

LECTURE NOTES

ON

ELECTRICAL MACHINES – III

III B. Tech I Semester

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SYNCHRONOUS GENERATORS

Principle and Constructional Features of Salient Pole and Round Rotor Machines – Armature Windings, Concentrated and Distributed Windings, Integral Slot and Fractional Slot Windings – Pitch, Distribution, and Winding Factors – E.M.F Equation- Harmonics in Generated E.M.F – Space and Slot Harmonics – Elimination of Harmonics- Armature Reaction – Synchronous Reactance and Impedance – Load Characteristics - Phasor Diagram.

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 $E_{av} = \frac{d\phi}{dt}$. The voltage induced in one conductor is $2\phi/(1/n) = 2\phi n$, where n =speed of rotation in r.p.s, for a 2 pole generator. Furthermore, when a coil consisting of N_c turns rotating in a uniform magnetic field, at a uniform speed, the average voltage induced in an armature coil is $E_{av} = 4\phi N_c n$ volts *coil* 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,

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

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

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

Where

$$N = \frac{rpm}{60}$$

P is the number of poles

$$\omega_m = \frac{2\pi \times rpm}{60}$$

N is the speed in rpm (rev/min)

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

f is. the frequency in hertz

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

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

$$f = \frac{P}{2} \times \frac{\omega_m \times 60}{2\pi \times 60} = \frac{P \omega_m}{2\pi}$$

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-

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

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 ,

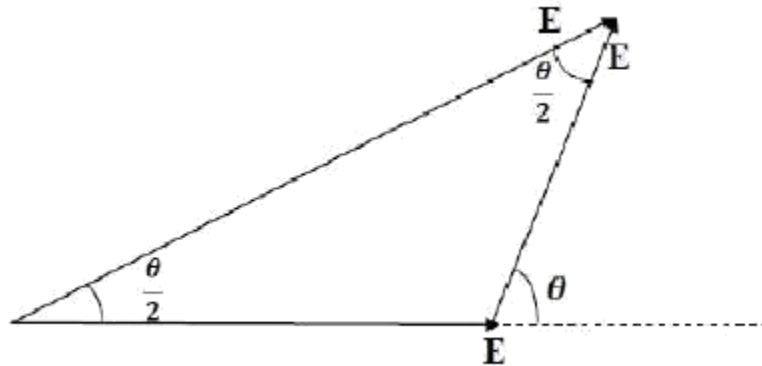


Fig: 1(a) Voltage phasor for short-pitch coil

- 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, E_R in the coil is phasor sum of two voltages, θ apart

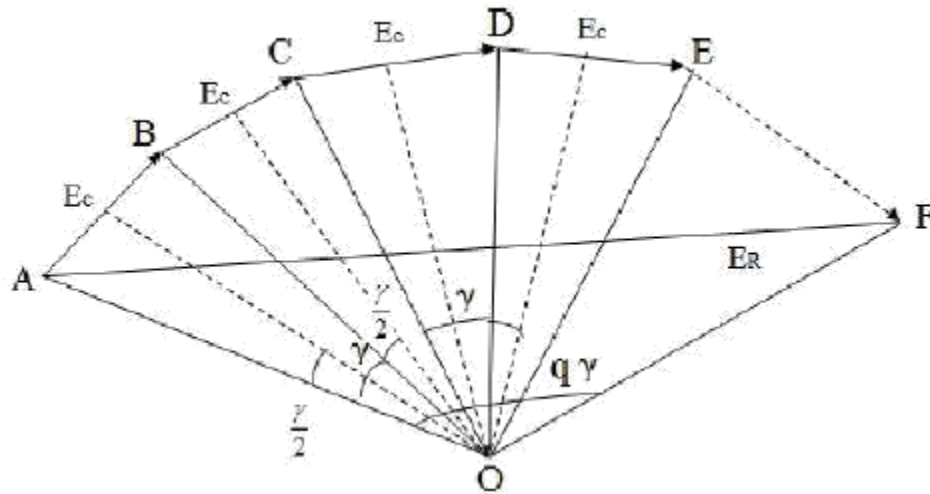
$$E_R = 2E \cos \theta/2$$

$$\text{Pitch Factor, } K_p = \frac{\text{Phasor sum of coil side emfs}}{\text{Arithmetic sum of coil side emfs}}$$

The pitch factor of the coil at the n th harmonic frequency can be expressed as

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

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 = E_c . Angular displacement between the slots, α . 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 E_c) and differ in phase (say by α) from each other. Fig



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.

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

$$\text{Arithmetic sum} = q \cdot 2 \cdot OA \sin \gamma \frac{2}{2}$$

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

The distribution factor for n^{th} order harmonic component is given as

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

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, ninth, 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 (K_d) and pitch factor K_p together is known as **winding factor K_w** .

$$k_w = k_p k_d$$

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

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

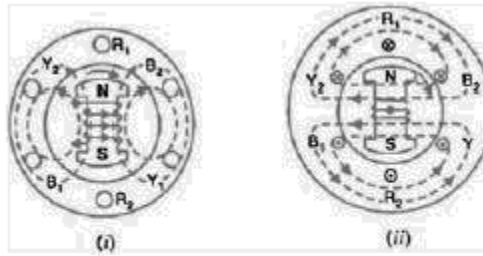


Fig: 1 (c)

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 the 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° .

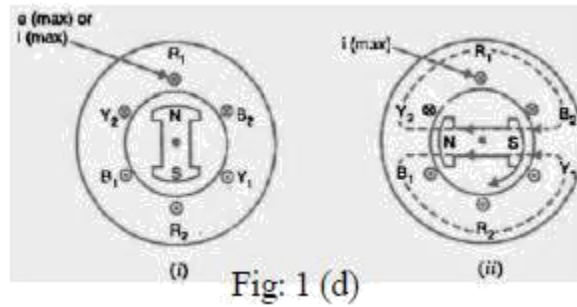


Fig: 1 (d)

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.

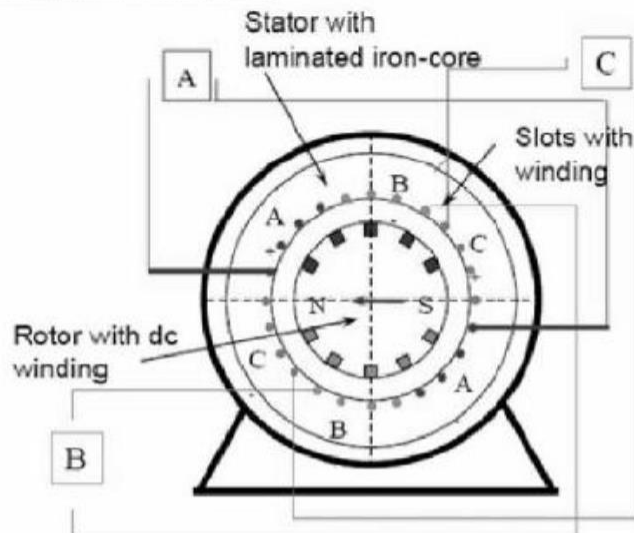
1.7.2 Rotating-Armature Type: The armature winding is on the rotor and the field system is on the stator.

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.

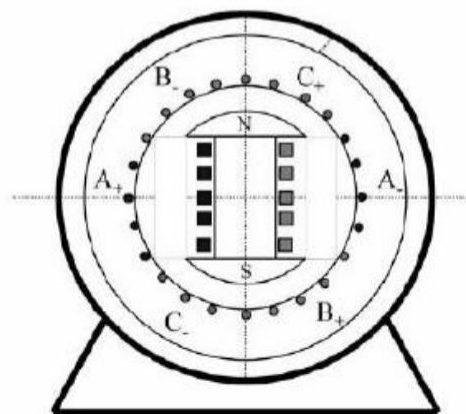
Concept (two poles)



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 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.

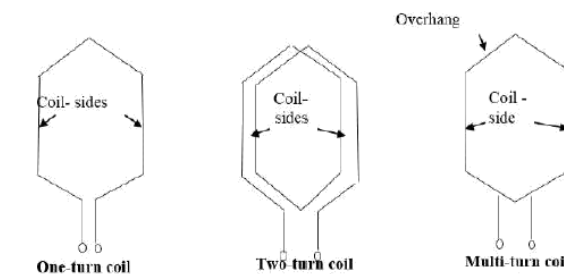


Fig: 1.1

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

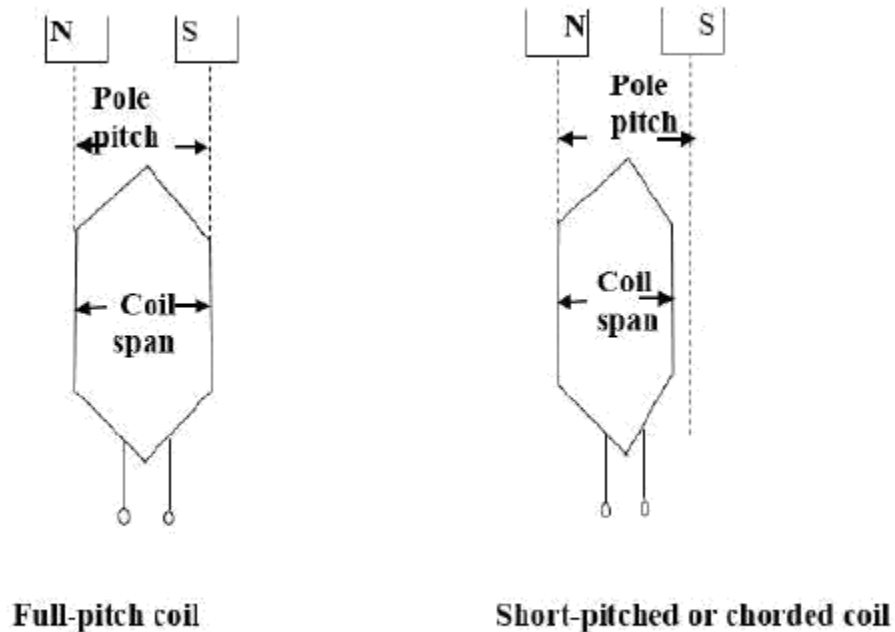


Fig: 1.2

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.

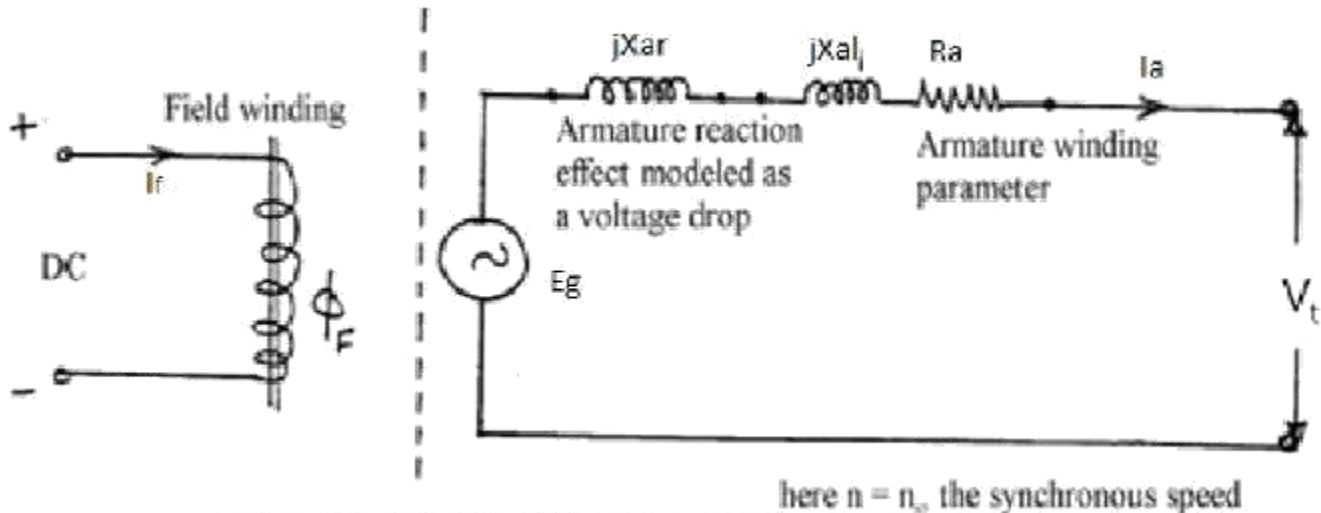


Fig: 1.3 Equivalent circuit of synchronous generator

For synchronous generator the terminal voltage V_t can be written as

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

$$V_t = E_g - jI_a X_s - I_a R_a$$

$$V_t = E_g - I_a (R_a + jX_s) = E_g - I_a Z_s$$

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 ϕ . The phasor diagram is shown below in Fig: 1.4.

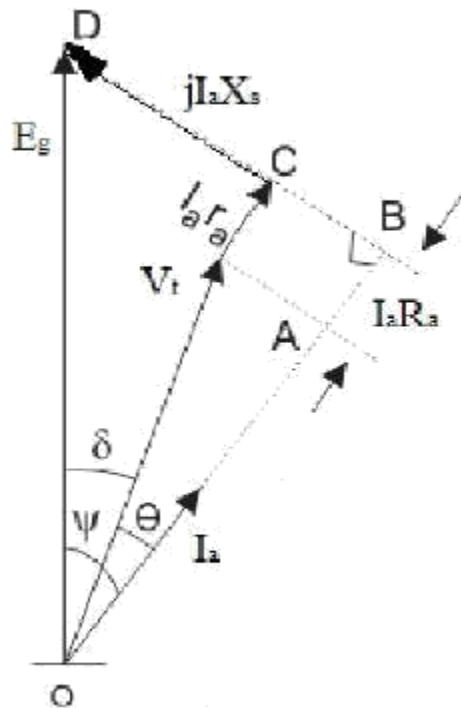


Fig: 1.4

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.

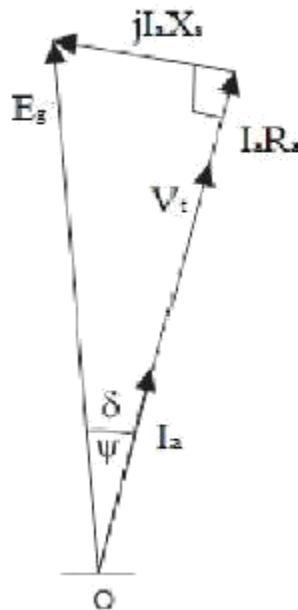


Fig: 1. 5 Phasor diagram of an alternator with unity power factor load

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 ϕ . The complete phasor diagram for leading power factor load is shown below in Fig: 1. 6.

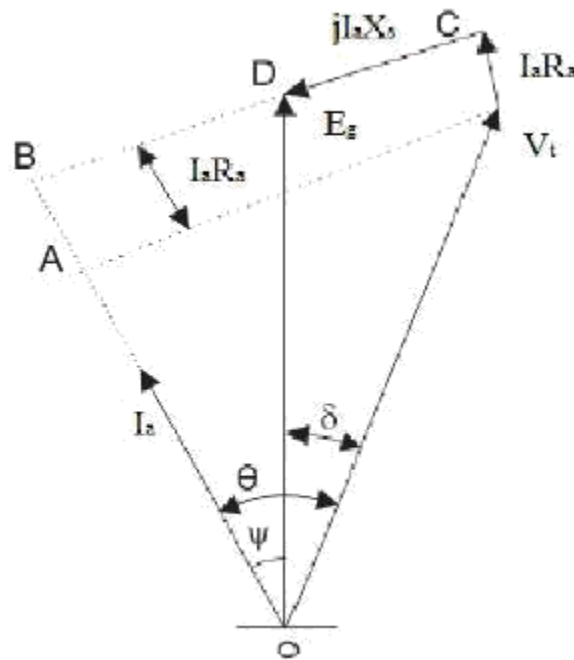


Fig: 1. 6 Phasor diagram of an alternator with leading power factor load

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, $I_a=0$, so $E_g = V_t$. 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.

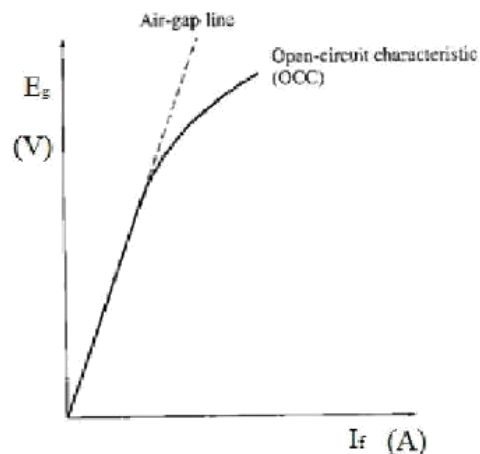


Fig: 1. 7 Open-circuit characteristic of alternator

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)

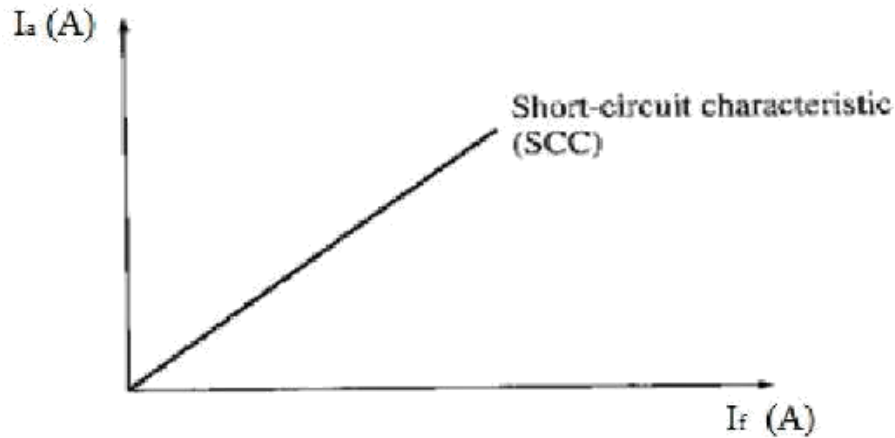


Fig: 1.8 Short-circuit characteristic of alternator

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° . Per phase armature current I_a produces armature mmf F_a which is in phase with I_a . The effective mmf is F_r .

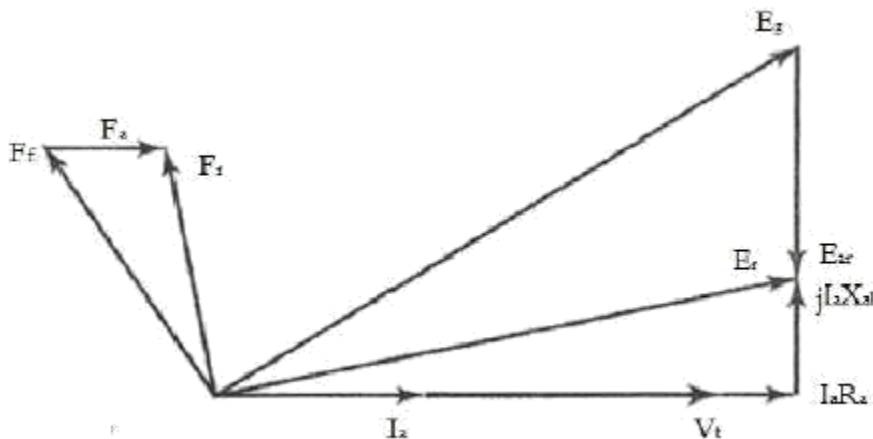


Fig : 1.9 Phasor diagram of an alternator at unity power factor

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

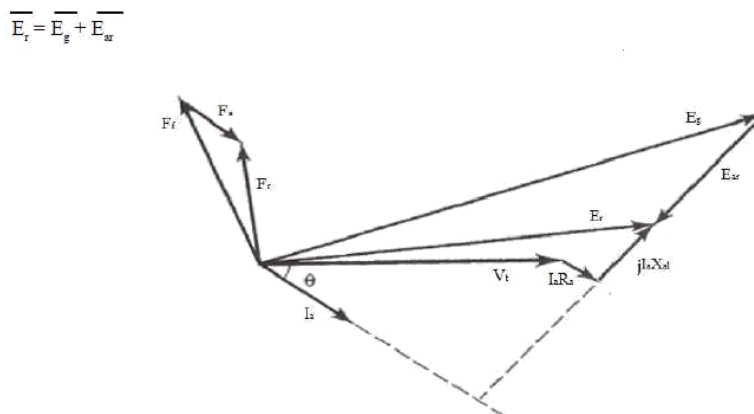


Fig: 1.10 Phasor diagram of an alternator at lagging power factor

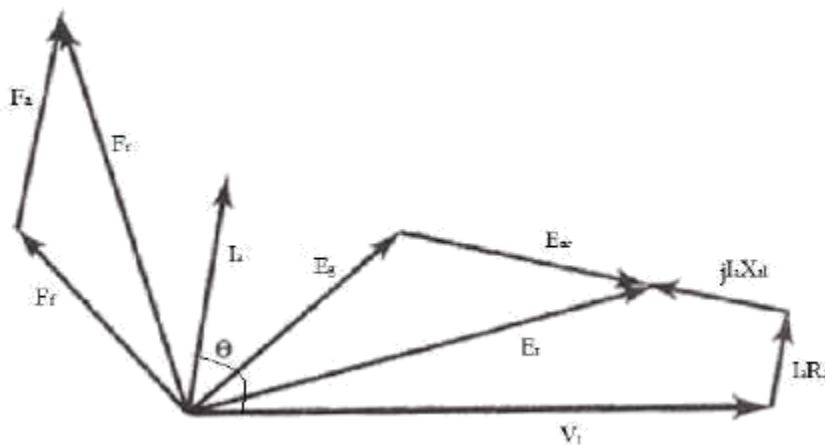


Fig: 1.11 Phasor diagram of an alternator at leading power factor

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° , so it can be expressed as

$$E_{ar} = -jI_a X_{ar}$$

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 reactances 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)**.

$$Z_s = R_a + jX_s$$

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.

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

$$\text{So, } SCR = \frac{1}{X_s}$$

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 $I_a Z_s$ 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 σ 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

$$V_t + I_a Z_s = E_g$$

$$V_t = E_g - I_a Z_s$$

Algebraically this can be written as-

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

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

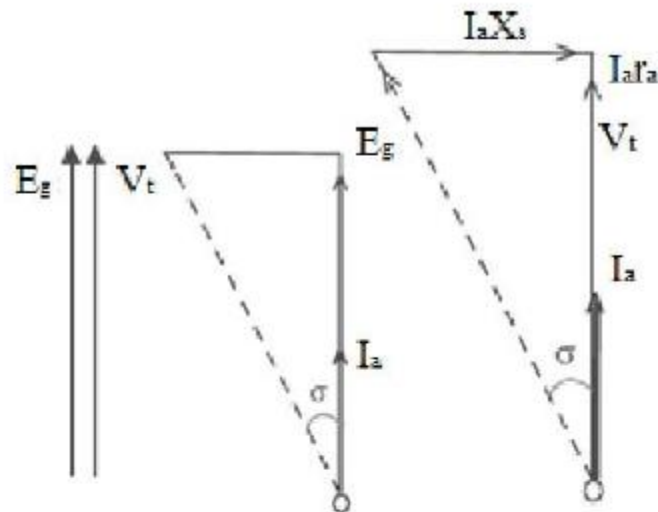
$$V_t^2 + I_a^2 X_s^2 \approx E_g^2 = \text{const}$$

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

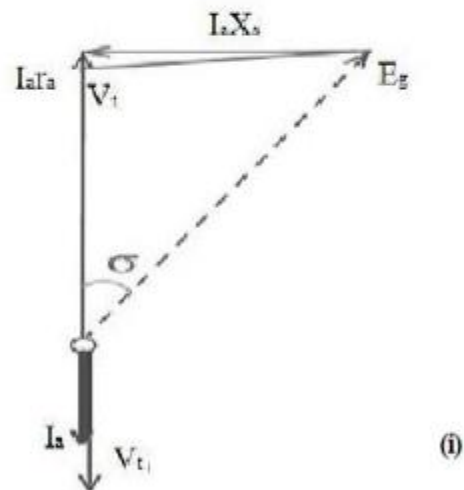
$$I_a = I_{sc} = E_g / Z_s \approx E_g / X_s$$

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

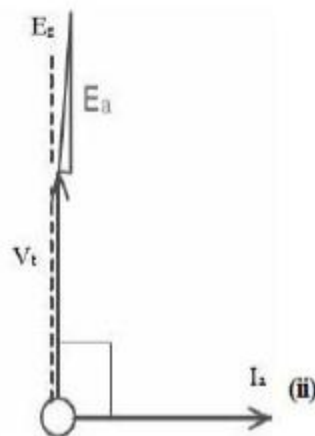
$$V_t \approx E_t - I_a X_s$$



1.12 (i) Phasor diagram for different R loads



(i)



(ii)

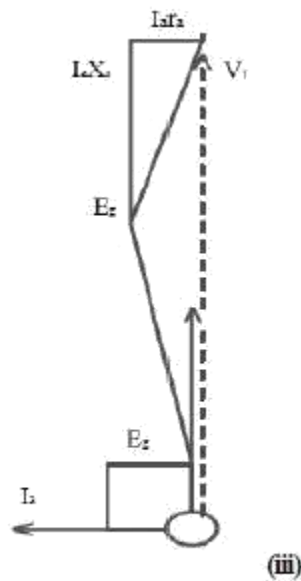


Fig: 1.13 Variation of voltage with load at constant Excitation

which is the straight line marked for $\cos \phi = 0$ lagging in Fig.1.14. A leading load of zero power factor Fig. 1.14 will have the voltage

$$V_t \approx E_t + I_a X_s$$

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.

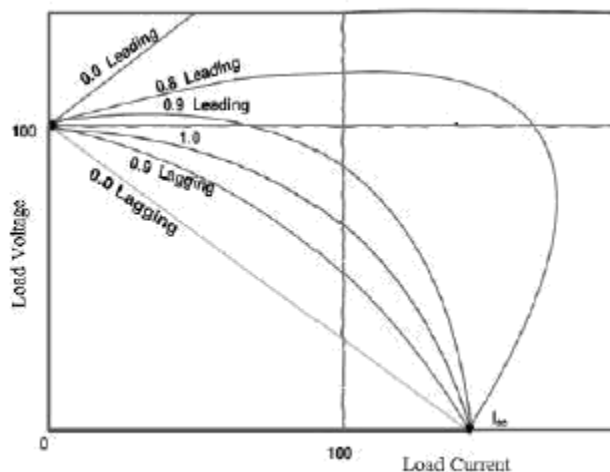


Fig: 1.14 Load characteristics of Alternator

UNIT – II REGULATION OF SYNCHRONOUS GENERATORS

Regulation of Salient Pole Alternator – Voltage Regulation Methods – E.M.F Method- MMF Method – ZPF Method – ASA Method – Short Circuit Ratio (SCR) – Two Reaction Theory –Determination of X_d and X_q (Slip Test) – Phasor Diagrams.

2.1 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 starts 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

$$\% \text{ Regulation} = (E_0 - V_t) / V_t \times 100$$

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

2.2 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 be 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.

2.2.1 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 :

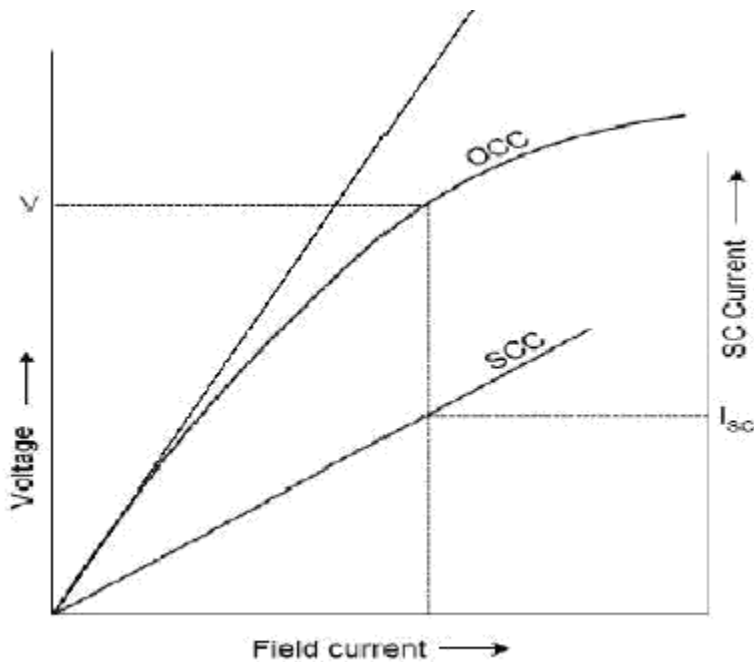


Fig: 1.16 OCC and SCC of alternator

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 from 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 $Z_s = (\text{open circuit voltage per phase}) / (\text{short circuit current per phase})$ for same I_f
Hence $Z_s = (V_{oc}) / (I_{sc})$ for same I_f

From Fig: 1.16 synchronous impedance $Z_s = V / I_{sc}$

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.

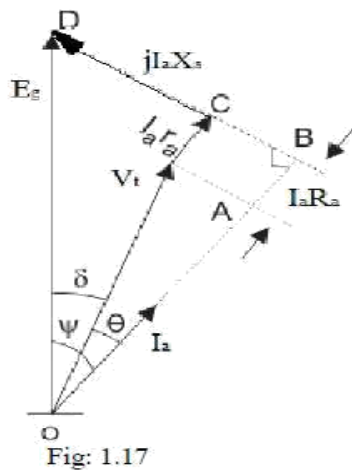


Fig: 1.17

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

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

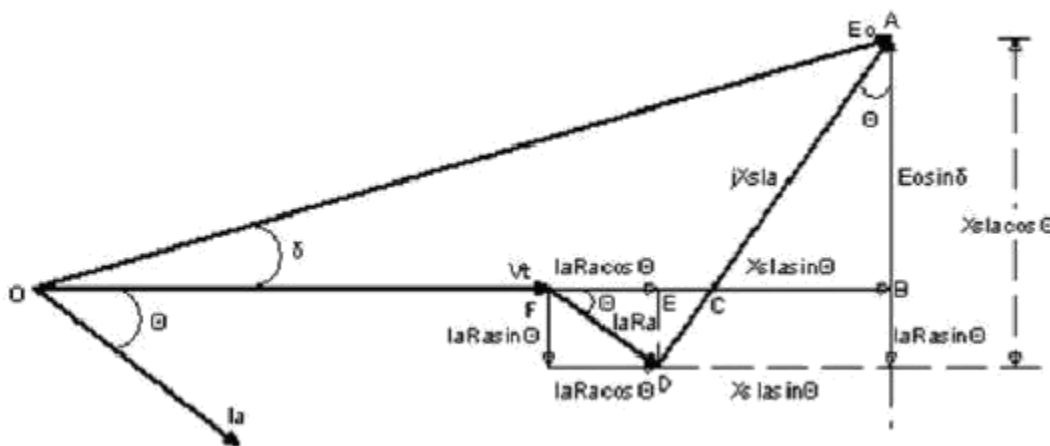
where V_t = phase voltage per phase = V_{ph} , I_a = load current per phase

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

$$\% \text{ Regulation} = \frac{E_g - V_t}{V_t} \cdot 100$$

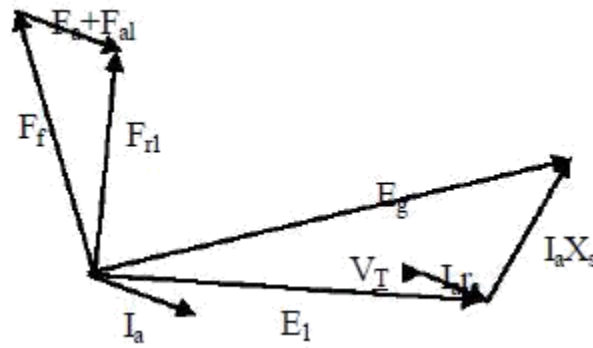
where E_g = no-load induced emf /phase, V_t = rated terminal voltage/phase

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.



2.2.2 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.



From the phasor diagram it can be seen that the mmf required to produce the emf $E_1 = (V + IR_a)$ is F_{r1} . In large machines resistance drop may be 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.

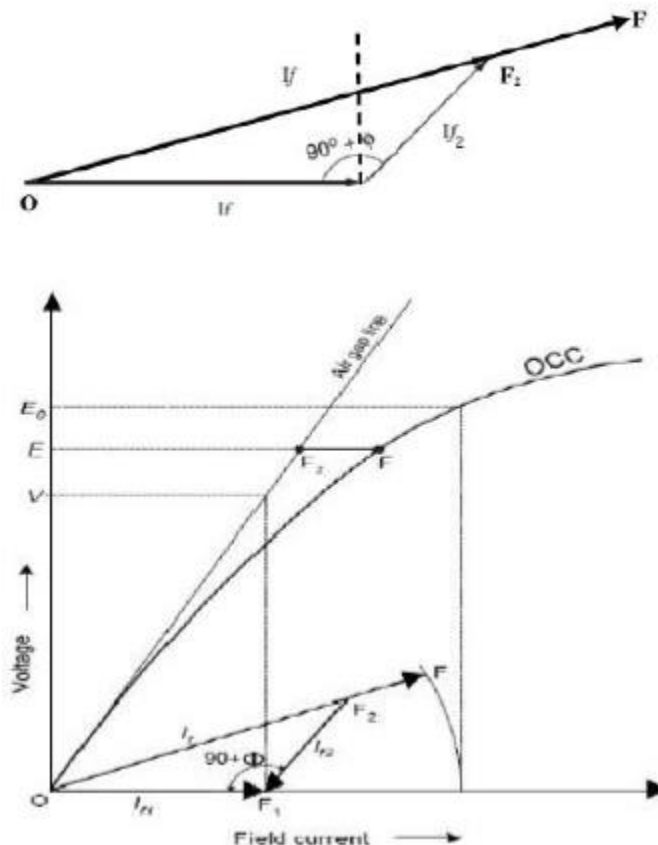
Following procedure can be used for determination of regulation by mmf method.

1. By conducting OC and SC test plot OCC and SCC.
2. From the OCC find the field current I_{f1} required to produce the voltage, $E_1 = (V + IR_a)$.
3. From SCC find the magnitude of field current I_{f2} ($\approx F_a + F_{al}$) to produce the required armature current. $F_a + F_{al}$ can also be found from ZPF characteristics.
4. Draw I_{f2} at angle $(90 + \Phi)$ from I_{f1} , where Φ is the phase angle of current w. r. t voltage. If current is leading, take the angle of I_{f2} as $(90 - \Phi)$.
5. Determine the resultant field current, I_f and mark its magnitude on the field current axis.
6. From OCC, find the voltage corresponding to I_f , which will be E_0 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.

2.2.3 ASA Modified MMF Method:

ASA or modified mmf method considers 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 FF_2 which can be computed from occ, scc and air gap lines as explained below referring to Fig: 1.20 (i) and (ii).



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 $(90^\circ + \phi)$ 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 E_0 using OCC. Hence regulation can be found by ASA method which is more realistic.

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

During the operation of the alternator, resistance voltage drop $I_a R_a$ and armature leakage reactance drop $I_a X_L$ 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 $I_a X_L$ vertically and horizontally by armature reaction mmf as shown below in Fig: 1.21. Following are the steps to draw ZPF characteristics.

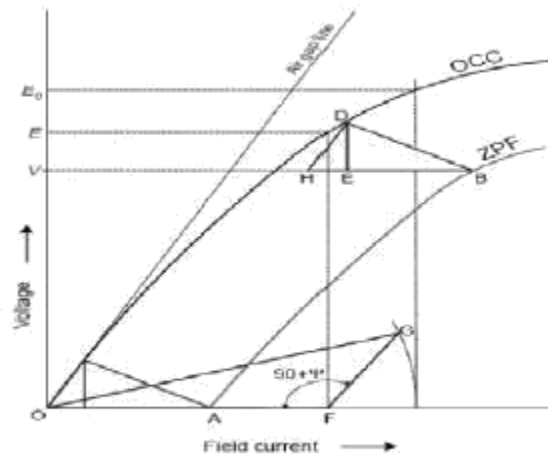


Fig: 1.21

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 IX_L 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 , $I_a R_a$, IX_L and Φ .

Use the expression $E = \sqrt{(V_f \cos \Phi + I_a R_a)^2 + (V_f \sin \Phi + I_a X_L)^2}$ to compute E . Find field current

corresponding to E . Draw FG with magnitude equal to BE at angle $(90 + \Psi)$ from field current axis,

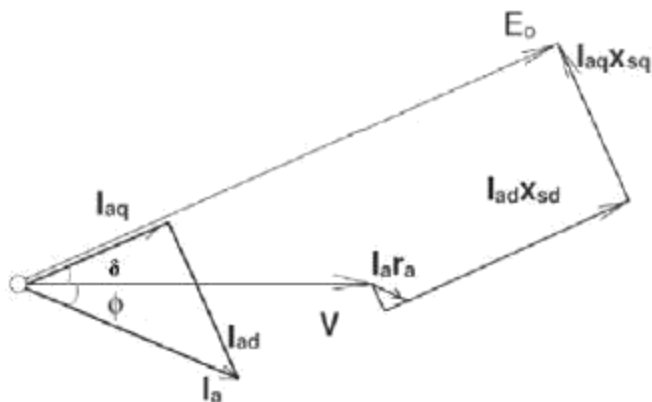
where Ψ is the phase angle of current from voltage vector E (internal phase angle).

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

2.3 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.

2.4 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

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

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

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:

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

$$I_a * \cos \phi = I_{aq} * \cos \sigma + I_{ad} * \sin \sigma$$

This can be expressed in terms of σ as

$$V * \cos \sigma = E_o - I_{ad} * x_{sd}$$

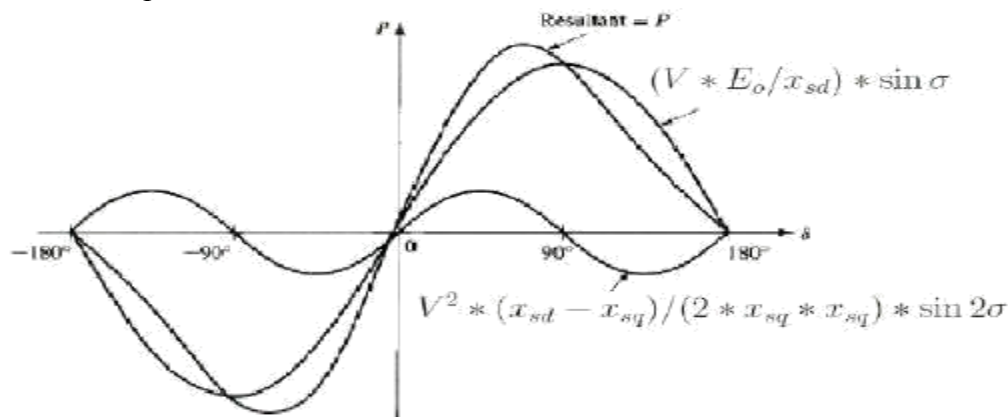
$$\text{and } V * \sin \sigma = I_{aq} * x_{sd}$$

Substituting these in the expression for power, we have.

$$P = V[(V * \sin \sigma / x_{sd}) * \cos \sigma + (E_o - V * \cos \sigma) / x_{sd} * \sin \sigma]$$

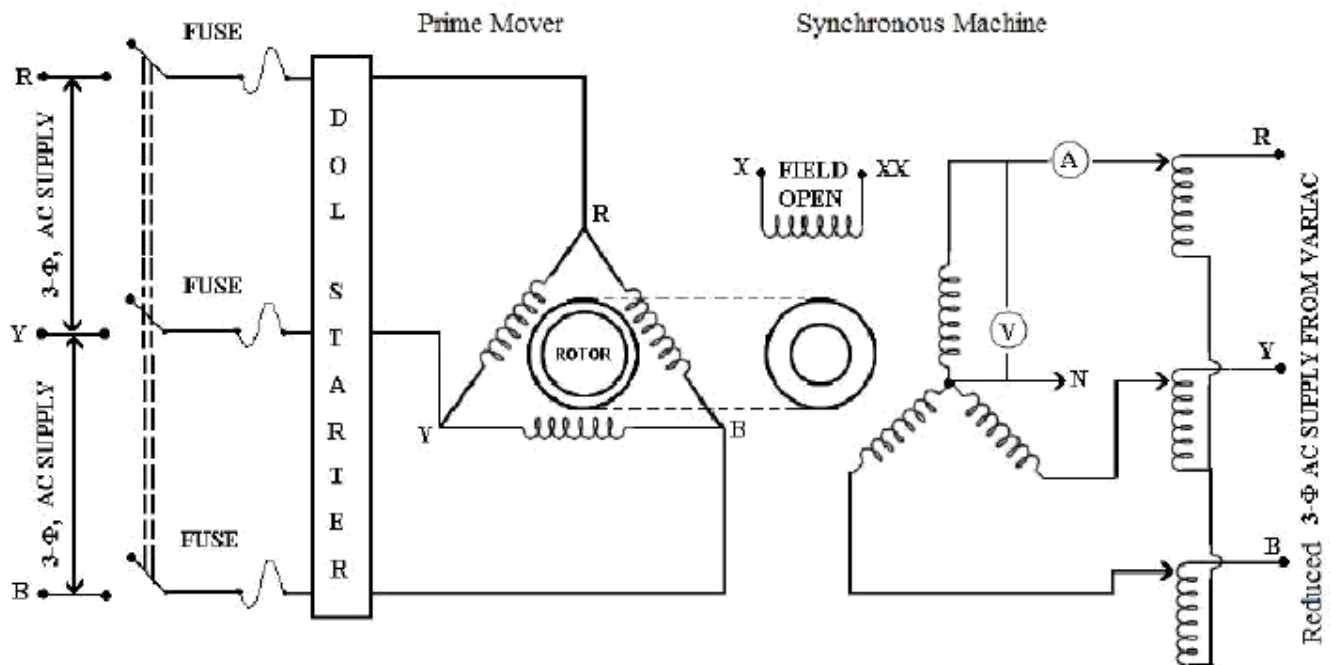
$$= (V * E_o / x_{sd}) * \sin \sigma + V^2 * (x_{sd} - x_{sq}) / (2 * x_{sq} * x_{sd}) * \sin 2\sigma$$

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 $(\sin 2)$ 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

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

UNIT –III PARALLEL OPERATION OF SYNCHRONOUS GENERATORS

Power Flow Equation in Alternators (Cylindrical and Salient Pole Machines) – Synchronizing Power and Torque – Parallel Operation and Load Sharing – Effect of Change of Excitation and Mechanical Power Input – Synchronizing Alternators with Infinite Bus Bars – Determination of Sub-Transient, Transient and Steady State Reactances.

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 in Fig: 1.23. For large size of generator armature resistance r_a is negligible.

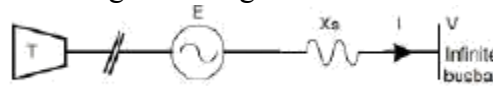


Fig: 1.22 Cylindrical-rotor alternator connected to infinite bus-bar single line diagram

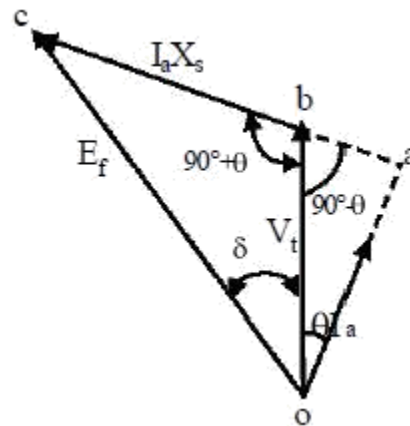


Fig: 1.23 Phasor diagram of an alternator for lagging power factor load with neglected armature resistance

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

$$P = V I_a \cos \theta$$

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

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

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

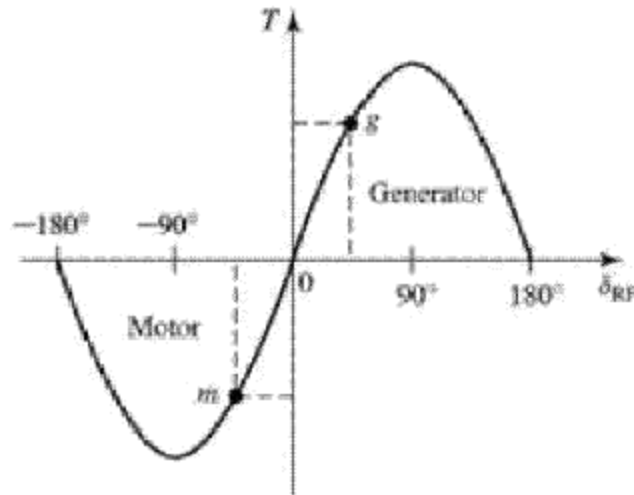
$$X_s I_a \cos \theta = E_f \sin \delta$$

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

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

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

The variation of power as derived above with respect to power-angle 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 **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 synchroscope.

The synchronizing lamp method 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 will then be 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:

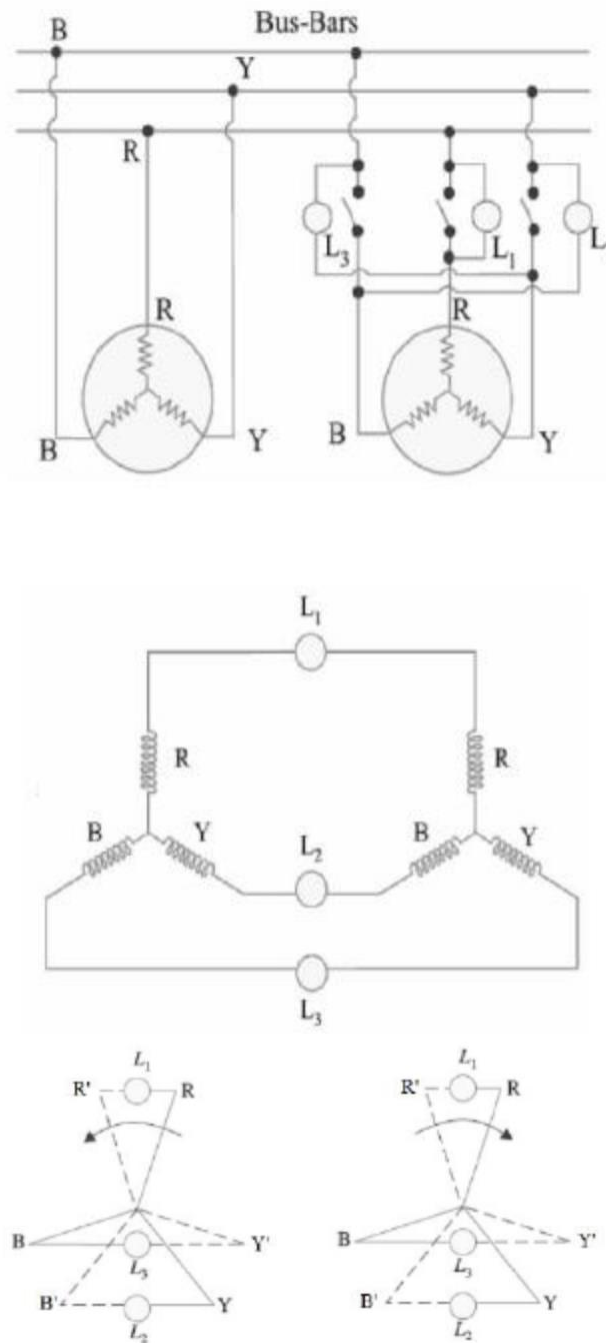


Fig: 2.6

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 synchroscope 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.

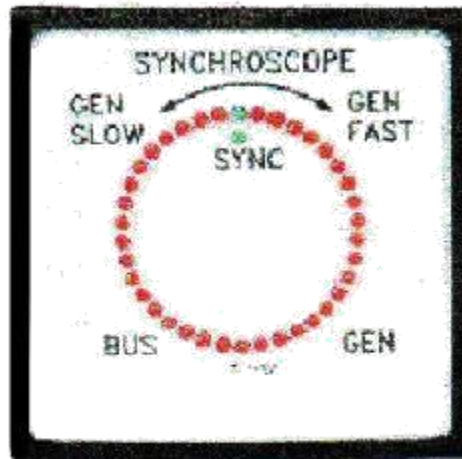
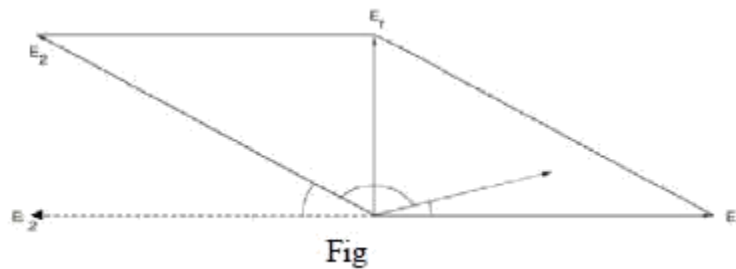


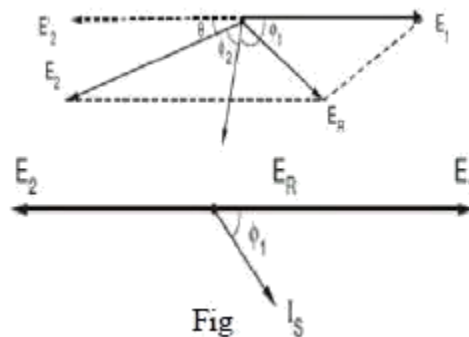
Fig:

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. E_1 is equal to and in phase opposition to emf of alternator 2, i.e. E_2 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 δ . 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 I_s is very nearly in quadrature with the resultant emf E_r acting on the circuit. Figure represents a single phase case, where E_1 and E_2 represent the two induced emfs, the latter having fallen back slightly in phase. The resultant emf, E_r , is almost in quadrature with both the emfs, and gives rise to a current, I_s , lagging behind E_r by an angle approximating to a right angle. It is, thus, seen that E_1 and I_s are almost in phase. The first alternator is generating a power $E_1 I_s \cos 1$, which is positive, while the second one is generating a power $E_2 I_s \cos 2$, 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 I_s 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, I_s , is called the synchronizing current.



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 $\cos$, each alternator delivers half the total current and $I_1 = I_2 = I/2$.



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, I_s , is zero. Since the armature resistance is neglected, the vector difference between $E_1 = E_2$ and V is equal to, $I_1 X_{s1} - I_2 X_{s2}$, this vector leading the current I by 90° , 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

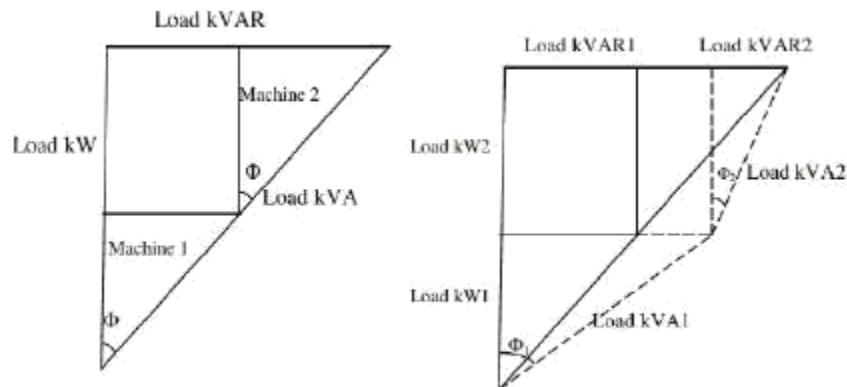


Fig: 2.9

Sharing of load when two alternators are in parallel Consider two alternators with identical speed load characteristics connected in parallel as shown in Fig:

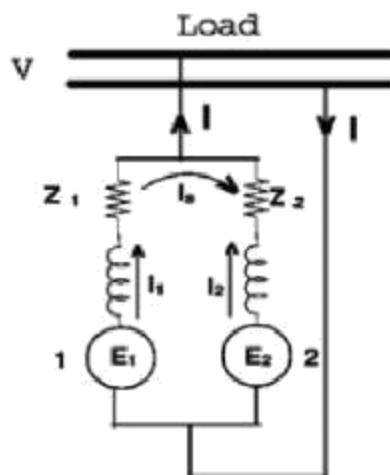


Fig:

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 $V = E_1 - I_1 Z_1 = E_2 - I_2 Z_2$ and
 hence, $I_1 = (E_1 - V) / Z_1$ and $I_2 = (E_2 - V) / Z_2$ and also $V = (I_1 + I_2) Z$

solving above equations

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

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

$$\text{The total current } I = I_1 + I_2 = [E_1 Z_2 + E_2 Z_1] / [Z(Z_1 + Z_2) + Z_1 Z_2]$$

$$\text{And the circulating current or synchronizing current } I_s = (E_1 - E_2) / (Z_1 + Z_2)$$

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

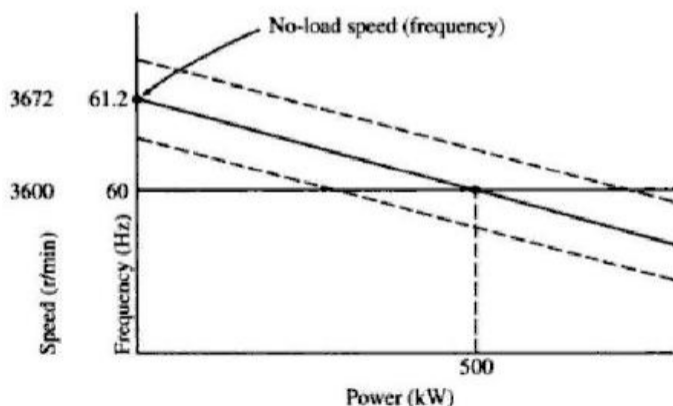
Governor speed regulation (GSR) is defined as:

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

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)



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

UNIT – IV SYNCHRONOUS MOTORS

Theory of Operation – Phasor Diagram – Power Flow Equations in Synchronous Motors- Variation of Current and Power Factor with Excitation – V and Inverted V Curves – Synchronous Condensers – Hunting, and Methods to Eliminate Hunting – Starting Methods of Synchronous Motor – Synchronous Induction Motor - Construction, Principle of operation and control of Brushless DC motor.

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.

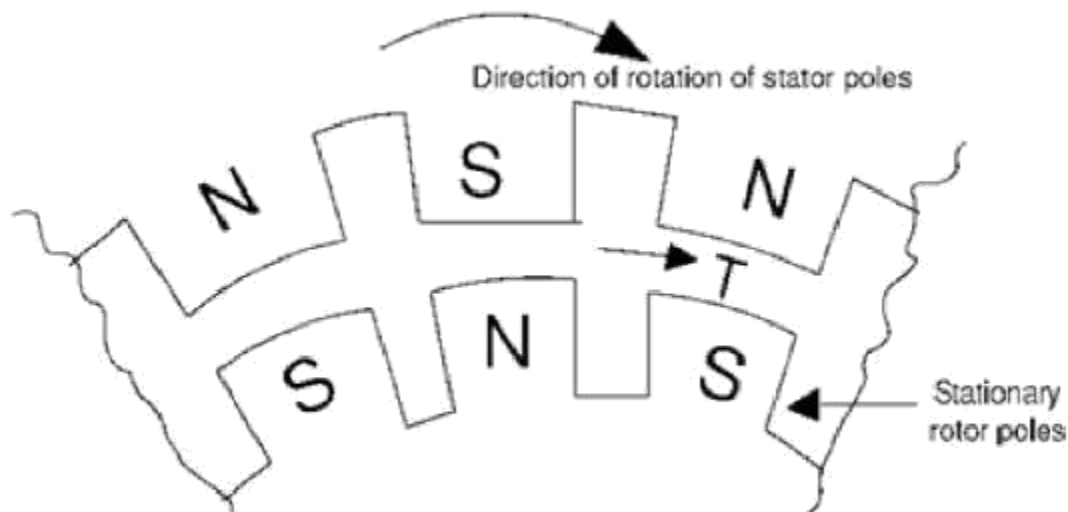


Fig:

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.

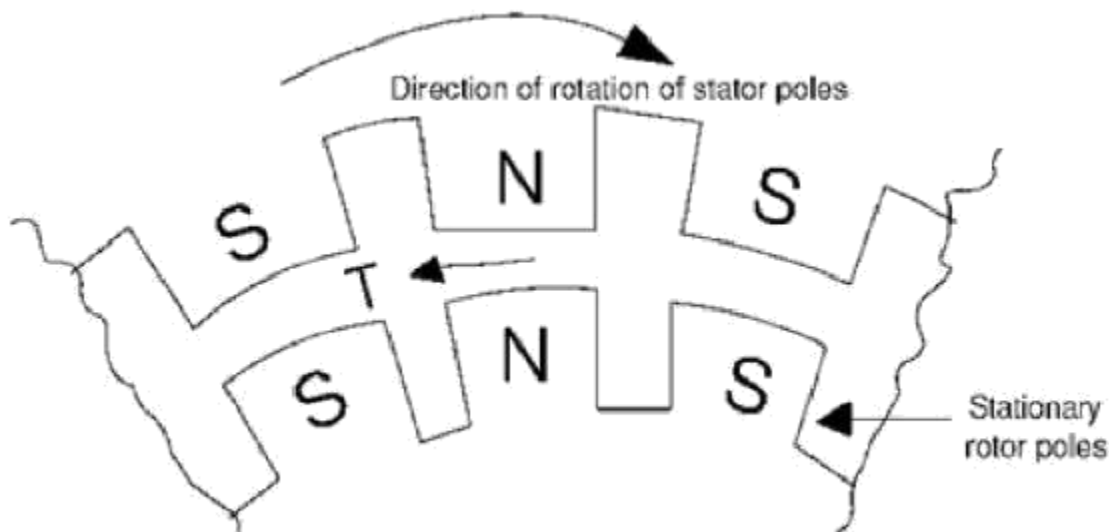


Fig:

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 NS and SS. The motor has direct voltage applied to the rotor winding and a 3-phase voltage applied to the stator winding. The stator winding produces a rotating field which revolves round

the stator at synchronous speed $N_s (= 120 f/P)$. 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., NS - SS) and a pair of stationary rotor poles (i.e., NR - SR).

(ii) Suppose at any instant, the stator poles are at positions A and B as shown in Fig: 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 $\frac{1}{2} f = 1/100$ 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.

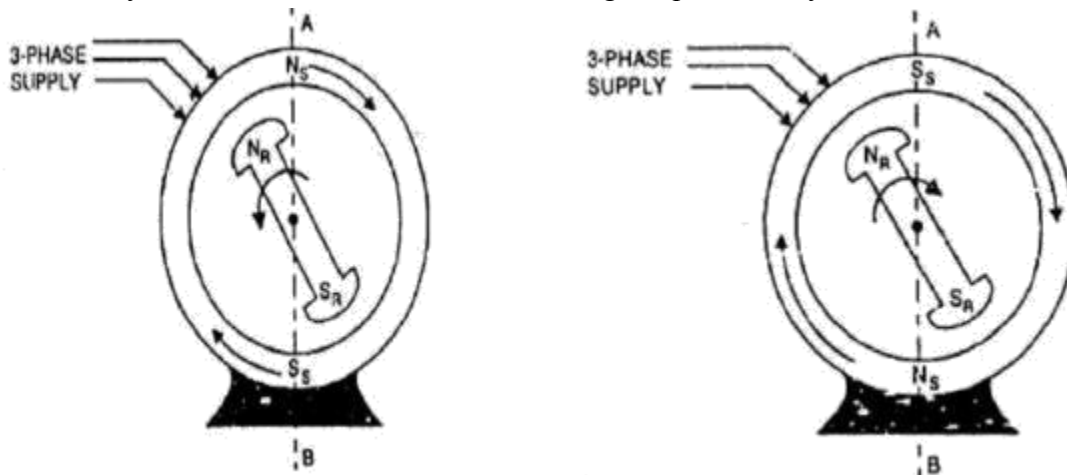


Fig:

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 X_s . A resistance R_a 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.

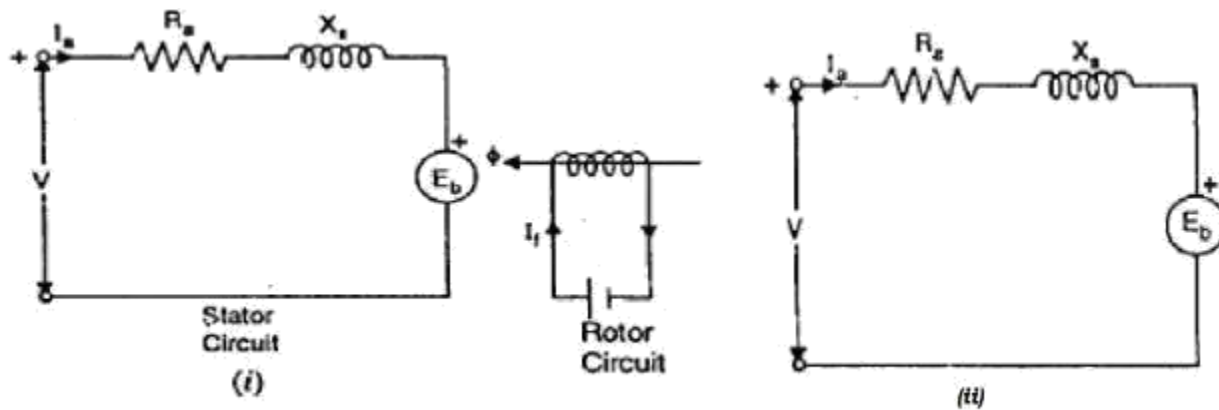


Fig:

(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 $E_r = V - E_b$ 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 $E_b = V$. If the field excitation is such that $E_b < V$, the motor is said to be under-excited. The motor is said to be over-excited if the field excitation is such that $E_b > V$. 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 ($E_b = V$), 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 E_r and, therefore, the stator current I_a 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 (I_a) is minimum at unity p.f and increases as the p.f. becomes less either leading or lagging

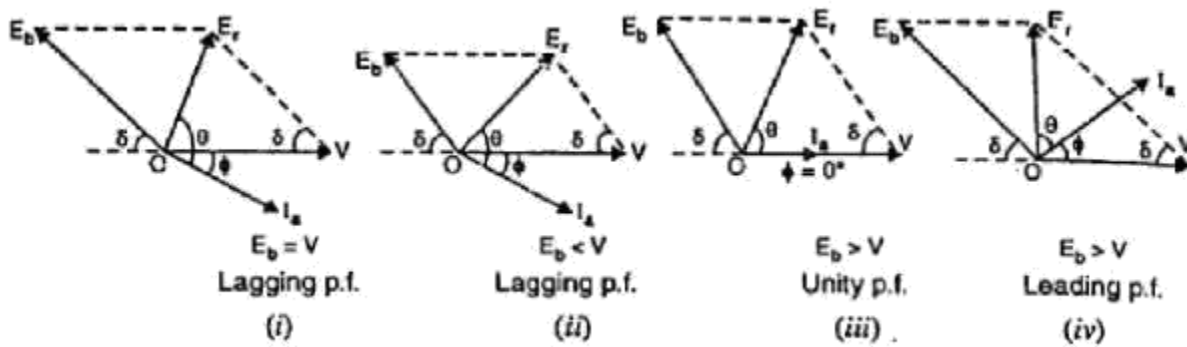


Fig: 2.24

Torque and Power Relations Motor Torque

Gross torque, $T = 9.55 P_m / N_s$ N-M where P_m = Gross motor output in watts = $E_b I_a \cos(\delta - \phi)$ N_s = Synchronous speed in r.p.m.

Shaft torque, $T_{sh} = 9.55 P_{shout} / N_s$ N-M

It may be seen that torque is directly proportional to the mechanical power because rotor speed (i.e., N_s) 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 R_a is assumed zero, $\tan \theta = X_s / R_a = \infty$ and hence $\theta = 90^\circ$.

Input power/phase = $V I_a \cos \phi$

Since R_a is assumed zero, stator Cu loss $(I_a R_a)^2$ will be zero. Hence input power is equal to the mechanical power P_m developed by the motor.

Mechanical power developed/ phase, $P_m = V I_a \cos \phi$, referring to the phasor diagram in Fig. .

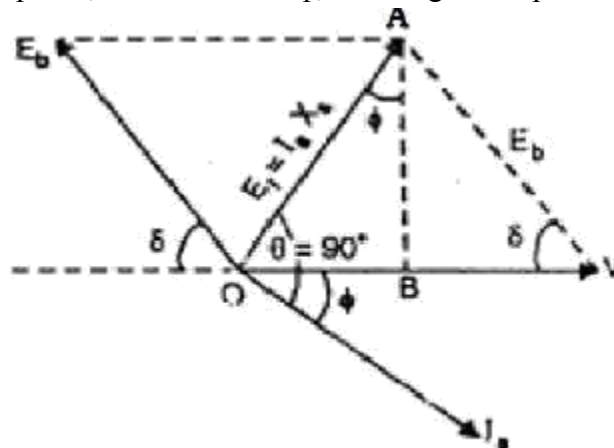


Fig:

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

$$AB = E_b \sin \delta$$

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

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

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

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

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

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

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

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

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 I_a 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.

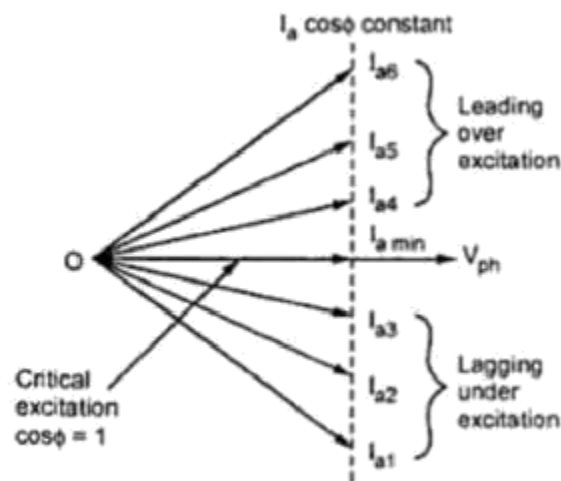


Fig: 2.26

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 (I_a) 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 ($\cos \phi$) 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 I_f at various load conditions are called Inverted V-curves of synchronous motor. These curves are shown in the Fig: 2.27 (b).

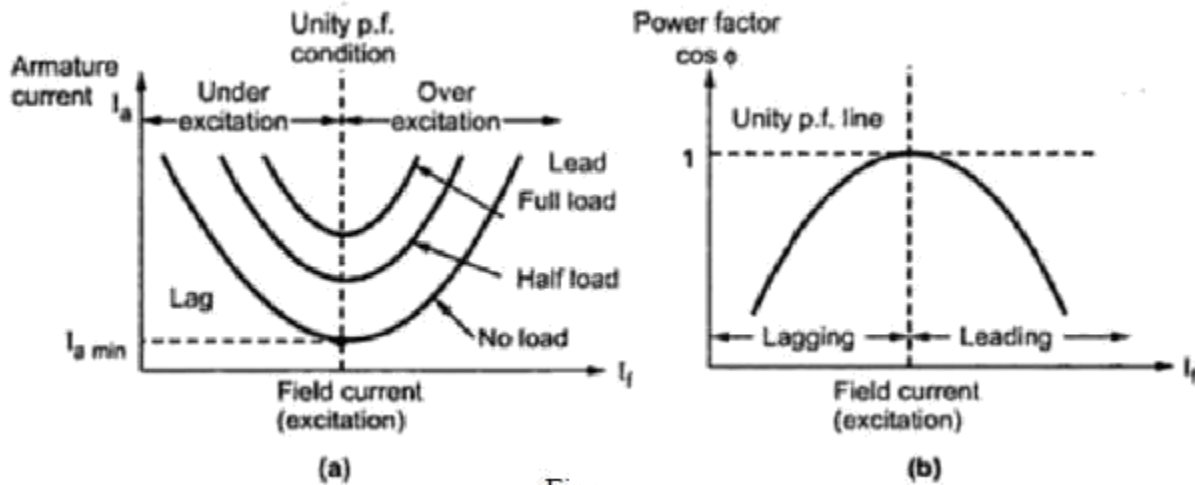


Fig:

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 I_a is determined by dividing the difference between V and E_b by the armature resistance R_a . Similarly, in a synchronous motor, the stator current (I_a) is determined by dividing voltage-phasor resultant (E_r) between V and E_b by the synchronous impedance Z_s . 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 ($=3 V \cdot I_a \cdot \cos \phi$) is also constant. This means that the in-phase component $I_a \cos \phi$ drawn from the supply will remain constant. If the field excitation is changed, back e.m.f E_b also changes. This results in the change of phase position of I_a w.r.t. V and synchronous motor for different values of field excitation. Note that extremities of current phasor I_a lie on the straight line AB . hence the power factor $\cos \phi$ of the motor changes. Fig: shows the phasor diagram of the synchronous motor.

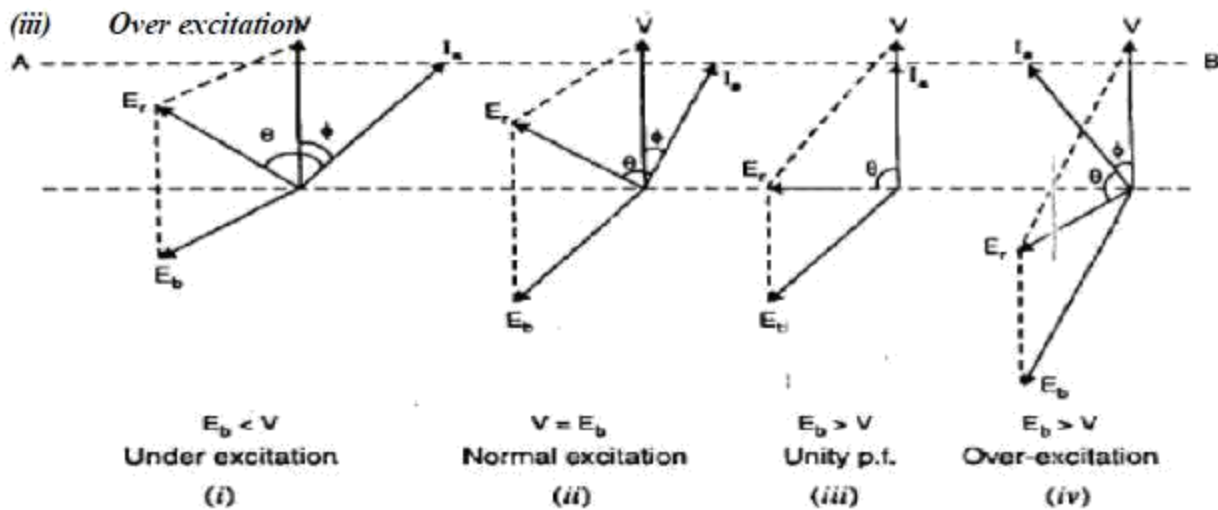
(i) Under excitation The motor is said to be under-excited if the field excitation is such that $E_b < V$.

Under such conditions,

the current I_a lags behind V so that motor power factor is lagging as shown in Fig: (i). This can be easily explained. Since $E_b < V$, the net voltage E_r is decreased and turns clockwise. As angle ($= 90^\circ$) between E_r and I_a is constant, therefore, phasor I_a also turns clockwise i.e., current I_a 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 $E_b = V$. This is shown in Fig: 2.28 (ii). Note that the effect of increasing excitation (i.e., increasing E_b) is to turn the phasor E_r and hence I_a in the anti-clockwise direction i.e., I_a phasor has come closer to phasor V . Therefore, p.f. increases though still lagging. Since input power ($=3 V \cdot I_a \cdot \cos \phi$) is unchanged, the stator current I_a must decrease with increase in p.f. Suppose the field excitation is increased until the current I_a

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 E_r and, therefore, I_a are minimum.



- (iii) Over Excitation: The motor is said to be overexcited if the field excitation is such that $E_b > V$. Under such conditions, current I_a leads V and the motor power factor is leading as shown in Fig: 2.28 (iv). Note that E_r and hence I_a further turn anti-clockwise from the normal excitation position. Consequently, I_a 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 (I_a) 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 is 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 - ϕ load takes current I_L at low lagging power factor $\cos \phi_L$. The synchronous condenser takes a current I_m which leads the voltage by an angle ϕ_m . The resultant current I is the vector sum of I_m and I_L and lags behind the voltage by an angle ϕ . It is clear that ϕ is less than ϕ_L so that $\cos \phi$ is greater than $\cos \phi_L$. Thus the power factor is increased from $\cos \phi_L$ to $\cos \phi$. Synchronous condensers are generally used at major bulk supply substations for power factor improvement.

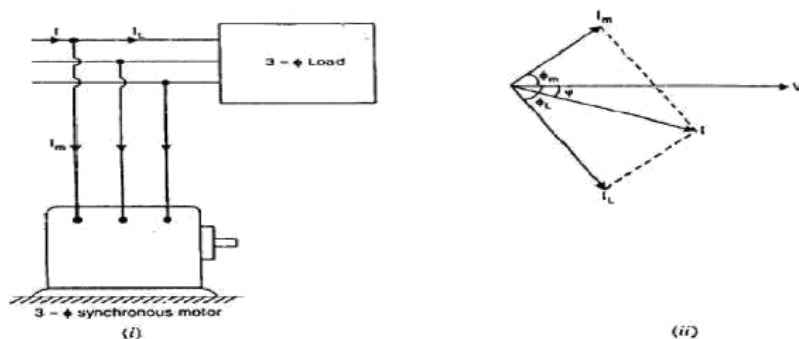


Fig.

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.

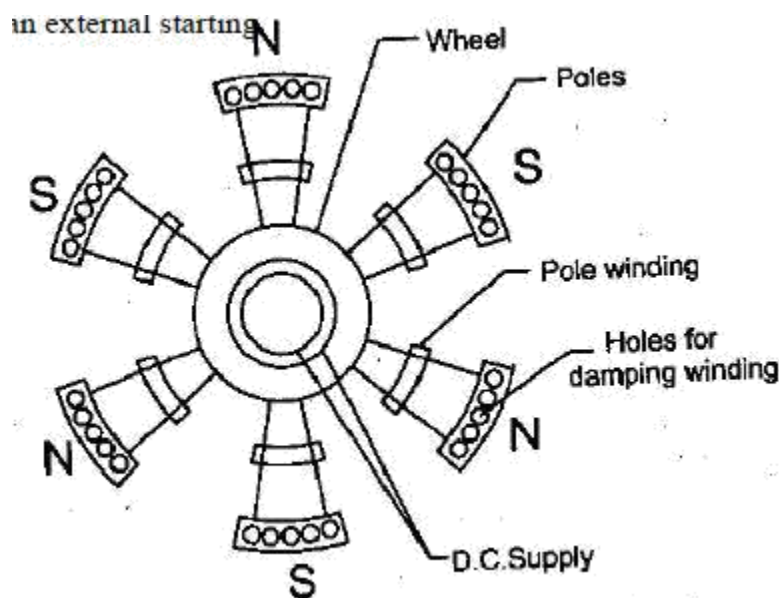
But the usual power supply systems generally regulate the frequency to be 50 or 60 Hz as the case may be. However, variable-frequency voltage source can be obtained from a dedicated generator only in the olden days and such a situation was obviously impractical except for very unusual or special drive 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) $E_A = K\phi\omega$ will be smaller than normal. As such the terminal voltage 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 BR 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 $I_a \cos \phi$ and $E_f \sin \delta$ are doubled. While redrawing the phasor diagrams to show new steady-state conditions, the line of action of the new $jI_a X_s$ phasor must be perpendicular to the new I_a phasor. Furthermore, as shown in Fig: if the excitation is not changed, increasing the shaft load causes the locus of the E_f 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 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.

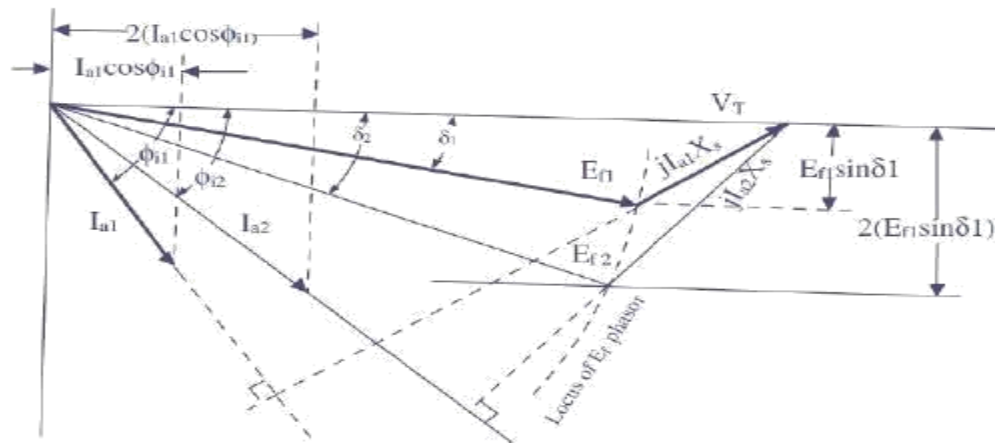


Fig:

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 $E_f \sin \delta$ must also be constant. An increase in E_f will cause a transient increase in $E_f \sin \delta$, and the rotor will accelerate. As the rotor changes its angular position, δ decreases until $E_f \sin \delta$ 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 E_f 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 I_a phasor is a line perpendicular to the V_T phasor.

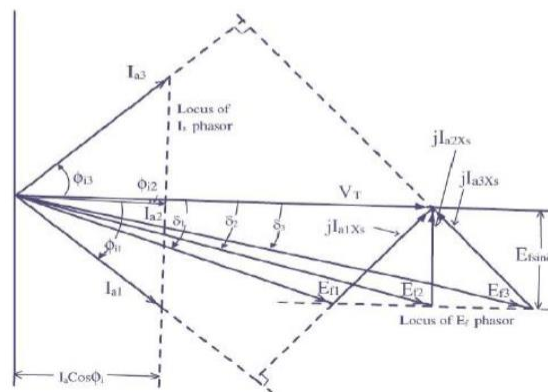


Fig:

Note that increasing the excitation from E_{f1} to E_{f3} in Fig: caused the phase angle of the current phasor with respect to the terminal voltage V_T (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, $|E_f| > |V_T|$. 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.

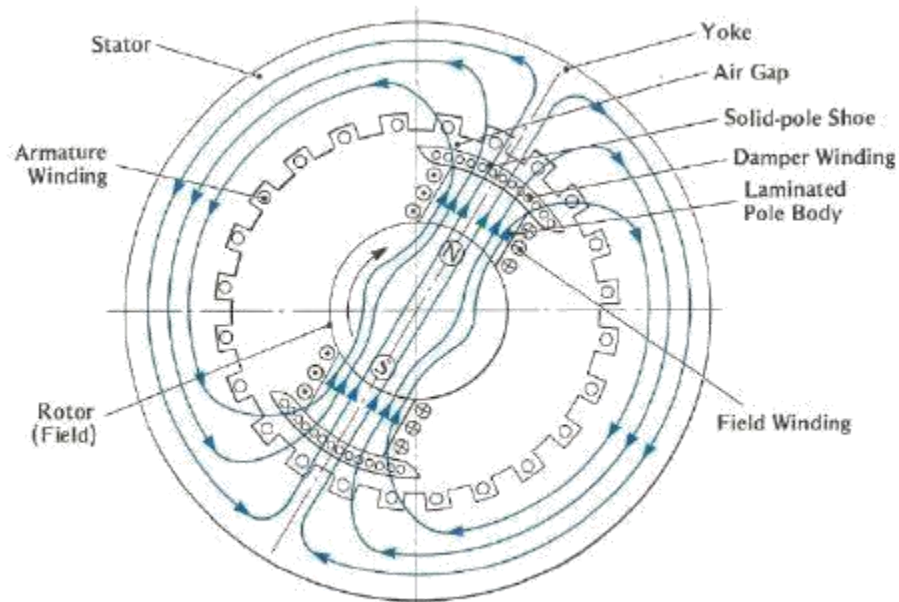


Fig:

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 – V**SINGLE PHASE AND SPECIAL MOTORS**

Single Phase Induction Motors - Constructional Features – Double Revolving Field Theory- Elementary Idea of Cross Field Theory – Split Phase Motors – Capacitor Start and Run Motors – Shaded Pole Motor. Principle and Performance of A.C Series Motor - Universal Motor – Single Phase Synchronous Motors – Reluctance Motor – Hysteresis Motor – Stepper Motor.

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

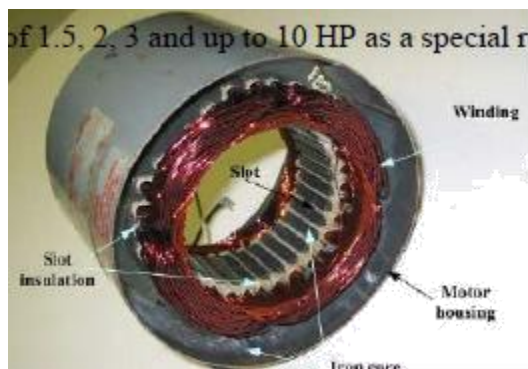
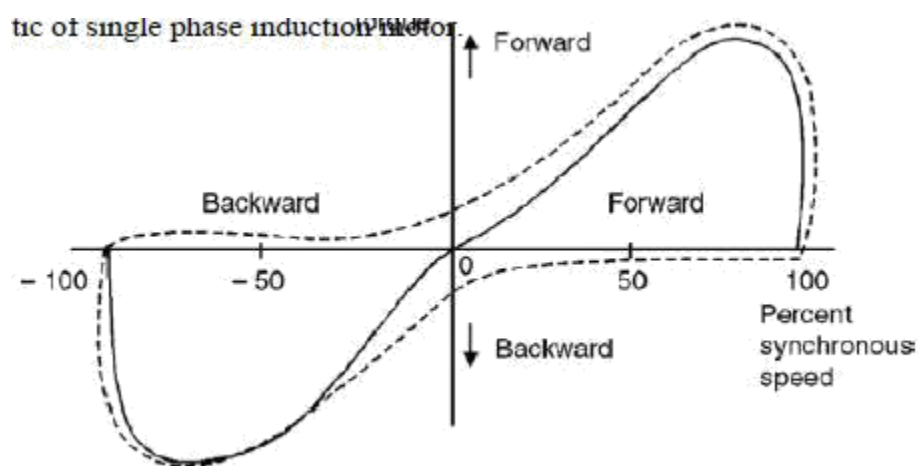


Fig: (a) Stator



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.



Such an alternating field 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:

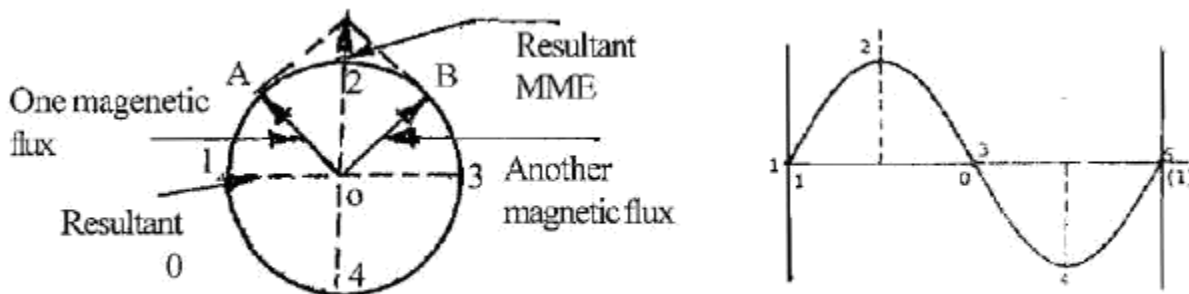


Fig: (b)

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.

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 polyphase induction motor. The main difference is that the single phase motor does not produce a rotating magnetic field but produces only a pulsating field. Hence, to produce the rotating magnetic field for self-starting, phase splitting is to be done to make the motor to work as a 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 field to produce a revolving field. 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 form a revolving magnetic field. There are several types of split phase motors.

TYPES OF SPLIT-PHASE INDUCTION MOTORS

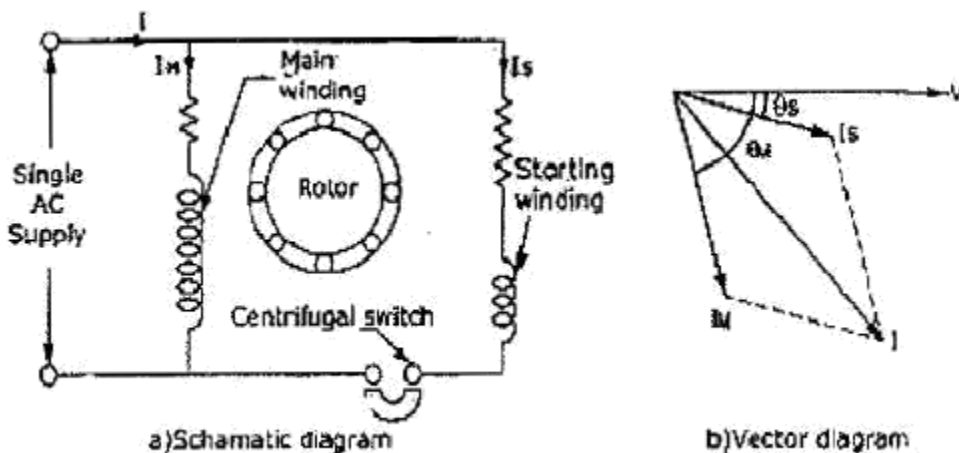
1. Resistance-start, induction-run motors
2. Capacitor-start, induction-run motors
3. Capacitor-start, capacitor-run motors
4. Shaded pole motors.

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).

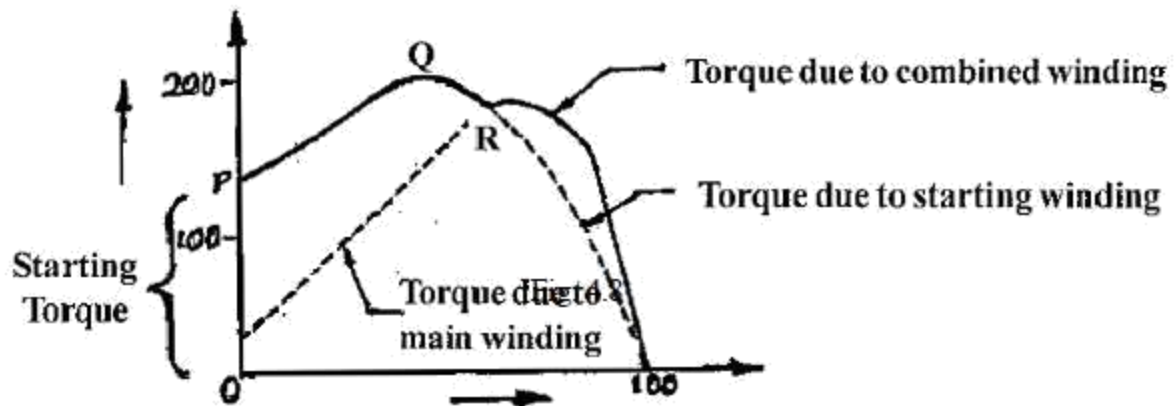


The starting current " I_s " will lag the main supply voltage " V " line by 15 degree and the main winding current. " I_m " main lags the main voltage by about 80 degree. Therefore, these currents will differ in time phase and their magnetic fields will combine to produce a rotating magnetic field. When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

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

CHARACTERISTICS

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



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.

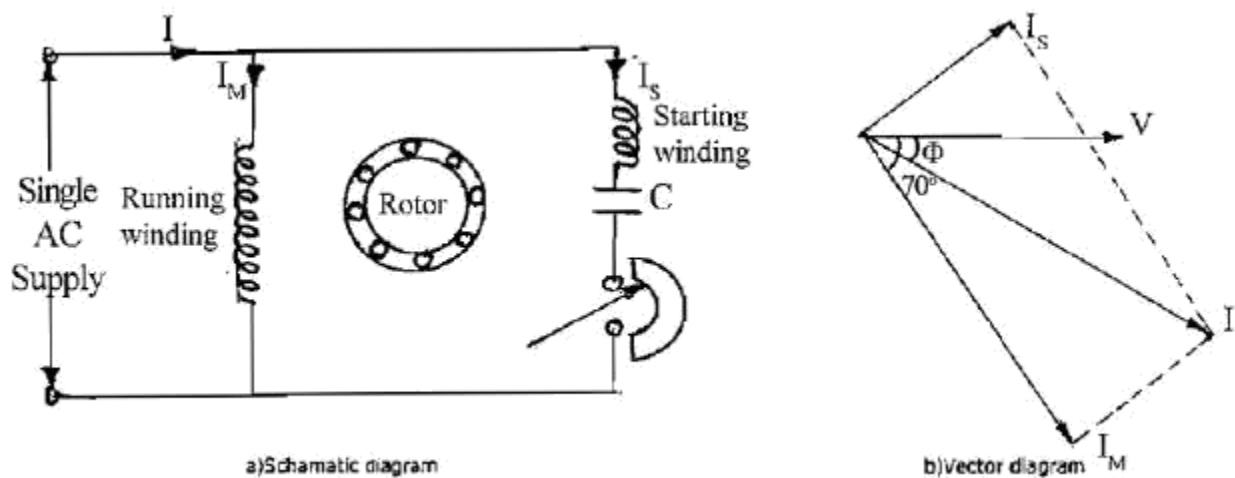
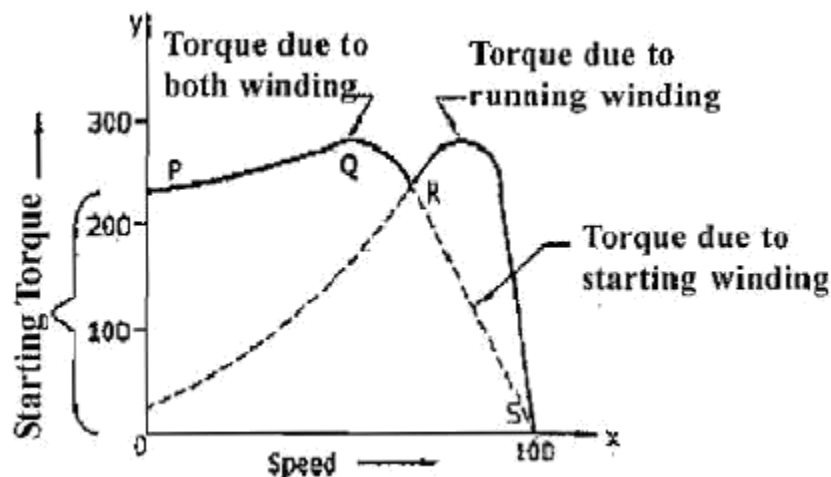


Fig:

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:.



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,

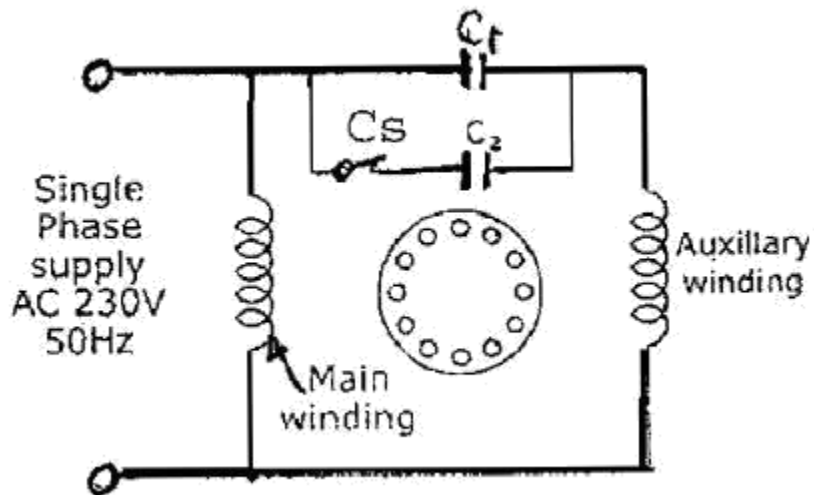
- Used in belted fans,
- Used in blowers dryers,
- Used in washing machines,
- Used in pumps and compressors.

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 is 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:.

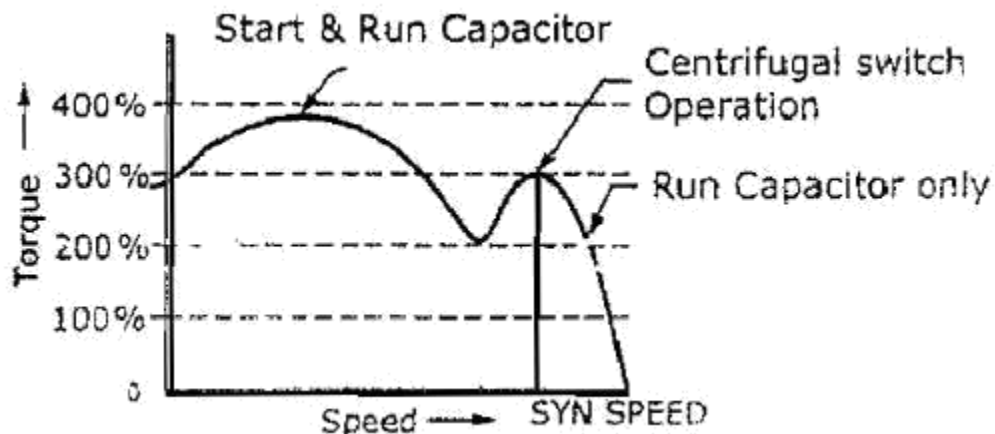


This motor also works in the same way as a capacitor-start, induction-run motor, with exception, that the capacitor C_1 is always in the circuit, altering the running performance to a great extent.

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:.



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.

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[$\propto$]. direction of the torque developed in a dc series motor is determined by both field 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:

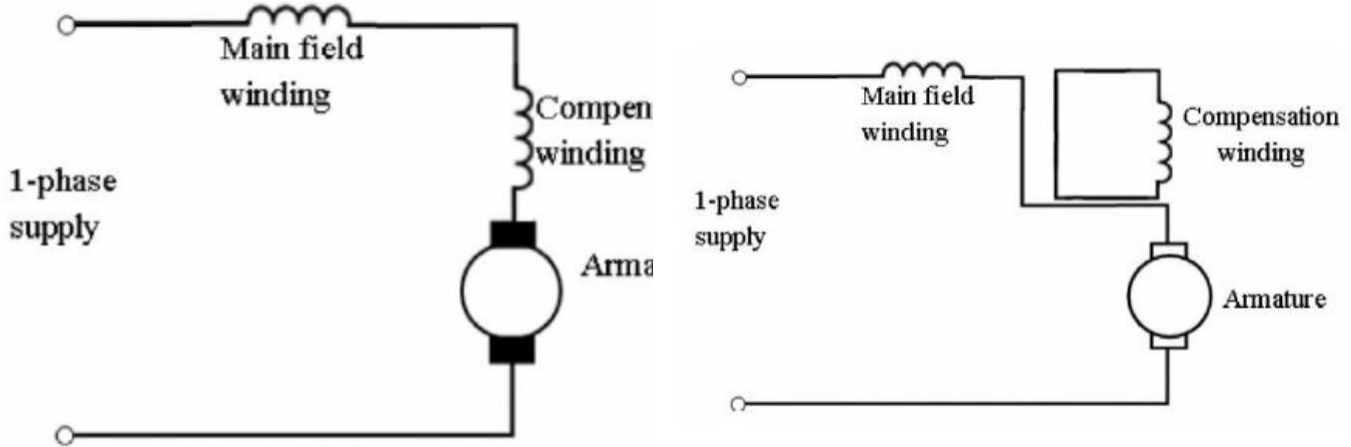
1. Its efficiency is low due to hysteresis and eddy-current losses.
2. The power factor is low due to the large reactance of the field and the armature winding.
3. The sparking at the brushes is excessive.

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:

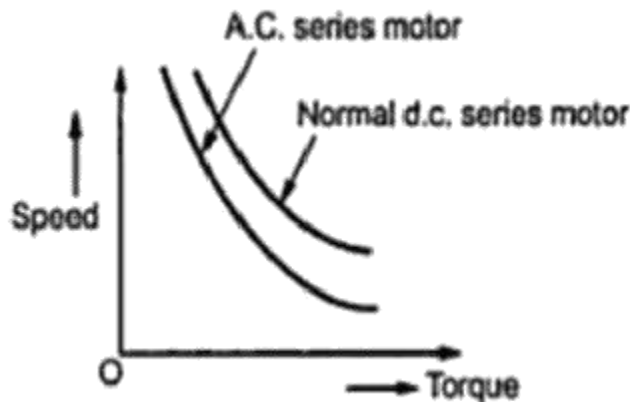
1. The field core is constructed of a material having low hysteresis loss. It is laminated to reduce eddy-current loss.
2. The field winding is provided with small number of turns. The field-pole areas is increased so that the flux density is reduced. This reduces the iron loss and the reactive voltage 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.

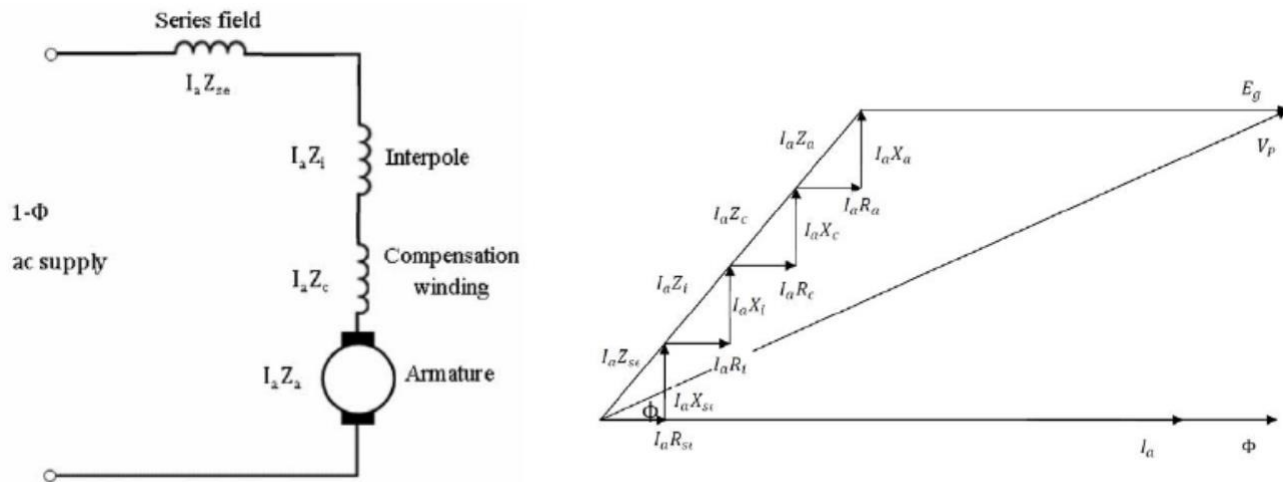


The characteristics of single-phase series motor are very much similar to those of D.C. series motors, but the series motor develops less torque when operating from an a.c. supply than when working from an equivalent D.C. supply [Fig:]. The direction of rotation can be changed by interchanging connections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



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.

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.



The resistance $I_a R_{se}$, $I_a R_i$, $I_a R_c$ and $I_a R_a$ 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 $I_a X_{se}$, $I_a X_i$, $I_a X_c$ and $I_a X_a$ are due to reactance of series field, interpole winding, compensating winding and of armature respectively lead current I_a by 90°. 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.

$$V_p = E_g + I_a Z_{se} + I_a Z_i + I_a Z_c + I_a Z_a$$

The power factor angle between V_p and I_a is .

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.

Hysteresis Motor

Hysteresis motor is defined as a synchronous motor that is having cylindrical rotor and works on hysteresis losses induced in the rotor of hardened steel with high retentivity. It is a single phase motor and its rotor is made of ferromagnetic material with non magnetic support over the shaft.

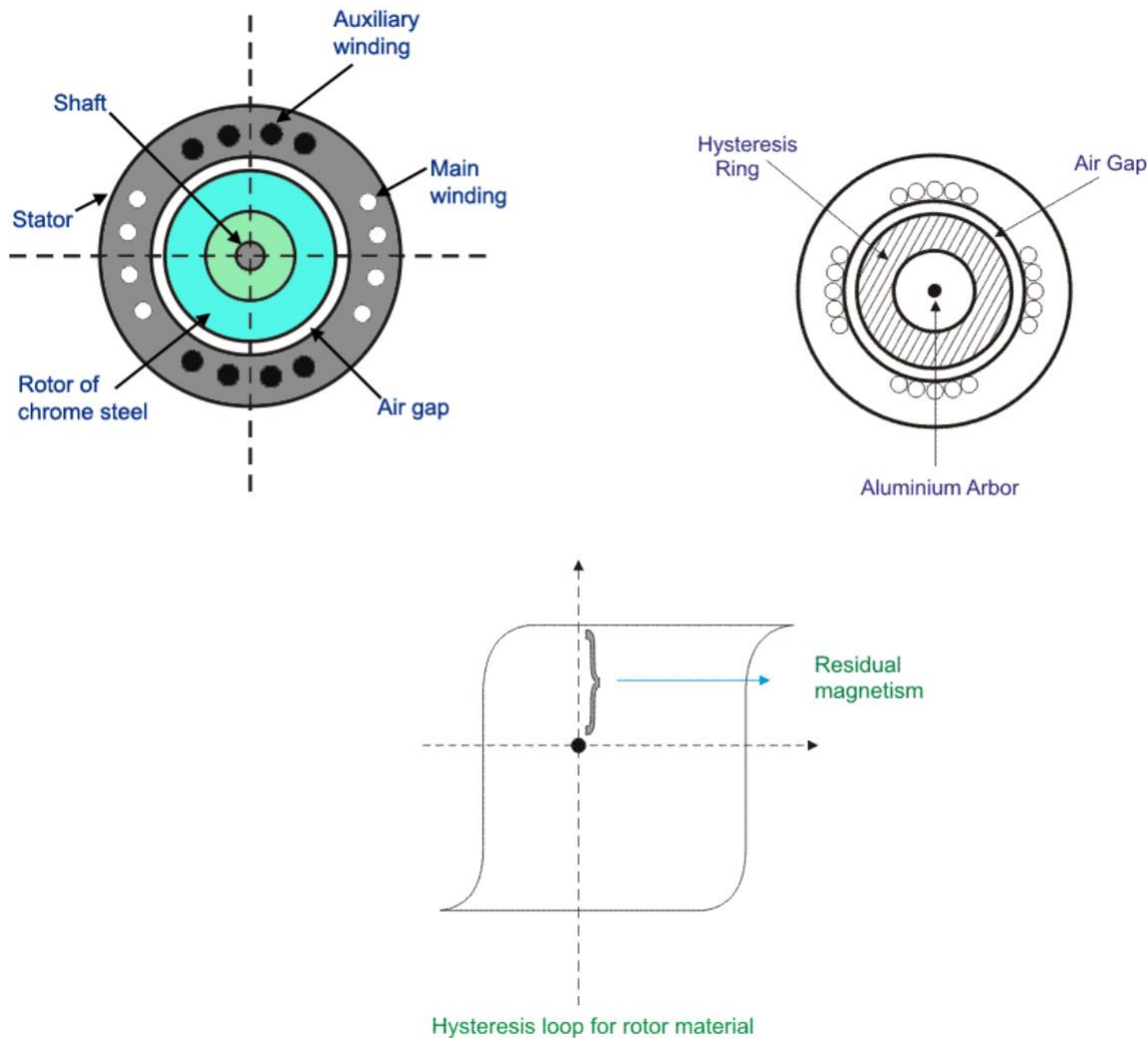
Constructional Feature of Hysteresis Motor

It consists of

1. Stator
2. Single phase stator winding
3. Rotor
4. Shaft
5. Shading coil

Stator: **Stator of hysteresis motor** is designed in a particular manner to produce synchronous revolving field from single phase supply. Stator carries two windings, (a) main winding (b) auxiliary winding. In another type of design of **hysteresis motor** the stator holds the poles of shaded type.

Rotor: Rotor of hysteresis motor is made of magnetic material that has high hysteresis loss property. Example of this type of materials is chrome, cobalt steel or alnico or alloy. Hysteresis loss becomes high due to large area of hysteresis loop. Rotor does not carry any winding or teeth. The magnetic cylindrical portion of the rotor is assembled over shaft through arbor of non magnetic material like brass. Rotor is provided with high resistance to reduce eddy current loss.



Working Principle of Hysteresis Motor

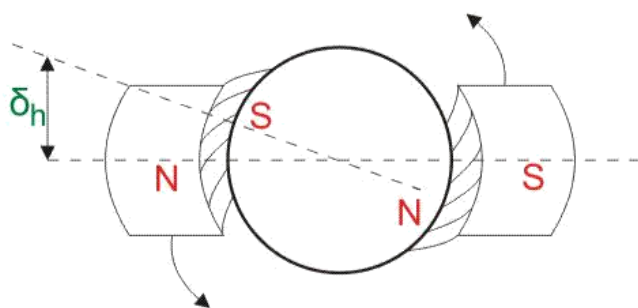
Starting behavior of a **hysteresis motor** is like a single phase induction motor and running behavior is same as a synchronous motor. Step by step its behavior can be realized in the working principle that is given below. **At the Starting Condition**

- When stator is energized with single phase AC supply, rotating magnetic field is produced in stator.
- To maintain the rotating magnetic field the main and auxiliary windings must be supplied continuously at start as well as in running conditions.
- At the starting, by induction phenomenon, secondary voltage is induced in the rotor by stator rotating magnetic field. Hence eddy current is generated to flow in the rotor and it develops rotor.
- Thus eddy current torque is developed along with the hysteresis torque in the rotor. Hysteresis torque in the rotor develops as the rotor magnetic material is with high hysteresis loss property and high retentivity.

- The rotor goes under the slip frequency before going to the steady state running condition.
- So it can be said that when the rotor starts to rotate with the help of these eddy current torque due to induction phenomenon, it behaves like a single phase induction motor.

At Steady State Running Condition

- When the speed of the rotor reaches near about the synchronous speed, the stator pulls the rotor into synchronism.
- At the condition of synchronism, the relative motion between stator field and rotor field vanishes. So there is no further induction phenomenon to continue. Hence no eddy current to generate in the rotor. Thus the torque due to eddy-currents vanishes.
- At the time of rotor's rotation at the synchronous speed, rotating magnetic field flux in the stator produces poles on the rotor by induction; they are named as north (N) and south (S) poles. Thus rotor behaves as a permanent magnet having rotor axis as the induced magnetic axis.
- For high residual magnetism or retentivity the rotor pole strength remains sustainable or unchanged. Again higher the retentivity, higher is the hysteresis torque and the hysteresis torque is independent of the rotor speed always. The high retentivity enables the continuous magnetic locking between stator and rotor and thus the motor rotates at synchronous speed.
- The maximum work done to establish the hysteresis losses under the magnetization cycle in the rotor is equal to the surface area inside B-H hysteresis curve.
- In lower load torque, the needed work done to rotate the rotor is equal to maximum magnetizing work of hysteresis phenomenon available already in the rotor. So induced magnetic pole axis always follows the rotating magnetic field axis of stator without any lag angle.
- But when the load torque is sufficiently high, the maximum magnetizing work in rotor by hysteresis phenomenon cannot fulfill the work done needed to rotate the rotor.
- So the induced magnetic field axis or rotor pole axis lags the rotating magnetic field axis of the stator at an angle δ_h . Hence the rotor pole axis tries to catch up the stator magnetic field axis.
- If the load torque is increased, this lagging angle will be increased up to $\delta_{\max}$ before dropping below the synchronous condition.
- The rotor poles are attracted towards the moving stator poles and runs at synchronous speed.



- As there is no slip at steady state running condition, only hysteresis torque is present to keep the rotor running at synchronous speed and it behaves like a synchronous motor.

Hysteresis Power Loss, P_h in Hysteresis Motor

Hysteresis power loss in the rotor of the hysteresis motor is given by $P_h = k_h f_r B_{\max}^n$. Where, f_r is the frequency of flux reversal in the rotor (Hz) $B_{\max}$ is the maximum value of flux density in the air gap (T) P_h is the heat-power loss due to hysteresis (W) k_h is the hysteresis constant

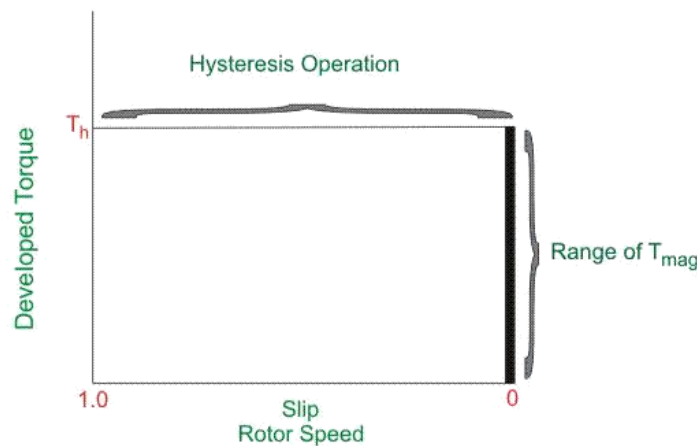
Equation of Hysteresis Torque in the Hysteresis Motor

$$\begin{aligned}
 P_{mech} &= P_h \left(\frac{1-s}{s} \right) & T_h &= \left(\frac{5252 k_h \cdot f \cdot B_{max}^n}{n_s} \right) \\
 P_h &= k_h \cdot f \cdot B_{max}^n \\
 \frac{T_h n_r}{5252} &= k_h \cdot f \cdot B_{max}^n \left(\frac{1-s}{s} \right) & n_s &= \frac{120 \cdot f_s}{P} \\
 n_r &= n_s (1-s) & T_h &= \frac{5252 k_h B_{max}^n}{\frac{120}{P}} \\
 f_r &= s f_s
 \end{aligned}$$

From the equation of the hysteresis torque, it is clear that hysteresis torque is independent of frequency and speed.

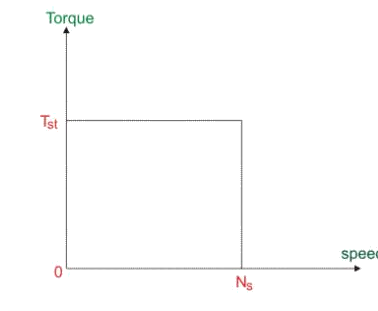
Torque-Speed Characteristic of Hysteresis Motor

Torque-speed characteristics of hysteresis motor is given below. We know that constant Hysteresis Torque occurs in the hysteresis motor. This constant valued torque allows the motor to synchronize any load it can accelerate. The normal operating range is mentioned with dark vertical line.



Speed-Torque Characteristics

The speed-torque characteristics of a hysteresis motor is shown below. The torque is almost constant from starting to running condition. At starting condition the starting torque is the eddy current torque along with the hysteresis torque. But in the running condition net running torque means only the hysteresis torque.



Starting Torque of the Hysteresis Motor

Suppose Φ_s is the stator flux at synchronous speed. Φ_r is the rotor flux. Due to hysteresis effect, Φ_r lags Φ_s at an angle α . Then the starting torque produced is given by $T_s = K \cdot \phi_s \times \phi_r \times \sin \alpha$ K is the proportional constant.

Types of Hysteresis Motors

There are various types of hysteresis motor by construction. They are

1. **Cylindrical hysteresis motors:** It has cylindrical rotor.
2. **Disk hysteresis motors:** It has annular ring shaped rotor.
3. **Circumferential-Field hysteresis motor:** It has rotor supported by a ring of non magnetic material with zero magnetic permeability.
4. **Axial-Field hysteresis motor:** It has rotor supported by a ring of magnetic material with infinite magnetic permeability.

Advantages of Use of Hysteresis Motor

The main **advantages of hysteresis motor** are given below.

- As no teeth and no winding in rotor, no mechanical vibrations take place during its operation.
- Its operation is quiet and noiseless as there is no vibration.
- It is suitable to accelerate inertia loads.
- Multi-speed operation can be achieved by employing gear train.

Disadvantages of use of Hysteresis Motor

The **disadvantages of hysteresis motor** are given below.

- **Hysteresis motor** has poor output that is one-quarter of output of an induction motor with same dimension.
- Low efficiency
- Low torque.
- Low power factor
- This type of motor is available in very small size only.

Applications of Hysteresis Motors

They are widely used in

1. Sound producing equipments,
2. Sound recording instruments,
3. High quality record players,
4. Timing devices
5. Electric clocks,
6. Teleprinters.

STEPPER MOTOR

It is a brushless electromechanical device which converts the train of electric pulses applied at their excitation windings into precisely defined step-by-step mechanical shaft rotation. The shaft of the motor rotates through a fixed angle for each discrete pulse. This rotation can be linear or angular. It gets one step movement for a single pulse input.



When a train of pulses is applied, it gets turned through a certain angle. The angle through which the stepper motor shaft turns for each pulse is referred as the step angle, which is generally expressed in degrees.

The number of input pulses given to the motor decides the step angle and hence the position of motor shaft is controlled by controlling the number of pulses. This unique feature makes the stepper motor to be well suitable for open-loop control system wherein the precise position of the shaft is maintained with exact number of pulses without using a feedback sensor.

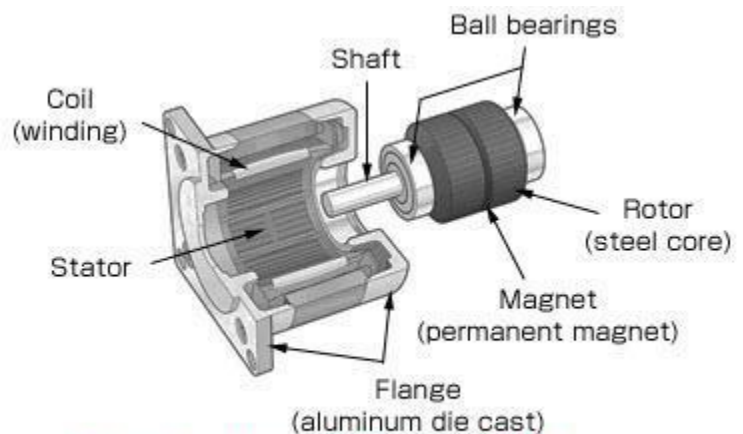
If the step angle is smaller, the greater will be the number of steps per revolutions and higher will be the accuracy of the position obtained. The step angles can be as large as 90 degrees and as small as 0.72 degrees, however, the commonly used step angles are 1.8 degrees, 2.5 degrees, 7.5 degrees and 15 degrees.

The direction of the shaft rotation depends on the sequence of pulses applied to the stator. The speed of the shaft or the average motor speed is directly proportional to the frequency (the rate of input pulses) of input pulses being applied at excitation windings. Therefore, if the frequency is low, the stepper motor rotates in steps and for high frequency, it continuously rotates like a DC motor due to inertia.

Like all electric motors, it has stator and rotor. The rotor is the movable part which has no windings, brushes and a commutator. Usually the rotors are either variable reluctance or permanent magnet kind. The stator is often constructed with multipole and multiphase windings, usually of three or four phase windings wound for a required number of poles decided by desired angular displacement per input pulse. Unlike other motors it operates on a programmed discrete control pulses that are applied to the stator windings via an electronic drive. The rotation occurs due to the magnetic interaction between poles of sequentially energized stator winding and poles of the rotor.

There are several types of stepper motors are available in today's market over a wide range of sizes, step count, constructions, wiring, gearing, and other electrical characteristics. As these motors are capable to operate in discrete nature, these are well suitable to interface with digital control devices like computers.

Due to the precise control of speed, rotation, direction, and angular position, these are of particular interest in industrial process control systems, CNC machines, robotics, manufacturing automation systems, and instrumentation.



Construction of Stepper Motor

Types of Stepper Motors

There are three basic **categories of stepper motors**, namely **permanent magnet stepper motor**, **variable reluctance stepper motor** and **hybrid stepper motor**. In all these motors excitation windings are employed in stator where the number of windings refer to the number of phases.

A DC voltage is applied as an excitation to the coils of windings and each winding terminal is connected to the source through a solid state switch. Depends on the type of stepper motor, its rotor design is constructed such as soft steel rotor with salient poles, cylindrical permanent magnet rotor and permanent magnet with soft steel teeth. Let us discuss these types in detail.

Variable Reluctance Stepper Motor

It is the basic type of stepper motor that has been in existence for a long time and it ensures easiest way to understand principle of operation from a structural point of view. As the name suggests, the angular position of the rotor depends on the reluctance of the magnetic circuit formed between the stator poles (teeth) and rotor teeth.

Construction of Variable Reluctance Stepper Motor:

It consists of a wound stator and a soft iron multi-tooth rotor. The stator has a stack of silicon steel laminations on which stator windings are wound. Usually, it is wound for three phases which are distributed between the pole pairs.

The number of poles on stator thus formed is equal to an even multiple of the number of phases for which windings are wound on stator. In the figure below, the stator has 12 equally spaced projecting poles where each pole is wound with an exciting coil. These three phases are energized from a DC source with the help of solid state switches.

The rotor carries no windings and is of salient pole type made entirely of slotted steel laminations. The rotor pole's projected teeth have the same width as that of stator teeth. The number of poles on stator differs to that of rotor poles, which provides the ability to self start and bidirectional rotation of the motor. The relation of rotor poles in terms of stator poles for a three phase stepper motor is given as, $N_r = N_s \pm (N_s / q)$. Here $N_s = 12$, and $q = 3$, and hence $N_r = 12 \pm (12 / 3) = 16$ or 8 . An 8-pole construction rotor without any excitation is illustrated below.

Working Variable Reluctance Stepper Motor:

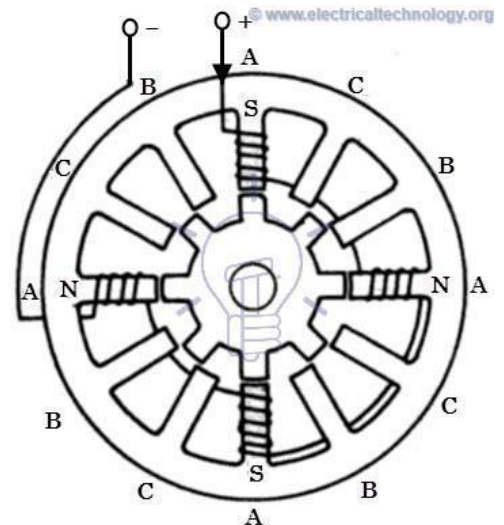
The stepper motor works on the principle that the rotor aligns in a particular position with the teeth of the excitation pole in a magnetic circuit wherein minimum reluctance path exist. Whenever power is applied to the motor and by exciting a particular winding, it produces its magnetic field and develops its own magnetic poles.

Due to the residual magnetism in the rotor magnet poles, it will cause the rotor to move in such a position so as to achieve minimum reluctance position and hence one set of poles of rotor aligns with the energized set of poles of the stator. At this position, the axis of the stator magnetic field matches with the axis passing through any two magnetic poles of the rotor.

When the rotor aligns with stator poles, it has enough magnetic force to hold the shaft from moving to the next position, either in clockwise or counter clockwise direction.

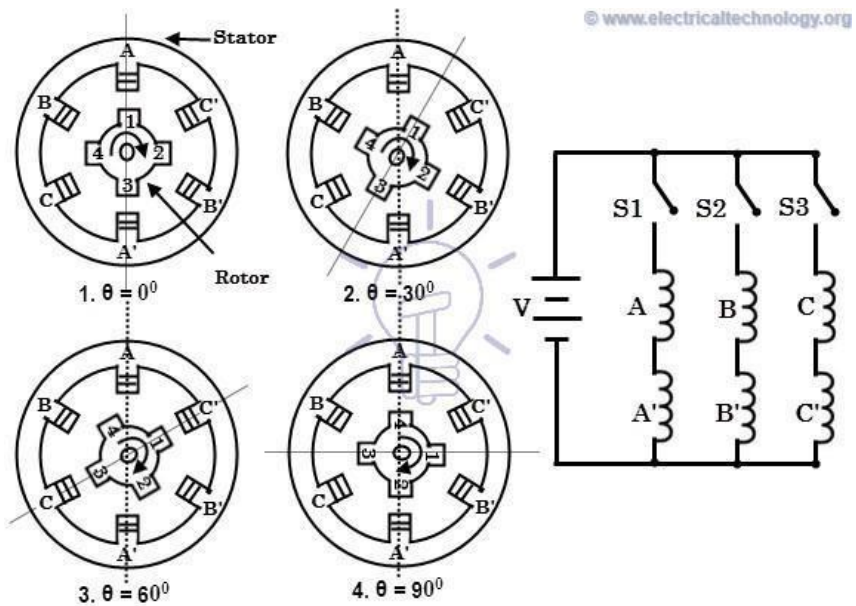
Consider the schematic diagram of a 3-phase, 6 stator poles and 4 rotor teeth is shown in figure below. When the phase A-A' is supplied with a DC supply by closing the switch -1, the winding become a magnet which results one tooth become North and other South. So the stator magnetic axis lies along these poles.

Due to the force of attraction, stator coil North Pole attracts nearest rotor tooth of opposite polarity, i.e., South and South Pole attract nearest rotor tooth of opposite polarity, i.e., North. The rotor then adjusts to its minimum reluctance position where the rotor magnetic axis exactly matches with stator magnetic axis.



When the phase B-B' is energized by closing switch -2 keeping phase A-A' remain de-energized by opening switch-1, winding B-B' will produce the magnetic flux and hence the stator magnetic axis shifts along the poles thus formed by it. Hence the rotor shifts to the least reluctance with magnetized stator teeth and rotates through an angle of 30 degrees in the clockwise direction.

When the switch-3 is energized after opening switch-2, the phase C-C' is energized, the rotor teeth align with new position by moving through an additional angle of 30 degrees. By this way, the rotor moves clockwise or counterclockwise direction by



successively exciting stator windings in a particular sequence. The step angle of this 3-phase 4-pole rotor teeth stepper motor is expressed as, $360 / (4 \times 3) = 30$ degrees (as step angle = $360 / N_r \times q$).

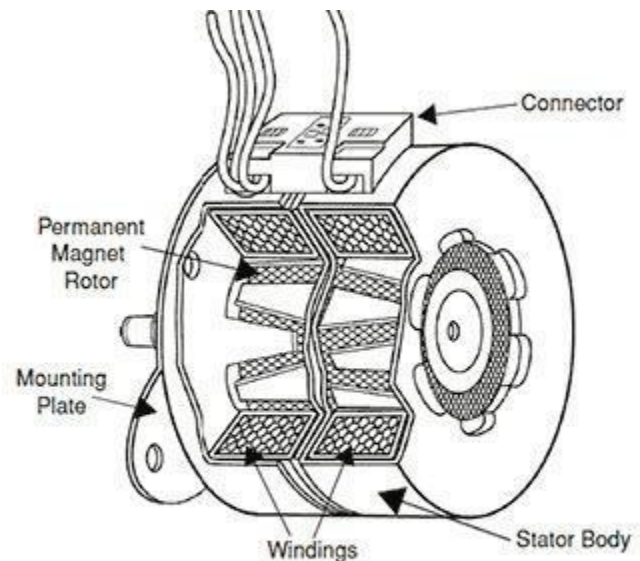
The step angle can be further reduced by increasing the number of poles on the stator and rotor, in such case motors are often wound with additional phase windings. This can also be achieved by adopting different construction of stepper motors such as multistack arrangement and reduction gear mechanism.

Permanent Magnet Stepper Motor

The permanent magnet design motor is perhaps the most common among several types of stepper motors. As the name implies, it adds permanent magnets to the motor construction. This type of stepper motors is also referred as **can-stack motor** or **tin-can motor**. The main advantage of this motor is its low manufacturing cost. This type of motor has 48-24 steps per revolution.

Construction Permanent Magnet Stepper Motor:

In this motor, the stator is of multipolar and its construction is similar to that of variable reluctance stepper motor as discussed above. It consists of slotted periphery on which stator coils are wound. It has projected poles on the slotted structure where the wound windings can be two or three or four-phase. The end terminals of all these windings are brought out and connected to the DC excitation via solid state switches in the drive circuit.



Permanent Magnet Stepper Motor Construction

The rotor is made up of a permanent magnet material like a ferrite that can be in the shape of either cylindrical or salient pole, but usually it is of smooth cylindrical type. The rotor designed to have an even number of permanent magnetic poles with alternate North and South polarities.

Working of Permanent Magnet Stepper Motor:

The operation of this motor works on the principle that unlike poles attract each other and like poles repel each other. When the stator windings are excited with a DC supply, it produces magnetic flux and establishes the North and South poles. Due to the force of attraction and repulsion between permanent magnet rotor poles and stator poles, the rotor starts moving up to the position for which pulses are given to the stator.

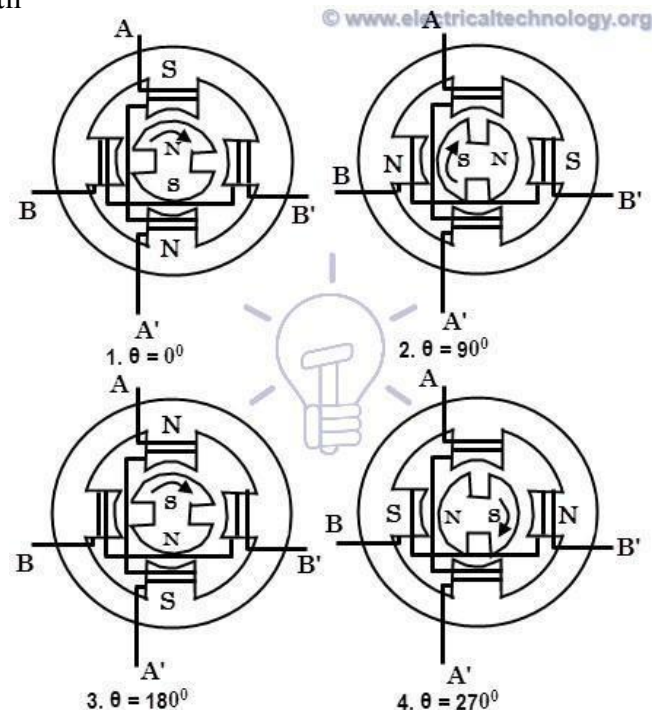
Consider a 2-phase stepper motor with two permanent magnetic rotor poles as shown in the figure below. When the phase A is energized with a positive with respect to the A', the windings establish North and South poles. Due to the force of attraction, the rotor poles align with stator poles such that the magnetic pole axis of rotor adjusts with that of stator as shown in figure.

When the excitation is switched to B phase and switching off phase A, the rotor further adjusts to magnetic axis of phase B, and thus rotates through 90 degrees in clockwise direction.

Next, if the phase A is energized with a negative current with respect to A', the formation of stator poles causes the rotor to move through another 90 degrees in clockwise direction.

In the same way, if the phase B is excited with negative current by closing phase A switch, the rotor rotates through another 90 degrees in the same direction. Next, if the phase A is excited with positive current, the rotor comes to the original position thus making a 360 degrees complete revolution. This implies that, whenever the stator is excited, the rotor tends to rotate through 90 degrees in clockwise direction.

The step angle of this 2-phase 2-pole permanent magnet rotor motor is expressed as, $360 / (2 \times 2) = 90$ degrees. The step size can be reduced by energizing two phases simultaneously or a sequence of 1-phase ON and 2-phase ON modes with a proper polarity.



Hybrid Stepper Motor

It is the most popular type of stepper motor as it provides better performance than permanent magnet rotor in terms of step resolution, holding torque and speed. However, these motors are more expensive than PM stepper motors. It combines the best features of both variable reluctance and permanent magnet stepper motors. These motors are used in applications that require very small stepping angle such as 1.5, 1.8 and 2.5 degrees.

Construction of Hybrid Stepper Motor:

The stator of this motor is same as its permanent magnet or reluctance type counterpart. The stator coils are wound on alternate poles. In this, the coils of different phases are wound on each pole, usually two coils at a pole which is referred as a bifilar connection.

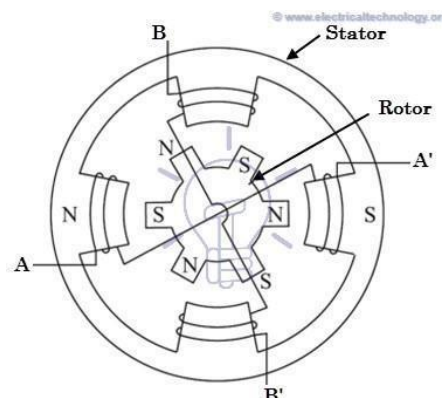
The rotor consists of a permanent magnet which is magnetized in axial direction to create a pair of magnetic poles (N and S poles). Each pole is covered with uniformly spaced teeth. The teeth are made up of soft steel and two section, of which on each pole are misaligned each other by a half-tooth pitch.

Working of Hybrid Stepper Motor:

This motor works similar to that of permanent magnet stepper motor. The figure above shows 2-phase, 4-pole, 6-tooth rotor hybrid stepper motor. When the phase A-A' is excited with a DC supply, keeping B-B' unexcited, the rotor aligns such that the south pole of the rotor faces north pole of the stator while north pole of rotor faces south pole of the stator.

Now, if the phase B-B' is excited, keeping A-A' switched off in such a way that upper pole becomes north and lower becomes south, then the rotor will align to a new position by moving through counterclockwise direction. If the phase B-B' is oppositely excited such that the upper pole becomes south and lower becomes north, then the rotor will turn clockwise direction.

By a proper sequence of pulses to the stator, the motor will turn in desired direction. For every excitation, rotor will get locked into new position, and even if excitation is removed motor still maintains its locked condition due to the permanent magnet excitation. The step angle of this 2-phase, 4-pole, 6-tooth rotor motor is given as $360 / (2 \times 6) = 30$ degrees. In practice, hybrid motors are constructed with more number of rotor poles in order to get high angular resolution.

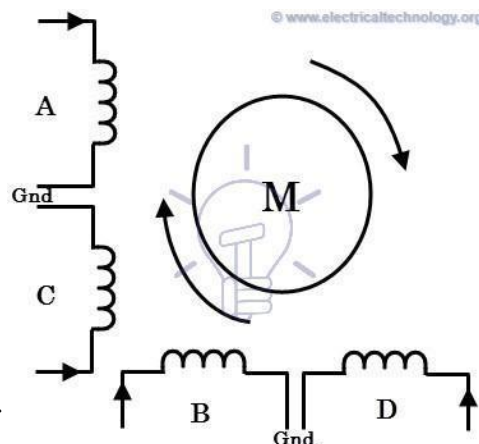


Unipolar and Bipolar Stepper Motors

The above discussed motors can be unipolar or bipolar based on the coil winding arrangements. A unipolar motor is employed with two windings per phase and hence the direction of current flow through these windings changes the rotation of the motor. In this configuration, the current flow is through one direction in one coil and opposite direction in another coil.

The figure below shows 2-phase unipolar stepper motor wherein A and C coils are for one phase and B and D are for other phase. In each phase each coil carries current in opposite direction to that of other coil. Only one coil will be carrying current at a time in each phase for achieving particular direction of rotation. So just by switching the terminals to each coil, the direction of rotation is controlled.

In case of a bipolar stepper motor, each phase consists of a single winding rather than two in case of unipolar one. In this, the direction of rotation is controlled by reversing the current through the windings. Hence, it requires a complex drive circuit for current reversal.



Stepping Modes of a Stepper Motor

A typical stepping action causes the motor to step through a sequence of equilibrium positions in response to current pulses given to it. It is possible to vary the stepping action in different ways simply by changing the sequence through which stator windings are energized. The following are the most common operating or driving modes of stepper motors.

1. **Wave step**
2. **Full step**

3. Half step

4. Microstepping

Wave Step

Wave step mode is the simplest of all other modes in which only one winding is energized at any given time. Each coil of the phase is connected to the supply alternatively. The table below shows the order through which coils are energized in a 4-phase stepper motor.

In this mode motor gives maximum step angle compared to all other modes. It is the simplest and most commonly used mode for stepping; however the torque produced is less as it uses some part of the total winding at a given time.

Step	Coil A	Coil B	Coil C	Coil D
1	ON	OFF	OFF	OFF
2	OFF	ON	OFF	OFF
3	OFF	OFF	ON	OFF
4	OFF	OFF	OFF	ON

Full Step

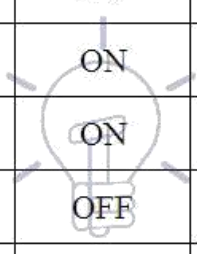
In this drive or mode, two stator phases are energized simultaneously at any given time. When two phases are energized together, the rotor will experience the torque from both phases and comes to the equilibrium position, which will be interleaved between two adjacent wave step positions or 1-phase excitations. So this step provides better holding torque than wave step. The table below shows the full step drive for 4-phase stepper motor.

Step	Coil A	Coil B	Coil C	Coil D
1	ON	OFF	OFF	OFF
2	OFF	ON	OFF	OFF
3	OFF	OFF	ON	OFF
4	OFF	OFF	OFF	ON

Half step

It is the combination of both wave and full step modes. In this, single phase and dual phase excitations are carried out alternatively, i.e., one-phase ON, two-phases ON, and so on. The step angle in this mode becomes half of the full step angle. This drive mode has highest torque and stability compared to all other

modes. The table containing phase pulsing sequence for a 4-phase motor in half stepping is given below.



Step	Coil A	Coil B	Coil C	Coil D
1	ON	OFF	OFF	OFF
2	ON	ON	OFF	OFF
3	OFF	ON	OFF	OFF
4	OFF	ON	ON	OFF
5	OFF	OFF	ON	OFF
6	OFF	OFF	ON	ON
7	OFF	OFF	OFF	ON
8	ON	OFF	OFF	ON

Microstepping

In this mode, each motor step is subdivided into several small steps, even hundreds of fixed positions, therefore a greater positioning resolution is obtained. In this, currents through the windings are continually varied in order to get very small steps. In this, two phases are excited simultaneously, but with the unequal currents in each phase.

For example, the current through phase -1 is held constant while the current through phase-2 is incremented in steps till the maximum value of current, whether it is negative or positive. The current in the phase-1 is then decreased or increased in steps till zero. Thus, the motor will produce a small step size. All these stepping modes can be obtained by each type of stepper motor discussed above. However, the direction of current in each winding during these steps can be varied depending on the type of motor and either it is unipolar or bipolar.