied voltage (DC drives) or when the rotor's synchronous frequency is greater than the applied frequency (AC drives).

Regeneration Braking: The technique of slowing or stopping a drive by regeneration.

Regeneration Control: A regeneration drive contains the inherent capability and/or power semi-conductors to control the flow of power to the motor and from the motor back to the power supply.

Regulation: The ability of a control system to hold speed once it has been set. Regulation is given in percentages of either base speed or set speed. Regulation is rated upon two separate sets of conditions:

1. **Speed Regulation -** is the percentage of speed change with a defined change in load, assuming all other parameters to be constant.
2. **Line Regulation -** is the percentage of speed change with a given line voltage change, assuming all other parameters to be constant.

Relay: An electrically controlled device that causes electrical contacts to change status. Open contacts will close and closed contacts will open when rated voltage is applied to the coil of the relay.

Reluctance: The characteristic of a magnetic material which resists the flow of magnetic lines of force through it.

Remote Control: Remote Control is a control function which provides for initiation or change of a control function from a remote point.

Reset: To reset is to restore a mechanism, storage or device to a prescribed state.

Resistance: The degree of obstacle presented by a material to the flow of electric current is known as resistance and is measured in ohms.

Resilient Mounting: A suspension system or cushioned mounting designed to reduce the transmission of normal motor noise and vibration to the mounting surface.

Resolution: The smallest distinguishable increment into which a quantity can be divided (e.g., position or shaft speed). It is also the degree to which nearly equal values of a quantity can be discriminated. For encoders, it is the number of unique electrically identified positions occurring in 360 degrees of input shaft rotation.

Response Time: The time required, following the initiation of a specified stimulus to a system, for an output going in the direction of necessary corrective action to first reach a specified value.

Reversing: Changing the direction of rotation of the motor armature or rotor. A DC motor is reversed by changing the polarity of the field or the armature, but not both. An AC motor is reversed by reversing the connections of one leg on the three phase power line or by reversing the leads on a single phase power line.

Reverse Torque: A torque created by harmonics in a three phase motor and often resulting in a motor running at a reduced speed. Normally the forces of the revolving field all rotate in the same direction but an improperly designed motor can cause counter rotating harmonic fields that exceed the strength of the forward field at some specific speed. This speed may be zero RPM or some speed below the rated value. This phenomenon is quite common in re-designs of motors to 10 poles or more.

Reversing: Changing the direction of rotation of the motor armature or rotor. A DC motor is reversed by changing the polarity of the field or the armature, but not both. An AC motor is reversed by reversing the connections of one leg on the three phase power line, or by reversing the leads on a single phase power line.

Rotation (Rot.): Direction in which shaft rotates:

1. CW = clockwise
2. CCW = counterclockwise
3. Rev (CW/CCW) = reversible or bi-directional rotation which can be changed.

Rotor: The rotating member of an induction motor with a shaft. Current is normally induced in the rotor which reacts with the magnetic field produced by the stator to produce torque and rotation.

Running Torque: Also called stable torque, or equilibrium torque. A term loosely used meaning available torque at full (rated) speed, as opposed to starting torque.

Saddle Torque: A torque developed, usually well below rated speed, that is much less than normal torque expected at that point. On the torque curve it creates a depression or ‘saddle’ and thus the name. Also called the ‘cusp’ of the curve.

Salient Pole: A motor has salient poles when its stator or field poles are concentrated in to confined arcs and the winding is wrapped around them (as opposed to distributing them in series of slots).

Schematic Diagram (Elementary Diagram): A schematic or elementary diagram is one that shows all circuits devices of a controller. The diagram does not show the physical arrangement of the devices or the actual wiring to the devices.

Screens: 1/4-inch mesh that covers the openings on open enclosure motors to keep rodents and other vermin from entering the motor cavity.

Seals - Double Lip: A rubber shaft seal to keep contaminants such as oil, water and dust from entering the bearing cavity.

Seals - Double Sealed Bearings: Bearings which have seals on both sides to keep the lubricant inside the bearing housing and keep out contaminants.

Seals - Labyrinth: A non-friction seal with a close fit of many turns which protects the bearing cavity from contaminants which can cause bearing failure.

Seals - Taconite: Seals which provide a seal so tight as to filter out iron ore (one of the finest dusts) from entering the bearing cavity.

Secondary Winding: The secondary winding of a motor is a winding which is not connected to the power source, but which carries current induced in it through its magnetic linkage with the primary winding.

Self-Release Coupling: A special feature of vertical hollow shaft motors which permits free spinning of the shaft while the pump water is receding without the pump shaft disengaging from the motor.

Semiconductor: A material, usually silicon or germanium, which permits limited current flow.

Service Deviation: See operating/Service Deviation.

Service Factor (SF): A multiplier which, when applied to the rated horsepower, indicates a permissible horsepower loading at rated voltage and frequency. Motors rated over 1.0 SF have more than normal margin, and are used where unusual conditions such as occasional high or low voltage, momentary overloads, etc., are likely to occur.

Service Factor - Gear: A method of classifying loads and sizing gear reducers based on severity of load. The service factor for gear applications is determined by AGMA and is contingent on the duty of the gear box.

Service Factor - Motor: A multiplier which, when applied to the rated horsepower, indicates a permissible horsepower loading at the rated voltage and frequency. The service factor advises how much extra horsepower the motor is capable of handling. For example, a 10 hp motor with 1.15 service factor can operate to 11.50 horsepower.

Service of a Controller: The service of a controller is the specific application in which the controller is to be used; for example:

1. General purpose.
2. Definite purpose.
    1.Crane and hoist.
    2. Elevator.
    3. Machine tool (Drill).

Set Speed: The desired operating speed.

Severe Duty: A totally enclosed motor with extra protection (for example: shaft slinger, gasketed terminal box…) to resist entry of contaminants. Used in extra dirty, damp or other non-hazardous contaminated environments.

Shaft Runout: Term used to advise how must shaft play there is at the end of the shaft extension in relation to the flange of the motor.

Shock Load: The load seen by a clutch, brake, or motor in a system which transmits high peak loads. This type of load is present in crushers, separators, grinders, conveyors, winches, and cranes.

Short-Circuit: A defect in a winding which causes part of the normal electrical circuit to be bypassed. This frequently results in reducing the resistance of impedance to such an extent as to cause overheating of the winding, and subsequent burnout.

Short Shaft Motor: NEMA standard MG-1 defines shaft length as the dimensions AH, or the distance from the face, flange or base of the machine to the end of the shaft. In a NEMA type TS frame a shorter than standard shaft extension is defined. This is usually used when the motor is direct connected to the load via couplings and no overhung load is encountered.

Silicon Controlled Rectifier (SCR): A solid state switch, sometimes referred to as a thyristor. The SCR has an anode, cathode and control rectification since it can be turned on at will. The SCR can rapidly switch large currents at high voltages. It is small sizes and low in weight.

Six Step Inverter: An old inverter design in which the outgoing produced wave takes the form of six steps, three up and three down.

Skew: Arrangement of laminations on a rotor or armature to provide a slight diagonal pattern of their slots with respect to the shaft axis. This pattern helps to eliminate low speed cogging effects in an armature, minimizes induced vibration in a rotor, and minimizes harmonic stray currents.

Skewing: Refers to time delay or offset between any two signals in relation to each other.

Slaving: A method of connecting controllers in cascade (series) or parallel. A number of slave units can be utilized, each running a drive at a different speed. When the manually operated master controller calls for a speed change, the slave units will respond in proportion, maintaining the speed ratios between them.

Slewing: An incremental motion of the motor shaft or machine table from one position to another at maximum speed without losing position control.

Slinger: A device on the shaft or rubbing on it that prevents entrance of abrasive material into the bearing. Also the washer-like attachment to a shaft or part of the shaft that prevents oil from leaking into the motor or out of the bearing.

Slip: The difference between the speed of the rotating magnetic field (which is always synchronous) and the rotor in a non-synchronous induction motor is known as slip and is expressed as a percentage of a synchronous speed. Slip generally increases with an increase in load.

Slip Compensation: Method of increasing the speed reference to the speed regulator circuit, based on the value of motor torque, to maintain motor speed as the load on the motor changes.

Slip Ring: A conductor band mounted on an armature and insulated from it. A brush slides on the band as the armature rotates. The function of the slip ring system is essentially the same as a commutator and brushes. Slip rings are also used to transmit current from the armature in a generator application.

Slip Speed: The speed difference between speed at any load and the synchronous speed.

Snowmaking Motor: A specialized motor design for use in snowmaking applications.

Space Heater: Motor accessory used to prevent moisture condensation in the motor during periods of rest. When the motor is not operational, the space heater is energized to keep the motor temperature 10 degrees above ambient.

Special Purpose Motor: A motor with special operating characteristics, special mechanical construction, or both, designed for a particular application and not falling within the definition of a general purpose or definite purpose motor as defined by NEMA.

Speed Range: The minimum and maximum speeds at which a motor must operate under constant or variable torque load condition. A 50:1 speed range for a motor with top speed of 1800 RPM means the motor must operate as low as 36 RPM and still maintain regulation within specifications.

Speed Regulation: The numerical measure in percent of how accurately the motor speed can be maintained. It is the percentage of change in speed between no load and full load.

Spherical Roller Bearing: A special bearing design used for extended life or higher thrust when designs merit. This bearing will take some radial load, but only if thrust is applied at all times. Spherical roller bearings, provided on U.S. MOTORS® brand products, employs sprig loading to ensure the bearing will not be damaged during starting and momentary upthrust conditions. These springs push up against the lower the lower race so the lower race is kept in contact. Since the spring pressure may be several thousand pounds, a considerable load is imposed on the guide bearing during start-up. Care must be taken not to specify life factors that would cause bearing failures due to insufficient load during normal operation.

Stability: The ability of a drive to operate a motor at constant speed (under varying load) without "hunting (alternately speeding up and slowing down). It is related to the characteristics of the load being driven and the electrical time constants of the drive's regulator circuits.

Stable Torque: The torque of a motor is stable if the motor torque required for a load never exceeds 75-80% of the maximum motor torque allowed.

Stacked Bearing: A ball or roller bearing that is preloaded, with two bearings in opposition, or just two bearings (thrust) together on one shaft. Used where weight or thrust exceed the capacity of a single bearing or where there is a heavy thrust in both directions parallel to the shaft.

Stalling Torque: The torque at which the load causes the motor to stall (or stop). The maximum torque a motor can deliver while running at rated voltage and frequency. No more than 80% of this value should be used for stable operation.

Starting - Across The Line (Full Voltage): Standard starting method used on motors. In this starting method, the motor terminal voltage equals the line voltage, the motor current equals the line current, and the starting torque equals the rated starting torque. This type starting is used where system capacity and stiffness are sufficient to stand the high starting current without excessive voltage drop.

Starting - Autotransformer Reduced Voltage: In this starting method, an autotransformer is placed in series with the motor during starting. The transformer action reduces the voltage applied to the motor terminals. Because of the transformer action the line current is less than the motor current. For a given starting current on the line side, the motor terminal voltage can be higher than for other reduced voltage start methods. Thus, this method gives the highest motor torque per line ampere.

Starting - Capacitor: In this method, large capacitors are connected with the motor so that the capacitors supply much of the current during the start cycle. Careful sizing and switching of the starting capacitors is required to ensure that the capacitor current is not all placed on the line at once, and that the capacitors are not left connected with the motor after acceleration is accomplished.

Starting - Double Delta: This method accomplishes the equivalent of reduced voltage starting by changing a delta connected winding from parallel groups to series groups during the start. Frequently called "double delta part winding".

Starting - Part Winding Start: This starting method uses only a portion (usually 1/2, but sometimes 2/3) of the motor winding, increasing the impedance seen by the power system. It is to be used only for voltage recovery, and must not be left on the start connection for more than 2-3 seconds. The motor is not expected to accelerate on the start connection, and may not even turn.

Starting - Series Reactance Reduced Voltage: In this method, a voltage-dropping reactance is placed in series with the motor during starting. The impedance seen by the power system then is that of the reactance plus that of the motor.

Starting - Series Resistance Reduced Voltage: This starting method has a voltage-dropping resistance placed in series with the motor during starting. The impedance seen by the power system then is that of the resistance plus that of the motor.

Starting - Solid State Reduced Voltage: In this method, a solid-state starter, consisting of power SCR's controlled by logic circuits, is used to chop the sine-wave power so that only a portion of the wave is applied to the motor.

Starting - Solid State Variable Frequency: In this method, a solid state variable frequency inverter is used to start the motor. With the variable frequency power source, the motor can supply full torque at full load current for the duration of acceleration. The initial applied frequency is very low, and the frequency is gradually increased to the desired running speed.

Starting Torque: The torque exerted by the motor during the starting period (a function of speed or slip).

Starting Variable Speed Drive: In this method, a variable speed drive (VFD) is installed between the motor and the driven load. This drive may be an eddy current clutch or fluid clutch (sometimes called fluid coupling). Use of such a drive allows the motor to accelerate without accelerating the driven load. After the motor is ramped up to speed, then the load is brought up to operating speed.

Starting - Wye Start/Delta Run: This method is actually reduced voltage, but is accomplished by changing the motor phase connections such that a winding that is designed to run with phase voltage equal to line voltage on delta connection is wye connected for starting to put less than line voltage on each phase.

Stator: That part of an induction motor's magnetic structure which does not rotate. It usually contains the primary winding.

Steady Bushing: An option to vertical hollowshaft motors which enable the motor to give impression of operating as a solid shaft motor.

Stiffness: The ability of a device to resist deviation due to load change.

Stopping - Counter Torque Braking for Reverse-Running Loads: A form of reversing used in wound rotor motors. (Wound rotor motors are not part of the U.S. MOTORS® brand product line.)

Stopping - DC Dynamic Braking: A form of braking and stopping the motor which does not cause rotation is reverse is to circulate direct current in the stator windings. This sets up a magnetic field that is stationary and tends to oppose the motion of the squirrel-cage through the field. The speed-torque curve for this situation is like that for normal running, except that the curve starts at synchronous speed and goes toward a peak torque near zero speed.

Stopping - Eddy-Current Braking: An electrical method of slowing a machine or load. Similar in principle to the DC dynamic braking of a squirrel cage motor. Stationary magnetic coils set up a controllable magnetic field throughout which a conducting disc or cylinder can turn. This disc or cylinder is coupled mechanically to the shaft that is to be brakes. When it turns through the magnetic field, eddy currents are generated and these cause a drag on the rotating shaft, just as a torque is set up in a squirrel-cage when currents flow in its short-circuited conductors.

Stopping - Mechanical Braking: Mechanical brakes are either disc type or shoe (or drum) type. Commonly, the shoes are raised from the wheel by an electromagnet and are set by a spring when the magnet is de-engerized.

Stopping - Plugging: A type of motor braking provided by reversing either voltage polarity or phase sequence so that the motor develops a counter-torque which exerts a retarding force to brake the motor.

Submersible Motor: A motor whose housing and terminal box is designed so that the motor can run under water (or another allowable liquid) -- completely submerged at a temperature of water not above 25° C.

Surge: A transient wave of current, voltage, or power in the electric circuit. **Note:** A transient has a high rate of change of current or voltage in the system.

Surge Protection: The process of absorbing and clipping voltage transients on an incoming AC line or control circuit. MOVs (Metal Oxide Varistors) and specially designed RC (Resistor-capacitor) networks are usually used to accomplish this.

Switch: A switch is a device for opening and closing or for changing the connections of a circuit. **Note:** A switch is understood to be manually operated unless otherwise stated.

Synchronous Speed: The speed of an AC induction motor's rotating magnetic field. It is determined by the frequency applied to the stator and the number of magnetic poles present in each phase of the stator windings. Mathematically it is expressed as Speed (RPM) = 120 x Applied Frequency (Hz) / Number of Poles Per Phase.

System Efficiency: The ratio of the mechanical power supplied to load to the total input power under specified operating conditions. The input power includes requirements for auxiliary functions, such as motor field, phase control, switching equipment, overload protection, and fans.

Tachometer: A small generator normally used as a speed sensing device.

Tachometer Generator (Tach): A generator, mechanically coupled to a rotating machine whose function is to generate a voltage, the magnitude or frequency of which is used either to determine the speed of rotation of the common shaft or to supply a signal to a control circuit to provide speed regulation.

Temperature Codes: In hazardous location motors, the temperature code is assigned by the National Electrical Code (NEC) to group together flammable liquids, vapors, dusts, and flyings into groups with similar flashpoints.

Temperature, Ignition: In hazardous location motors, the temperature at which once attained will cause an explosion to occur in the volatile environment.

Temperature Rise: The measurable rise above the ambient temperature at which the fully loaded motor operates. This temperature rise is the result of the heat losses in the stator winding, core, and rotor. On most motors, manufacturers have replaced the Rise rating on the motor nameplate with a listing of the Ambient temperature rating, insulation class and service factor.

Temperature, Ultimate: The highest temperature of any spot to which a specific class of insulating materials can be continuously subjected without marked decrease in the system’s designed life.

Terminal Blocks or Strips: An accessory available to titan frame motors which fits into the conduit box and provides a means to group terminating leads from accessories separately from the main leads.

Test - Complete Initial: A motor test which consists of full load heat run, percent slip, no load current, full load current, locked rotor current, locked rotor torque, breakdown torque (calculated), efficiency and power factor at 100%, 75% and 50% full load, winding resistance, high potential, and bearing inspection. Complete initial tests are per IEEE 112 Method B and performed on a dyno.

Test - Noise: A motor test of the sound levels produced by the motor at certain distances. All sound tests are performed at no load in a free field. Noise tests are per IEEE 85.

Test - Short Commercial: Motor test conforming to NEMA MG1-12.51, consisting of no load current, locked rotor current, winding resistance, high potential, and bearing inspection.

Test - Spray: A test of the motor stator on sealed, form wound stators only. The stator is sprayed with water and then measured for seepage in the winding.

Test - Vibration: A test of the motor when operating to ensure the vibration does not exceed certain levels.

Thermal Overload Relay: A thermal overload relay functions (trips) by means of a thermally responsive system.

Thermal Protector: A protective device for assembly as an integral part of the machine and which, when properly applied, protects the machine against dangerous overheating due to overload and, in a motor, failure to start. Especially important for motors that start automatically, are located remotely, unattended or out-of-sight of operator.

Notes:

1. It may consist of one or more temperature sensing elements integral with the machine and a control device external to the machine;
2. When a thermal protector is designed to perform its function by opening the circuit to the machine and then automatically closing the circuit after the machine cools to a satisfactory operating temperature, it is an automatic reset thermal protector;
3. When a thermal protector is designed to perform its function by opening the circuit to the machine but must be reset manually to close the circuit, it is a manual reset thermal protector.

Basic types:

1. Automatic Reset (Auto) – After motor cools, thermal protector automatically restores power. Should not be used where unexpected restarting would be hazardous.
2. Manual Reset (Man.) – An external button must be pushed to restore power to motor. Preferred where unexpected restarting would be hazardous, as on saws, conveyors, compressors, etc.
3. Impedance (Imp.) or Impedance Protected – Motor is designed so that it will not burn out in less than 15 days under locked rotor (stalled) conditions, in accordance with UL standard No. 519.

Thermal Protector, Winding - Therma-Sentry: A complete thermal protection system for U.S. MOTORS® brand products for windings, protecting the motor from running overloads. It will also protect the motor from abnormally high ambient temperatures, voltage unbalance, high or low voltage, ventilation failure and single phasing. It consists of three thermistors, solid state control for mounting in the customer supplied panel, with 3 amps control circuit capacity.

Thermal Protector, Winding - Thermistors: A non-linear resistance temperature detector made from semi-conductor material. There are two general types, positive temperature coefficient (PTC) which has a resistance that increases with increasing temperature, and negative temperature coefficient (NTC) that has a resistance that decreases with increasing temperature. Standard on U.S. MOTORS® brand products is PTC. Lines should not exceed 50 ohms.

Thermal Protector, Winding - Thermocouples: A pair of two dissimilar materials which generates a minute voltage in proportion to its temperature. Such devices may be used as a signal source in indicating instruments and control equipment.

Thermal Protector, Winding - Thermostats: Snap action, bi-metallic, temperature actuate switches installed in the connection end-turns of the motor winding. Their purpose is to activate a warning device or shutdown the motor upon excessive winding temperatures.

Thermal Protector, Winding - Winding RTD's: Precision, wire-wound resistors with a known temperature-resistance characteristic. Recognized for their accuracy, the RTDs resistance increases with temperature rise in a known and highly repeatable manner. 2 RTDs per phase/6 per motor are standard offerings on U.S. MOTORS® brand products.

Thermistor: A non-linear resistance temperature detector made from semi-conductor material. The thermistor trip point is defined as the point where resistance suddenly rises or falls depending on the type of thermistor. It is usually used with a solid state controller that monitors the thermistor resistance and performs a preprogrammed f unction at the thermistor trip point. Thermistors are available with a multitude of preset non-adjustable trip points. This type of temperature detection device is used in the THERMASENTRY motor protection device.

Thermocouple: A junction of two dissimilar materials which generates a minute voltage in proportion to its temperature. Such devices may be used as a signal source in indicating instruments and control equipment.

Thermostat: A temperature sensing device, with external leads, which must be properly connected to the control circuit of the motor controller to limit the frame or winding temperature of the motor.

Thread Speed: A fixed low speed, usually adjustable, supplied to provide a convenient method for loading and threading machines. May also be called a preset speed.

Thrust: In vertical motors an unusually heavy weight or load in one or both directions.

Thrust Bearing: A specialized bearing design to handle heavy weights or loads in one or both directions.

Thyristor: A three junction semiconductor device that can be switched from the off state to the on state or vice versa.

Time Delay: A time interval that is purposely introduced in the performance of a function.

Torque: A turning force applied to a shaft, tending to cause rotation. Torque is normally measure in pound/feet and is equal to the force applied times the radius through which it acts.

Torque, Breakdown: The maximum torque the motor will develop with rated voltage applied at rated frequency without an abrupt drop in speed. Usually expressed as a percentage of full-load torque.

Torque, Constant: An application which requires the same torque at all operating speeds. Horsepower varies directly with the speed. Examples of constant torque applications include conveyors, hoists, and positive displacement pumps.

Torque Control: Motor torque is regulated instead of motor speed.

Torque, Full-Load: The torque necessary to produce its rated horsepower at full-load speed.

Torque, Locked-Rotor: The torque the motor will develop at rest (for all angular positions of the rotor) with rated voltage and frequency applied.

Torque, Locked Rotor or Starting Torque: The maximum torque produced at initial start.

Torque, Pull-Up: The minimum torque developed during the period of acceleration from locked-rotor to the speed at which breakdown torque occurs. For motors which do not have a definite breakdown torque (NEMA design D), pull-up torque is the minimum torque developed up to the rated full-load speed. Usually expressed as percentage of full-load torque.

Torque, Variable: An application in which the torque required varies as the square of its speed. Horsepower requirements increase as the cube of the speed. Examples include: centrifugal pumps and blowers, turbine pumps, and fans.

Totally Enclosed Machine (Motor): A totally enclosed machine is one so enclosed as to prevent the free exchange of air between the inside and the outside of the case, but not sufficiently enclosed to be termed airtight.

1. **Totally Enclosed Fan-Cooled -** is totally enclosed machine equipped for exterior cooling by means of a fan or fans integral with the machine, but external to the enclosing parts.
2. **Hazardous Location Machine -** is a totally enclosed machine whose enclosure is designed and constructed to withstand an explosion of a specified gas or vapor which may occur within it and to prevent the ignition of the specified gas or vapor surrounding the machine by sparks, flashes or explosions of the specified gas or vapor which may occur within the machine casing.
3. **Dust-Ignition-Proof Machine -** is a totally enclosed machine whose enclosure is designed and constructed in a manner which will exclude ignitable amounts of dust or amounts that might affect performance or rating and will not permit arcs, sparks or heat, otherwise generated or liberated inside of the enclosure, to cause ignition of exterior accumulations or atmospheric suspensions of a specific dust on or in the vicinity of the enclosure.
4. **Waterproof Machine -** is a totally enclosed machine constructed so that it will keep out water sprayed onto it. Leakage may occur around the shaft but will be prevented from entering the oil reservoir. Provision is made for automatically draining the machine. The means for automatically draining may be a check valve or a tapped hole at the lowest part of the frame which will serve for application of a drain pipe.
5. **Totally Enclosed Water Cooled Machine -** is a totally enclosed machine which is cooled by circulating water, the water or water conductors coming in direct contact with the machine parts.
6. **Totally Enclosed Water-Air Cooled Machine -** is totally enclosed machine which is cooled by circulating air which, in turn, is cooled by circulating water. It is provided with a water cooled heat exchange for cooling the internal air and a fan or fans, integral with the rotor shaft or separate, for circulating the internal air.
7. **Totally Enclosed Air to Air Cooled Machine -** is a totally enclosed machine which is cooled by circulating the internal air through a heat exchanger which, in turn, is cooled by circulating external air. It is provided with an air to air heat exchanger for cooling the internal air, a fan or fans, integral with the rotor shaft or separate, for circulating the internal air and a separate fan for circulating the external air.
8. **Totally Enclosed Fan Cooled Guarded Machine -** is a totally enclosed fan cooled machine in which all openings giving direct access to the fan are limited in size by the design of the structural parts or by screens, grilles, expanded metal, etc. to prevent accidental contact with a cylindrical rod 0.75 inch in diameter, and a probe shall not contact the blades, spokes or other irregular surfaces of the fan.
9. **Totally Enclosed Air-Over Machine -** is a totally enclosed machine intended for exterior cooling by a ventilating means external to the machine.

Transducer: A device that converts one energy form to another (e.g., mechanical to electrical). Also, a device that when actuated by signals from one or more systems or media, can supply related signals to one or more other systems or media.

Transient: A momentary deviation in an electrical or mechanical system.

Translator: A solid state, three terminal device that allows amplification of signals and can be used for switching and control. The three terminals are called the emitter, base and collector.

Trigger Circuit: The circuit used to gate a thyristor that causes it to conduct current.

Turn: A complete encirclement of the slots into which the coil is placed.

UL Component Recognition: A classification by Underwriter's Laboratories which recognizes the components of a given product meet UL standards, although the actual finished product may not be UL listed.

UL Listed Product: A classification by Underwriter's Laboratories for equipment which met certain evaluations of concern as determined by UL.

Undervoltage Protection: Undervoltage or low voltage protection is the effect of a device, operative on the reduction or failure of voltage, to cause and maintain the interruption of power to the main circuit. The main objective of the device is to prevent restarting of the equipment on an undervoltage condition.

Variable Resistor: A resistor connected in series with a motor which can be adjusted to vary the amount of current available and thereby alter motor speed.

Variable Torque: A multi-speed motor wound so that the horsepower varies as the square of the speed.

Vector: A quantity that has magnitude and direction. This quantity is commonly represented by a directed line segment whose length represents the magnitude and whose orientation in space represents the direction.

Ventilated Enclosure: A ventilated enclosure is provided with means to permit circulation of sufficient air to remove an excess of heat, fumes or vapors.

Viscosity: The friction in liquid particles that prevents the liquid from flowing freely. The viscosity value is a number for a specific temperature, in comparison with a known liquid.

Voltage: The force that causes a current to flow in an electrical circuit. Analogous to pressure in hydraulics, voltage is often referred to as electrical pressure.

Voltage Relay: A voltage relay operates at a predetermined value of voltage. It may be an overvoltage relay, an undervoltage relay or a combination of both.

Volts per Hertz (V/Hz): The basic measurement of proper AC motor excitation level for adjustable frequency AC drive operation.

VVI (Variable Voltage Inverter): A type of AC adjustable frequency drive that controls the voltage and frequency to the motor to produce variable speed operation. A VV. type drive controls the voltage in a section other than the output section where frequency generation takes place. The frequency control is accomplished by an output bridge circuit which switches the variable voltage to the motor at the desired frequency.

Watt: Unit of electrical power. Watt = El x PF

Wiring (or Connection) Diagram: A wiring, or connection, diagram is one which locates and identifies electrical devices, terminals and interconnecting wiring in an assembly.

Work: A force moving an object over a distance. Measured in foot pounds (ft. lbs.). Work = Force X Distance.

Wound Rotor Motor: A slip ring induction motor with the rotor wound into definite poles. (Not offered in the U.S. MOTORS® brand product line).

Zero Speed Switch: A motion sensing switch that is used to prevent the motor from being plugged while the motor shaft is in motion.

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Review questions

UNIT I

SYNCHRONOUSGENERATOR

1. **What do you mean by the salient-pole type rotor?**

Salient - pole type rotor means a low and moderate speed rotor having large diameter and small axial length with projected poles coming out of the rotor frame the outer surface of which almost follows the inner cylindrical surface of the stator frame.

2. **Define voltage regulation of an alternator**

The voltage regulation of an alternator is defined as the increase in terminal voltage when full load is thrown off, assuming field current and speed remaining the same. Percentage regulation = (E_0 – V) /V x 100

E_0 = No load terminal voltage

V = Full load rated terminal voltage.

3. **What are the advantages of having rotating field system?**

1. Better insulation 2. Ease of current collection
3. Increased armature tooth strength. 4. More rigid construction
5. Reduced armature leakage reactance. 6. Lesser number of sliprings.
7. Lesser rotor weight &intertia 8. Improved ventilation & heat dissipation.

4. **Why is EMF method called Pessimistic method?**

The value of voltage regulation obtained by EMF method is always more than the actual value, therefore it is called Pessimistic method.

5. **Why is MMF method called Optimistic method?**

Compared to the EMF method, MMF method, involves more number of complex calculation steps. Further the OCC is referred twice and SCC is referred once while predetermining the voltage regulation for each load condition. Reference of OCC takes care of saturation effect. As this method require more effort, the final result is very close to the actual value. Hence this method is called optimistic method. .

6. **Compare salient pole rotor & smooth cylindrical rotor.**

Salient Pole Rotor	Cylindrical Rotor
1 Large diameter and short axial	1 . Small diameter and long axial length, length
2. Used for low speed alternators	2. Used for high - speed turboalternators
3.Has projecting poles	3. No projecting poles
4. Needs damper windings	4. Does not need damper windings.
5.Windage loss is more	5. Windage loss is less

7.How is the armature winding in alternators different from those used in dc machines?

The armature winding of the alternator is placed in the stator, but the in case of dc machines, armature winding is placed in rotor.

8. **What are the methods by using zero p.f. lagging curve can be obtained?**

Zero power factor characteristic of an alternator gives the variation of terminal voltage with field current, when the alternator is delivering its full rated current to a zero power factor (lagging) load. This characteristic is obtained by running the machine at synchronous speed and connecting a purely inductive

3phase load to its terminals. The load is varied in steps and at each step the field current is adjusted, so that the armature current is equal to its rated value.

9. What are squirrel-cage windings of alternators? How and why are they used?

Damper windings are squirrel cage windings of the alternators.
This winding is placed in rotor pole shoes

10. Write down the equation for frequency of emf induced in an Altenator.

Frequency of emf induced in an Alternator,f ,expressed in cycles per second or Hz, is given by the following equation

F = (PN)/120 Hz,

Where P- Number of poles
N-Speed in rpm

11. What are the advantages of salient pole type construction used forSynchronous machines? Advantages of salient-pole type construction are :

They allow better ventilation •

The pole faces are so shaped that the radial air gap length increases from the pole center to the pole tips so that the flux distribution in the air-gap is sinusoidal in shape which will help the machine to generate sinusoidal emf

Due to the variable reluctance the machine develops additional reluctance power which is independent of excitation

12. Name the types of Alternator based on their rotor construction.

Alternators can be classified into the following two types according to its rotor construction Smooth cylindrical type alternator •
Salient pole alternator

13.Why is short pitch winding preferred over full-pitch winding ?

Advantages

- Waveform of the emf can be approximately made to a sine wave and distorting harmonics can be reduced or totally eliminated.
- Conductor material , copper , is saved in the back and front end connections due to less coil-span.
- Fractional slot winding with fractional number of lots/phase can be used which in turn reduces the tooth ripples.
- Mechanical strength of the coil is increased.

14. Define winding factor.

The winding factor K_d is defined as the ratio of phasor addition of emf induced in all the coils belonging to each phase winding to their arithmetic addition.

15. Why are Alternators rated in kVA and not in kW?

The continuous power rating of any machine is generally defined as the power the machine or apparatus can deliver for a continuous period so that the losses incurred in the machine gives rise to a steady temperature rise not exceeding the limit prescribed by the insulation class

Apart from the constant loss incurred in Alternators is the copper loss, occurring in the 3 -phase winding which depends on I^2 R, the square of the current delivered by the generator.

As the current is directly related to apparent - power delivered by the generator , the Alternators have only their apparent power in VA/kVA/MVA as their power rating.

16.What is the necessity for predetermination of voltage regulation?

Most of the Alternators are manufactured with large power rating ,hundreds of kW or MW, and also with large voltage rating upto 33kV. For Alternators of such power and voltage ratings conducting load test is not possible. Hence other indirect methods of testing are used and the performance like voltage regulation then can be predetermined at any desired load currents and power factors.

17. Name the various methods for predetermining the voltage regulation of 3-phase Alternator.

The following are the three methods which are used to predetermine the voltage regulation of smooth cylindrical type Alternators

Synchronous impedance / EMF method
Ampere-turn / MMF method
Potier / ZPF method

18. What are the advantages and disadvantages of estimating the voltage regulation of an Alternator by EMF method?

Advantages:
Simple no load tests (for obtaining OCC and SCC) are to be conducted
Calculation procedure is much
simpler Disadvantages:
The value of voltage regulation obtained by this method is always higher than the actual value

19. What are the test data required for predetermining the voltage regulation of an Alternator by MMF method?

Data required for MMF method are :
Effective resistance per phase of the 3-phase winding R
Open circuit characteristic (OCC) at rated speed/frequency
Short circuit characteristic (SCC) at rated speed/frequency

22. State the condition to be satisfied before connecting two alternators in parallel.

The following are the three conditions to be satisfied by synchronizing the additional Alternator with the existing one or the common bus-bars.

The terminal voltage magnitude of the incoming Alternator must be made equal to the existing Alternator or the bus-bar voltage magnitude.
The phase sequence of the incoming Alternator voltage must be similar to the bus-bar voltage.
The frequency of the incoming Alternator voltage must be the same as the bus-bar voltage.

23.List the factors that affect the load sharing in parallel operating generators?

The total active and reactive power delivered to the load, connected across the common bus-bars, are shared among Synchronous generators, operating in parallel, based on the following three factors

Prime-mover characteristic/input
Excitation level and
Percentage synchronous impedance and its R/X ratio

24.WhyalmostalllargesizeSynchronousmachinesareconstructedwithrotatingfieldsystemtype?

The following are the principaladvantages of the rotating field system typeconstructionof Synchronousmachines:

Therelativelysmallamountofpower,about2%,requiredforfieldsystemviaslip-rings and brushes.

Forthesameairgapdimensions,whichisnormallydecidedbythekVArating, morespaceisavailableinthestatorpartofthe machinefor providing more insulationtothesystemofconductors,especiallyformachinesratedfor11kVor above.

Insulationtostationarysystemofconductorsisnotsubjectedtomechanicalstresses due to centrifugal action.

Stationarysystemof conductors caneasily be braced to preventdeformation.

It is easytoprovide coolingarrangementfor a stationarysystemof conductors.

Firm stationaryconnectionbetweenexternalcircuitandsystemofconductors enable he machine to handle large amount of volt-ampere as high as500MVA.

25.Why do cylindrical Alternatorsoperatewith steam turbines?

Steamturbinesarefoundtooperateatfairlygoodefficiencyonlyathighspeeds.Thehighspeedoperationofrotorstendstoincreasemechanicallossesandsotherotors shouldhaveasmoothexternalsurface.Hence,smoothcylindricaltyperotorswithlessdiameterandlargeaxiallengthareusedforSynchronousgeneratorsdrivenbysteamturbines with either 2 or4 poles.

26.Whichtype of Synchronous generators are used in Hydro-electricplants and why?

AsthespeedofoperationislowforhydroturbinesusedinHydro-electricplants,salientpoletypeSynchronousgeneratorsareused.Theseallowbetterventilationandalsohave other advantages oversmoothcylindricaltype rotor.

27.Howdoes electricaldegree differ from mechanicaldegree?

Mechanicaldegreeistheunitforaccountingtheanglebetweentwopointsbasedontheirmechanicalorphysicalplacement.Electricaldegreeisusedtoaccounttheanglebetweentwo pointsinrotatingelectricalmachines.Sinceallelectricalmachinesoperatewiththehelpofmagneticfields,theelectricaldegreeisaccountedwithreferencetothemagneticfield.180electricaldegreeisaccountedastheanglebetweenadjacentNorthandSouth poles.

28.What is distributedwinding?

Whencoilsidesbelongingtoeachphasearehousedordistributedinmorethanoneslotundereachpoleregionthenthewindingiscalleddistributedwinding.Afullpitchcoilhaswidthofcoilotherwisecalledcoil-spanas180º-anglebetweenadjacentslotsinelectrical degree and x=1,2,3…

29.Definewinding factor.

ThewindingfactorKdisdefinedastheratioofphasoradditionofemfinducedinallthe coilsbelonging toeach phasewinding to theirarithmeticaddition.

30.What are the causes of changesin voltagein Alternatorswhen loaded?

VariationsinterminalvoltageinAlternatorsonloadconditionareduetothefollowing threecauses:

□ Voltage variation dueto theresistance of the winding, R
□ Voltage variation dueto theleakage reactanceofthe winding,Xt

31.What ismeant by armature reaction in Alternators?

Theinteractionbetweenfluxsetupbythecurrentcarryingarmatureandthemainis defined asthe armature reaction.

32.What do you mean by synchronous reactance?

SynchronousreactanceXs=(Xl+Xa)ThevalueofleakagereactanceXl isconstantforamachinebasedonitsconstruction.Xadependsonsaturatingconditionofthemachine.ItistheadditionofXa,whichrepresentthearmaturereactioneffectbetweentwosynchronouslyactingmagneticfieldsthatmakesthetotalreactanceXatobecalledsynchronous reactance.

33.What ismeant by synchronous impedance of an Alternator?

Thecomplexadditionofresistance,Randsynchronousreactance,jXscanberepresented together bya single complex impedanceZs called synchronous impedance. In complex formZs = (R +
jXs)In polar formZs = |Zs|
<Where |Zs|= ¥_52 + X2 s
)

34.What ismeant by load angle ofan Alternator?

The phaseangleintroducedbetweentheinducedemfphasor, E andterminalvoltagephasor , U during theload conditionofan Alternator is called load angle.

35.Why is the statorcore of Alternator laminated?

The stator core of Alternator is laminated to reduce eddy currentloss.

36.State the condition tobe satisfiedbefore connectingtwoalternators in parallel

ThefollowingarethethreeconditionstobesatisfiedbysynchronizingtheadditionalAlternator withtheexisting one or thecommon bus-bars.

□ Theterminalvoltage magnitudeof theincomingAlternatormustbemadeequalto the existingAlternatoror the bus-bar voltage magnitude.
□ Thephase sequenceoftheincomingAlternator voltage mustbesimilarto thebus-bar voltage.
□ ThefrequencyoftheincomingAlternatorvoltagemustbethesameasthebus-bar voltage.

37.How do the synchronizinglamps indicate the correctnessof phasesequencebetween existing and incoming Alternators?

Thecorrectnessofthephasesequencecanbecheckedbylookingatthethreesetsoflampsconnectedacrossthe3-poleofthesynchronizingswitch.Ifthelampsgrowbrightanddarkinunisonitisanindicationof thecorrectnessofthephasesequence.Ifontheotherhand,theybecomebrightanddarkoneafter theother,connectionstoanytwomachineterminals have to be interchanged after shutting down the machine.

38.Whataretheadvantagesanddisadvantagesofthreedarklampsmethodofsynchronizin g?

Advantages:

□ Thesynchronous switch using lamps is inexpensive
□ Checkingforcorrectnessofthephasesequencecanbeobtainedina simplemannerwhichisessentialespeciallywhentheAlternatorisconnectedforthefirsttime or for fresh operation after disconnection .

Disadvantages:

- □ Therate offlickeringof the lampsonly indicatesthe frequency differencebetweenthebus-barandtheincomingAlternator.Thefrequencyoftheincoming Alternator in relation tothe bus-bar frequencyis not available.

39.Howsynchronoscope is used for synchronizingAlternators?

SynchronoscopecanbeusedforpermanentlyconnectedAlternatorswherethecorrectnessof phasesequenceis already checked by othermeans.Synchronoscope iscapableofrotatinginbothdirections.Therateofrotationofthepointerindicatestheamountoffrequencydifferencebetweenthe Alternators.ThedirectionofrotationindicateswhetherincomingAlternatorfrequencyishigherorlowerthantheexistingAlternator.TheTPSTswitchisclosedtosynchronizetheincomingAlternatorwhenthepointerfacesthetop thicklinemarking.

40.Whysynchronousgeneratorsaretobeconstructedwithmoresynchronousreactance andnegligibleresistance?

The presence of moreresistance in theSynchronousgeneratorswillresist oroppose theirsynchronousoperation.Morereactanceinthegeneratorscancausegoodreactionbetweenthetwoandhelpthegeneratorstoremaininsynchronisminspiteofanydisturbanceoccurring inany one of the generators.

41.List the factors that affect the load sharing in parallel operating generators?

Thetotalactiveandreactivepowerdeliveredtotheload,connectedacrossthecommonbus-bars,aresharedamongSynchronousgenerators,operatinginparallel,basedonthefollowing three factors

- □ Prime-mover characteristic/input
- □ Excitation leveland
- □ Percentagesynchronous impedance and its R/X ratio

42. Howdoes the change in prime mover input affect the load sharing?

An increase in prime-mover input to a particular generator causes the active power shared by it to increase and a corresponding decrease inactive- power shared by other generators.The change in reactivepower sharing is less appreciable.The frequency of the bus-bar voltage will also subjected to slight increase in value.

43. How does change in excitation affects theload sharing?

Thedecreaseinexcitationinonegeneratorcausesthereactivepowersharedbyittodecreaseandacorrespondingincreaseinreactive-powersharedbyothergenerators.Thechangeinactive-powersharingislessappreciable.Therewillbeaslightdecreaseinterminal voltage magnitude also.

44.WhatstepsaretobetakenbeforedisconnectingoneAlternatorfromparalleloperation?

Thefollowingstepsaretobetakenbeforedisconnectingone Alternatorfromparalleloperation

Theprime-mover input of the outgoing generator has to be decreased and that of other generators has to be increased and by this the entire active-power delivered by the outgoing generator is transferred to other generators.

- □ Theexcitation of the outgoing generator has to be decreased and that of othergeneratorshavetobeincreasedandbythistheentirereactive-powerdeliveredby the outgoing generator is transferred to other generators.
- □ Afterensuring the current delivered by the outgoing generator is zero,it has to be disconnected from parallel operation.

45.What is meant by infinite bus-bars?

The source or supply lines with non-variable voltage and frequency are called infinite bus-bars. The source lines are said to have zero source impedance and infinite rotational inertia.

46.HowdoesincreaseinexcitationoftheAlternatorconnectedtoinfinitebus-bars affect this operation?

Increase in excitation level of the synchronous generator will effectively increase the reactive component of the current supplied by the generator and hence the activepower delivered.

47.Uponwhat factors does the load angle depend?

Angle is positive during generator operation and negative during motor operation.

48.AnAlternatorisfoundtohaveitsterminalvoltageonloadconditionmorethan that on no load. What is the nature of the load connected?

The nature of the load is of leading power factor ,load consisting of resistance and capacitive reactance.

UNIT II SYNCHRONOUSMOTOR

1. What does hunting of synchronous motor mean?

When the load applied to the synchronous motor is suddenly increased or decreased, the rotor oscillates about its synchronous position with respect to the stator field. This action is called hunting.

2. What could be the reasons if a 3-phase synchronous motor fails to start?

It is usually due to the following reasons

a. Voltage may be too low. ,b. Too much starting load.

c. Open circuit in one phase or short circuit. d. Field excitation may be excessive

3. What is synchronous condenser?

An over-excited synchronous motor under no load ,used for the improvement of power factor is called as synchronous condenser because, like a capacitor it takes a leading current.

4. Write the applications of synchronous motor.

a. Used for power factor improvement in sub-stations and in industries.

b. Used in industries for power applications.

c. Used for constant speed drives such as motor-generator set, pumps and compressors.

5. What is an inverted 'V' curve?

For a constant load, if the power factor is plotted against various values of field exciting current, the curve formed is inverted V Shape and called as inverted 'V' curve. Also draw draws the graph.

6. A synchronous motor starts as usual but fails to develop its full torque. What could it be due to?

a. Exciter voltage may be too low.

b. Field spool may be reversed.

c. There may be either open-circuit or short-circuit in the field.

7. What are the two types of 3-phase induction motor?

a. Squirrel cage induction motor. b. Slip ring induction motor.

8. Write the two extra features of slip ring induction motors.

a. Rotor is having 3-phase winding.

b. Extra resistance can be added in the rotor circuit by connecting through the help of three slip rings for improving the power factor, increasing Starting Torque, limiting the starting current.

9. Can we add extra resistance in series with squirrel cage rotor? State the reason?

We cannot add extra resistance in series with the rotor because all the copper bars of the rotor are short circuited in both the sides by copper end rings to have a closed circuit.

10. Why an induction motor is called rotating transformer?

The rotor receives electrical power in exactly the same way as the secondary of a two winding transformer receiving its power from primary. That is why an induction motor can be called as a rotating transformer

i.e., in which primary winding is stationary but the secondary is free to rotate.

11. Why an induction motor will never run at its synchronous speed?

If it runs at synchronous speed then there would be no related speed between the two, hence no rotor emf, no rotor current so no rotor torques to maintain rotation. That is why the rotor runs at its synchronous speed.

12. Define SCR?

Short circuit ratio (SCR) is defined as the ratio of field current required to produce rated voltage on open-circuit to field current required to produce rated armature current with the terminals shorted, while the machine runs at synchronous speed.

13**. When does a synchronous motor get over excited?**

If the field excitation of the motor is increased, the field flux will become strong and Eb will increase. As a result Eb will exceed V and the motor will be called an over excited motor.

14. Define pullout torque?

The pullout torque is the torque, beyond which the synchronous link between field poles and resultant flux wave is severed and the machine falls out-of-slip.

15.State thecharacteristic featuresof synchronous motor.

a. the motor is not inherentlyselfstarting
b. The speed of operation is alwaysin synchronouswith the supplyfrequency irrespective ofload conditions
c. The motor is capable ofoperatingat any power factor.

16.In what way synchronous motor is different from other motors?

Alldcandacmotorsworkonthesameprinciple.Synchronousmotoroperatesdueto magnetic locking taking place betweenstator and rotor magnetic fields.

17.Name any two methods of starting a synchronous motors

- ☐ By an extra 3 phase cage inductionmotor
- ☐ Byprovidingdamperwinding in pole phases
- ☐ Byoperating the pilot excitor as a dc motor

18.Whatistheeffectonspeediftheloadisincreasedona3phasesynchronousmotor?

Thespeedofoperationremainsconstantfromnoloadtomaximumloadinthemotor operating at constant frequency bus bars.

19.Why a synchronous motor is a constant speed motor?

Synchronousmotorworkontheprincipleofforcedevelopedduetothemagneticattractionestablishedbetweentherotatingmagneticfieldandthemainpolefeed.Sincethespeedofrotatingmagneticfieldisdirectlyproportionaltofrequencythemotoroperatesatconstant speed.

20.Whatisthephasorrelationbetweeninducedemfandterminalvoltageofa3phase Synchronous motor?

Therotatingmagneticfieldisinitiallyestablishedbytheprimesourceofsupply V.T he main field then causes an emf eto get induced in the 3phase winding.Hence when the machine operates as asynchronous motor the emf phasor always lags the terminal voltage phasor by the load/torque

21.What are V andinverted V curves of synchronous motor?

ThevariationofmagnitudeoflinecurrentwithrespecttothefieldcurrentiscalledVcurve.ThevariationofpowerfactorwithrespecttothefieldcurrentiscalledinvertedVcurve.

22.Whathappenswhenthefieldcurrentofasynchronousmotorisincreasedbeyondt he normalvalue at constantinput?

Increaseinemfcausesthemotortohavereactivecurrentintheleadingdirection.Theadditionalleadingreactivecurrentcausesthemagnitudeoflinecurrent,accompaniedby the decrease in power factor.

23.Distinguishbetween synchronous phase modifier and synchronous condenser.

Asynchronousmotorusedtochangethepowerfactororpowerfactorinthesupplylinesiscalledsynchronousphasemodifier.Asynchronousmotoroperatedatnoloadwithoverexcitationconditiontodrawlargeleadingreactivecurrentandpoweriscalledasynchronouscondenser.

24.Howthe synchronous motor can be used as s synchronous condenser?

Synchronousmotorisoperatedonoverexcitationsoastodrawleadingreactivecurrentandpowerfromthesupplylines.Thiscompensatesthelaggingcurrentandpowerrequire mentoftheloadmakingthesystempowerfactortobecomeunity.Themotordoesthe job of capacitors and hence called as synchronous condenser.

UNIT III

THREEPHASEINDUCTION MOTOR

1. What are types of 3- phase induction motor?

i. Squirrel cage induction motor ii. Slip ring induction motor

2. Why the rotor slots of a 3-phase induction motor are skewed?

The rotor slots of a three -phase induction motor are skewed

i. to make the motor run quietly by reducing the magnetic hum ii. to reduce the locking tendency of the rotor

3. Why the induction motor is called asynchronous motor?

Since the induction motor runs always at a speed lesser than synchronous speed, it is called asynchronous motor.

4. What are slip rings?

The slip rings are made of copper alloys and are fixed around the shaft insulating it. Through these slip rings and brushes the rotor winding can be connected to external circuits.

5. State the difference between slip ring rotor and cage rotor of an induction motor?

Slip ring rotor has 3-phase windings. Three ends of which are stared and the other three ends are brought up and connected to 3 slip rings mounted in the shaft. Extra

resistance can be added in the rotor circuit. Squirrel cage rotor has short-circuited copper bars.

Extra resistance can’t be added as slip ring rotor.

6. Write an expression for the slip of an induction motor.

Percentage slip = (Ns -Nr) / Ns * 100.

7. What is cogging of an induction motor?

When the number of stator and rotor teeth’s is equal or integral multiple of rotor teeth

,they have a tendency to align themselves exactly to minimum reluctance position. Thus the rotor may refuse to accelerate. This phenomenon is known as cogging.

8. Explain why the no load current of an induction motor is much higher than that of an equivalent transformer.

In induction motor, due to the presence of the air gap, the magnetizing current that is required to set up the flux is much higher. The working component of the current has to meet the hysteresis

loss, eddy current loss, friction and windage losses. Hence the no load current of induction motor is higher.

9. State the effect of rotor resistance on starting torque

Starting torque increases with increase in value of rotor resistance.

10. What are the advantages of cage motor?

Ø Since the rotor has very low resistance, the copper loss is low and efficiency is high

Ø On the account of simple construction of rotor, it is mechanically robust.

Ø Initial cost is less.

Ø Maintenance cost is less.

Ø Simple stating arrangement

11. Give the conditions for maximum torque for 3-phase induction motor?

The rotor resistance and rotor reactance should be equal for developing maximum torque i.e. R2 = s X2 where s is the slip –under running conditions.

R2 = X2 under starting conditions

12. What is reason for inserting additional resistance in rotor circuit of a slip ring induction motor?

Introduction of additional resistance in the rotor circuit will increase the starting torque as well as running torque. Also it limits the starting current, improves the power factor.

13. List out the methods of speed control of cage type 3-phase induction motor?

a) By changing supply frequency

b) By changing the number of poles

c) By operating two motors in cascade

14. Mention different types of speed control of slip ring induction motor?

a) By changing supply frequency

b) By changing the number of stator poles c) By rotor rheostat control

d) By operating two motors in cascade

15. What are the advantages of 3-phase induction motor?

a) It was very simple and extremely rugged, almost unbreakable construction b) Its cost is very low and it is very reliable

c) It has been suffiently high efficiency .No brushes are needed and hence

frictional losses are reduced

d) It requires minimum of maintenance.

16. What does crawling of induction motor mean?

Squirrel cage type, sometimes exhibit a tendency to run stably at speeds as low as

1/7 the of their synchronous speed, because of the harmonics this phenomenon is known as crawling

17. State the application of an induction generator?

a) Used in windmill for generating electric power.

b) Used in regenerative breaking places like traction.

18. Name the two windings of a single-phase induction motor.

I. Running winding ii. Starting winding.

19. What are the various methods available for making a single-phase motor self-starting?

I. By splitting the single phase into 2 phases ii. By providing shading coil in the poles.

20. What is the function of capacitor in a single-phase induction motor?

I. To make more phase difference between the starting and running winding. ii. To improve the power factor and to get more torque.

21. Give the names of three different types of single-phase motor.

I. Split phase motor

ii. Shaded pole motor.

iii. Single phase series motor. iv. Repulsion motor.

22. What is the use of shading ring in a pole motor?

The shading coil causes the flux in the shaded portion to lag behind the flux in unshaded portion of pole. This gives in effect a rotation of flux across the pole face and under the influence of this moving flux a stating torque is developed.

23. State any four use of single-phase induction motor.

Fans, Wet grinders, Vacuum cleaners, small pumps, compressors, drills

24. Why is the efficiency of a 3-phase induction motor less than of a transformer?

In induction motor, there is a mechanical loss due to the rotation of the rotor. Hence the efficiency of an induction motor is less than that of the transformer.

25. What are the types of starters?

Stator rheostat, Autotransformer and Star to Delta switch

Rotor resistance starter.

26.Namethetestlater to beconductedforpredeterminingtheperformanceof3-phaseinductionmachine.

(a) No load test
(b) Blockedrotor test

27.What are the informationsobtained fromno-load testin a 3-phase I M?

(i) No –loadinput current per phase,Io
(ii) Noloadpowerfactorand hence no load phase angle
(iii) Iron and mechanical losses together
(iv) elements of equivalent circuit shunt branch

28.What are the informationsobtained fromblocked rotor testin a3-phase I M?

(i) Blocked rotor input current perphase at normal voltage
(ii) Blocked rotor powerfactor and hence phase angle
(iii) Total resistance andleakage reactance per phase of the motor asrefered tothestator

29.What is circle diagram of an I M?

WhenanIMoperatesonconstantvoltageandconstantfrequencysource,thelociofstatorcurrentphasorisfoundtofallonacircle.Thiscirclediagramisusedtopredicttheperformance of the machine at differentloading conditionsas well as mode of operation.

30.What are the advantages and disadvantages of circle diagrammethodofpredetermining the performance of 3–phase I M?

ThepredictioncanbecarriedoutwhenanyofthefollowinginformationisavailableTheinputlinecurrent.,theinputpowerfactor,Theactivepowerinput,Thereactivepowerinput,Theapparentpowerinput,Theoutputpower,Theslipofoperation,Thetorquedeveloped,Theequivalentrotorcurrentperphase,Maximumoutputpower,Maximumtorquedeveloped.Theonlydisadvantageis,beingageometricalsolution,errorsmadeduring measurements will affect theaccuracy ofthe result.

31.What are the advantages and disadvantages of direct load test for 3–phase I M?

AdvantagesDirectmeasurementofinputandoutputparametersyieldaccurateResults AsidefromtheusualperformanceotherperformanceslikemechanicalVibration,noiseetccanbestudied.Byoperatingthemotoratfullloadforacontinuousperiod,thefinalsteadytemperaturecanbemeasured.DisadvantagesTestinginvolveslargeamountofpowerandtheinputenergyandtheentireenergydeliveredis wastedLoadingarrangementcannotbeprovided for motors of large power rating

32.What typeof singlephase inductionmotor wouldyou use for the followingapplications?

(i)Ceilingfan(ii)WetgrinderCeilingfan–capacitorstartandrunmotorWetgrinder–capacitor start motor

33.After servicing a single phase fan it was found to run inreverse direction.What could be the reason?

The connection to the starting/ auxiliary winding would have reversed.

34.What will be the direction of rotation of a shaded pole single phase induction motor?

The motor rotates in the direction specified by the unshaded to shaded region in the pole phase

UNIT IV

STARTINGANDSPEED CONTROL OF THREEPHASEINDUCTION MOTOR

1. What are the types of starters?
Stator rheostat, Autotransformer Star to Delta starter and rotor resistance starter.
2. List out the methods of speed control of cage type 3-phase induction motor? a) By changing supply frequency
b) By changing the number of poles
c) By operating two motors in cascade
3. Mention different types of speed control of slip ring induction motor?
e) By changing supply frequency
f) By changing the number of stator poles g) By rotor rheostat control
h) By operating two motors in cascade
4.State the advantages of capacitor start run motor over capacitor start motor. Running torque is more; Power factor during running is more.
5. Explain why single-phase induction motor is not self-starting one.

When the motor is fed from a single phase supply its stator winding produces an alternating or pulsating flux, which develops no torque which is explained in Double revolving field theory..

6.What type of motor is used for ceiling fan?

Capacitor start and capacitor run single-phase motor is used for ceiling fans.

7.What is the type of induction motor used in wet grinders?

Capacitor start capacitor run single-phase induction motor.

8.What kind of motor is used in mixie?

Single-phase ac series motor is used in mixie.

9.What is the application of shaded pole induction motor?

Because of its small starting torque, it is generally used for small fans, toys, instruments, hair driers, ventilators, electric clock etc.

10. In which direction does a shaded pole motor run?

The rotor starts rotation in the direction from unshaded part to the shaded part.

11.Why single-phase induction motor has low power factor?

The current through the running winding lags behind the supply voltage by a very large angle. Therefore power factor is very low.

12.Diffrentiate between "capacitor start "and "capacitor start capacitor run "induction motor?

In capacitor start motor, capacitor is connected in series with the starting winding. But it will be disconnected from the supply, when the motor picks up its speed. But in capacitor start capacitor run motor the above starting winding and capacitor are not disconnected, but always connected in the supply .so it has high starting and running torque.

13. State the application of an induction generator?

Used in windmill for generating electric power.

Used in regenerative breaking places like traction.

14. What do you mean by residual EMF in a generator.

The EMF induced in the armature conductor only due to the residual flux in the field poles is known as residual EMF

15. State the effect of rotor resistance on starting torque?

Starting torque increases with increase in value of rotor resistance.

16. How can varying supply frequency control speed?

We know that

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

From the equation it is clear that by varying frequency speed can be varied it is vary rarely.

17.How is speed control achieved by changing the number of stator poles?

Here change in stator poles is achieved by having two or more independent stator windings in the same slot. Each winding gives different number of poles and different speeds. At a time only one winding is used and other is closed.

18.What are the main disadvantages of rotor rheostatic control?

Ø The speed can be decreased by increasing the rotor resistance, but increases I2R loss and hence decreases efficiency.

Ø Speed depends on load also and so used for small periods only.

19.What are the methods of speed control preferred for large motors?

Ø Kramer system

Ø Scherbius system

20.What is an induction regulator?

An induction regulator is used to obtain the constant voltage at the feeder end. Varying the range between the magnetic axes of the primary and secondary windings controls the voltage; it may be a single phase. Rotor is moved usually by a maximum of 180 degree.

21.Define-Slip frequency.

The relation motion of the stator flux and the rotor conductors induces the voltage of frequency Sf called slip frequency.

22.Define- Asynchronous torque.

When stator and rotor fields are stationary with respect to each other, a steady torque is produced and rotation is maintained. Such a torque existing at any mechanical speed other than synchronous speed is called as an asynchronous torque.

23.What is the main use of squirrel cage winding in synchronous motor starting?

When a squirrel cage winding called the amortissuer or damper winding is inserted in the rotor pole faces, the rotor comes up to the synchronous speed by induction motor action with the field winding unexcited.

24.What is breakdown torque?

From the torque verses slip charactertics, we can infer that as the torque increases, slip increases upto a maximum torque developed is called a breakdown torque.

25.What is the function of rotary converter? Where it is used?

Rotary converter converts low slip ac power. It is used in Kramer system, which is for the speed control of three-phase induction motor.

26.What are the advantages of Kramer system of speed control?

Any speed with in the working range can be obtained

When rotary converter is overexcited, it will take leading current, compensates with the lagging current drawn by the motor, thus improving power factor.

27.Write the expression for concatenated speed of the set.

Cumulative mode (Nsc) = $\frac{120f}{Pa + Pb}$

Differential mode (Nsc) = $\frac{120f}{Pa - Pb}$

Pa – no of poles of motor A Pb – no of poles of motor B

28.Canthe starting torque of of a slipring induction motor beingincreased?

Yes. It can be increasedby adding resistances to the rotor.

29.Whatwouldhappenifa3phaseinductionmotorisswitchedonwithonephasedisconnected?

The motor is likely to burn .

30.What happens if the air gap flux density in aninductionmotor increases?

The increase in air gap flux increases iron loss andhence efficiency decreases.

31.State the advantages of skewing?

Itreduceshummingandhencequiterunningofmotorisachieved.Itreducesmagneticlocking of thestator androtor.

32.Statetheconditionatwhichthestartingtorquedevelopedinaslip-ringinductionmotor is maximum.

When $R2=X2$

33.Whataretheeffectsofincreasingrotorresistanceonstartingcurrentandstartingtorque?

Theadditionalexternalresistancereducestherotorcurrentandhencethecurrentdrawnfromthesupply.It improvesthestarting torque developedby improvingthepowerfactorinhigh proportion to the decrease in rotor current.

34.What is slip of an induction motor?

The slip speedexpressed as the ratio of synchronous speed is defined asslip.
Percentage slip$S=Ns-N/Ns*100$

35.Howthe magnitude ofrotor emfis related to the slip in an I M?

Rotor circuit emfper phase $E2r=SE2$

36.Howthe frequency of rotor emfis related to the slip in an I M?

Frequency of rotor emf/current$fr=Sfs$

37.What is the normal value of slip of anI M operating atfull load?

3 - 5%

38.WhyisnotpossiblefortherotorspeedofanIMtobeequaltothespeedofitsrotatingmagneticfield?

The machine will not be able to develop any mechanicaltorque to run asa motor.

UNIT-V

SINGLEPHASE INDUCTIONMOTORS ANDSPECIAL MACHINES

1. Name the two winding of single phase induction motor? Running and starting winding.

2. What are methods available for making single phase induction motor a self starting? By splitting the single phase, by providing shading coil in the poles.

3. What is the function of capacitor in single phase induction motor?
To make phase difference between starting and running winding, to improve PF and to get more torque.

4. State any four use of single phase induction motor?
Fans, wet grinders, vacuum cleaner, small pumps, compressors, drills. Explain

5. Why single phase induction motor is not a self starting one?
When motor fed supply from single phase, its stator winding produces an alternating flux, which doesn't develops any torque.

6. What kind of motors used in ceiling fan and wet grinders?
Ceiling fan # Capacitor start and capacitor run single phase induction motor, wet grinders# Capacitor start capacitor run single phase induction motor.

7. What is the application of shaded pole induction motor?
Because of its small starting torque, it is generally used for small toys, instruments, hair driers, ventilators.etc.

8. In which direction a shaded pole motor runs?
The rotor starts rotation in the direction from unshaded part to the shaded part.

9. Why single phase induction motor have low PF?
The current through the running winding lags behind the supply voltage by large angle so only single phase induction motor have low PF.

10. Differentiate between "capacitor start" & "Capacitor start capacitor run" single phase induction motor?
Capacitor start – capacitor is connected series with starting winding, but it will be disconnected from supply when motor pick up its speed. Capacitor start capacitor run# starting winding and capacitor will not be disconnected from supply even though motor pickup its speed.

11. What are the principal advantages of rotating field type construction?
Relatively small amount of power required for field system can easily supplied to rotating system using slip rings and brushes, more space is available in the stator part of the machine to provide more insulation, it is easy to provide cooling system, stationary system of conductors can easily be braced to prevent deformation.

12. Why an induction motor never runs at its synchronous speed?
If it runs at sy.speed then there would be no relative speed between the two, hence no rotor emf, so no rotor current, then no rotor torque to maintain rotation.

13. What are the advantages of cage motor?
Since the rotor has low resistance, the copper loss is low and efficiency is very high. On account of simple construction of rotor it is mechanically robust, initial cost is less; maintenance cost is less, simple starting arrangement.

14. Why an induction motor is called as rotating transformer?

The rotor receives same electrical power in exactly the same way as the secondary of a two winding transformer receiving its power from primary. That is why induction motor is called as rotating transformer.

15. What is the use of shading coil in the shaded pole motor?

In shaded pole motors the necessary phase –splitting is produced by induction. These motors have salient poles on stator and a squirrel cage type rotor. The poles are shaded ie each pole carries a copper band one of its unequally divided part is called shading band. When single phase ac supply is given to the stator winding due to shading provided to the poles a rotating magnetic field is generated.

16. Why capacitor –start induction motors advantageous?

In capacitor start induction motors capacitor is connected in series with the auxiliary winding. When speed of the motor approaches to 75 to80%of the synchronous speed the starting winding gets disconnected due to the operation of the centrifugal switch. The capacitor remains in the circuit only at start. The starting torque is proportional to phase angle ά and hence such motors produce very high starting torque.

17. List out 4 applications of shaded pole induction motor?

Shaded pole motors have very low starting torque, low power factor and low efficiency. The motors are commonly used for small fans, toy motors, advertising displays, film projectors, record players, gramophones, hair dryers , photocopying machines etc

18. What are the drawbacks of the presence of the backward rotating field in a single phase induction motor?

Due to cutting of flux, emf gets induced in the rotor which circulates rotor current .the rotor current produces rotor flux. This flux interacts with forward component φf to produce a torque in one particular direction say anticlockwise direction. While rotor flux interacts with backward component φb to produce a torque in the clockwise direction. So if anti clock wise torque is positive then clockwise torque is negative thus net torque experienced by the rotor is zero at start.

19. Why is hysteresis motor free from mechanical and magnetic vibrations?

The stator of hysteresis motor carries main and auxiliary windings to produce rotating magnetic field or of shaded pole type also. The rotor is smooth cylindrical type made up of hard magnetic material. The torque in this motor is constant at all speeds it runs at synchronous speed. There is not relative motion between stator and rotor field so the torque due to eddy current vanishes. Only hysteresis torque is present which keeps rotor running at synchronous speeds .the high retentivity ensures continuous magnetic locking between stator and rotor. Hence it is free from magnetic vibrations

20. What types of motor is used in computer drives and wet grinders?

For computer drives permanent magnet dc motors are used while in wet grinder’s universal motor may be used.

21. Give two advantages and two applications of stepper motor. Advantages:

*These motors are compatible with digital equipments and are flexible in operation. *The dynamic response is fast

Applications:

Stepper motors are widely used in computer peripherals such as serial printers tape drives, floppy disk drivers. They are also used in control of machine tools. Robotics.

22. List some applications of linear induction motor?

They are used in machine tool industry and in robotics .They are used in trains operated on magnetic levitation , reciprocating compressors can also be driven by linear motors

23. What are the specific characteristic features of the repulsion motor?

Repulsion motors give excellent performance characteristics. A very high starting torque of about 300 to350% of full load can be obtained with starting currents of about 3 to 4 times the full load current. Thus it has got very good operating characteristics. The speed of the motor changes with load .with compensated type of repulsion motor the motor runs with improved power factor as the quadrature drop in the field winding is neutralized. Also the leakage between armature and field is reduced which gives better regulation.

24. Discuss characteristics of single phase series motor

* To reduce the eddy current losses, yoke and pole core construction is laminated

*The power factor can be improved by reducing the number of turns. But this reduces the field flux. But this reduction in flux increases the speed and reducing the torque. To keep the torque same it is necessary to increase the armature turns proportionately. This increases the armature inductance.

25. What are the demerits of repulsion motor? *very expensive

*speed changes with load

* on no load speed is very high causing sparking at brushes*low power factor on no load

26. List four applications of reluctance motors?

This motor is used in signaling devices, control apparatus, automatic regulators, recording instruments, clocks and all kinds of timing devices, teleprinters, gramophones 27. What is a universal motor?

There are small capacity series motors which can be operated on dc supply or single phase ac supply of same voltage with similar characteristics called universal motors. The construction of this motor is similar to that of ac series motor

27.Definestep angle?

Itisdefinedasanglethroughwhichthesteppermotorshaftrotatesforeachcommand pulse. It is denoted asβ, i)$\beta=[(Ns-Nr)/Ns.Nr]x360^{o}$ Where Ns= no. of statorpoles or stator teeth

Nr=no. ofrotorpoles or rotor teeth

ii)$\beta = 360^{0}/mNr$

Wherem= no. ofstator poles

28.What are different types of stepper motor?

1. Variable reluctance(VR)motor
2. Permanentmagnet (PM) stepper motor
3. Hybrid stepper motor

29.What isthe advantage in usingstepper motor?

1. it can drive open loopwithout feedback
2. itrequireslittle or nomaintenance.

30.Givethe applications of steppermotor?

1. Robotics
2. Computerperipherals
3. Facsimilemachine
4. Aerospace

31.What are the adv. of reluctance m/c?

1. Motor speedis constant
2. Simple construction

32.What is Universal motor?

A Universal motor is defined as a motor, which may be operated either on direct current or single-phase ac supply.

33.State some application of universal motor.

Used for sewing machines, table fans, Vaccum cleaners, hair driers, blowers etc

REVIEW QUESTIONS

UNIT I

1. Explain the constructional details and working principle of alternator.
2. Explain the EMF equation.
3. What is synchronous reactance and explain the effect of armature reaction?
4. Explain the voltage regulation of alternator by EMF method.
5. Explain the voltage regulation of alternator by MMF method.
6. Explain the voltage regulation of alternator by ASA method.
7. Explain the voltage regulation of alternator by ZPF method
8. Explain in detail about parallel operation of alternator.
9. Explain about two reaction theory.

10. What is synchronous reactance and explain slip test?
11. Explain the characteristics alternator in detail.

UNIT II

1. Explain the constructional details and working principle of syn. Motor.
2. Derive the torque equation of syn motor.
3. Draw and explain V curves and inverted V curves.
4. Explain in detail about bus bar operation.
5. Explain in detail about power equations.
6. Explain the starting methods of syn. Motor.

UNIT III

1. Explain the constructional details and working principle of 3 phase IM.
2. Draw the equivalent circuit of 3 phase IM.
3. What is slip and explain slip torque characteristics of 3 phase IM?
4. Write the condition for maximum torque of 3 phase IM?
5. Explain losses and efficiency of 3 phase IM.
6. Explain the tests in detail 3 phase IM.
7. Draw circle diagram in detail.
8. How to separate no-load losses of 3 phase IM.
9. Explain double cage IM.
10. Explain induction generator and syn. IM.

UNIT IV

1. Explain the need of starter and types of starter in detail.
2. Explain rotor resistance starter.
3. Explain auto transformer starter.
4. Explain star delta starter.
5. What is speed control and how to control speed of three phase IM?
6. Explain slip power recovery scheme.
7. Explain cascade connection in detail

UNIT V

1. Explain the constructional details and working principle of 1phase IM.
2. Explain double field revolving theory.
3. Draw equivalent circuit.
4. Explain starting methods of single phase induction motor.
5. Explain shaded pole and linear reluctance motor.
6. Explain reluctance and ac series motor.
7. Explain repulsion and hysteresis motor.