LECTURE NOTES

Synchronous Machine

Subject Code – PC EE 501

B-Tech 5th SEM EE

College of Engineering and Management, Kolaghat

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.

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

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

$$N_p = CN_c$$

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

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

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

$$E_{\frac{av}{coil}} = 4\phi N_c n \quad \text{volts}$$

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

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

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

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

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

1.2 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-

$$E_L = E_{ph}$$

1.3 Relation between speed and frequency

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

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

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

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

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

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

Where

P is the number of poles

N is the speed in rpm (rev/min)

f is. the frequency in hertz

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

ω_e is the speed electrical radians per second.

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

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

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

Where ***K_p*** is called ***pitch factor*** and ***K_d*** is called ***distribution factor.***

1.4.1 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 (K_p)*** or ***coil span factor (K_c)*** 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***,

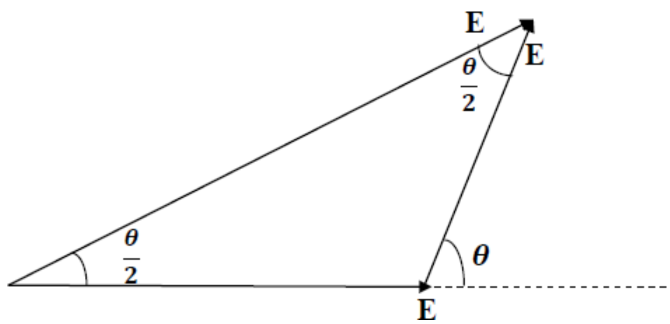


Fig: 1(a) Voltage phasor for short-pitch coil

- 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

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

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

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

$k_{pn} = \cos\frac{n\theta}{2}$ where n is the order of harmonic

1.4.2 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 (K_b)*** or ***distribution factor (K_d)***

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, γ^{o}

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

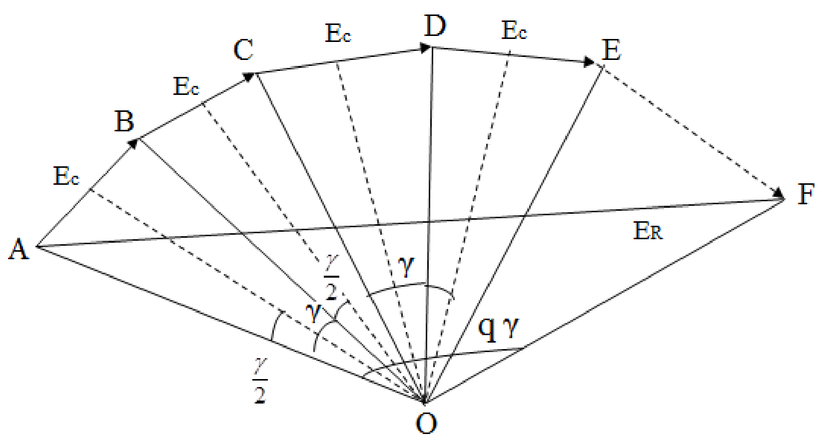


Fig: 1(b)

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

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

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

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

The distribution factor for nth order harmonic component is given as

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

1.4.3 Harmonic Effect

- The flux distribution along the air gaps of alternators usually is non- sinusoidal so that the emf in the individual armature conductor likewise is non-sinusoidal
- The sources of harmonics in the output voltage waveform are the non- sinusoidal waveform of the field flux.
- Fourier showed that any periodic wave may be expressed as the sum of a d-c component (zero frequency) and sine (or cosine) waves having fundamental and multiple or higher frequencies, the higher frequencies being called harmonics.
- All the odd harmonics(third, fifth, seventh, night, etc.) are present in the phase voltage to some extent and need to be dealt with in the design of ac machines.
- Because the resulting voltage waveform is symmetric about the center of the rotor flux, no ***even harmonics*** are present in the phase voltage.
- In ***Y- connected***, the *third-harmonic* voltage between any two terminals will be zero. This result applies not only to third-harmonic components but also to any multiple of a third-harmonic component (such as the ninth harmonic). Such special harmonic frequencies are called ***triplen***

harmonics

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

1.4.4 Winding Factor

Both distribution factor *(K_d)* and pitch factor K_p together is known as ***winding factor K_w.***

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

1.5 Armature Reaction

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

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

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

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

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

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

When load p.f. is unity

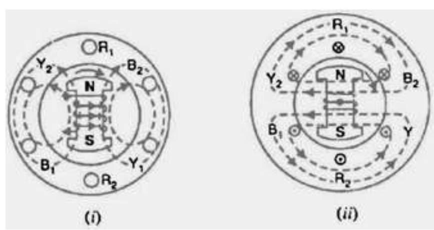


Fig: 1 (c)

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

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

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

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

When load Power Factor is Zero lagging

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

When load Power Factor is Zero leading

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

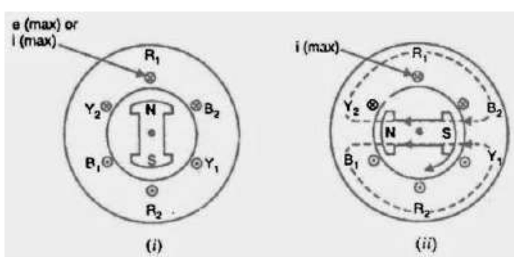


Fig: 1 (d)

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

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

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

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

1.6 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.

1.6.1 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.

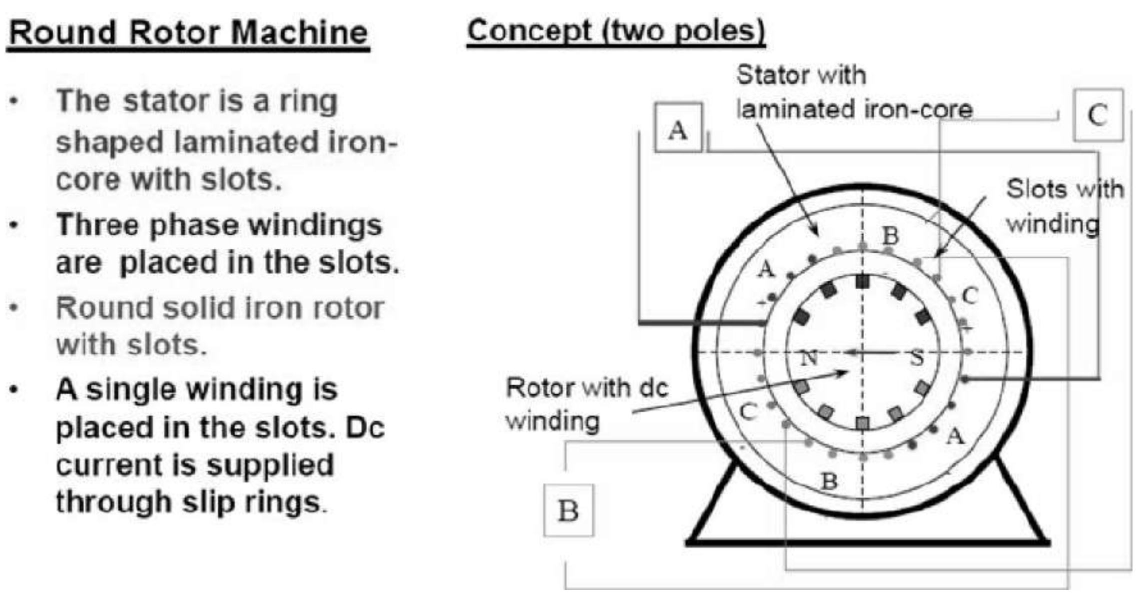
1.6.2 Rotating-Armature Type:

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

1.6.3 Rotating-Field Type:

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

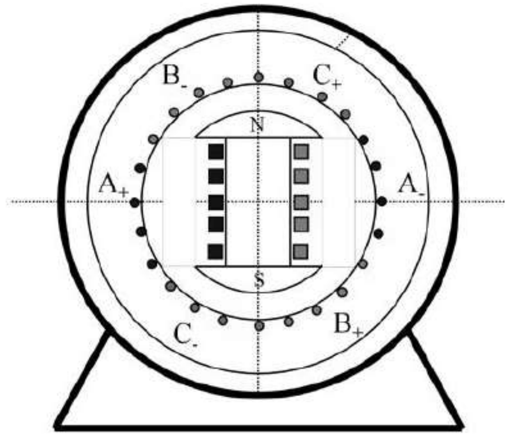
According to the shape of the field, synchronous machines may be classified as ***cylindrical-rotor*** (***non-salient pole***) ***machines*** and ***salient-pole machines***



Salient Rotor Machine

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

- Concept (two poles)



AC winding design

The windings used in rotating electrical machines can be classified as

Concentrated Windings

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

Distributed Windings

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

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

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

Turn. One turn consists of two conductors.

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

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

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

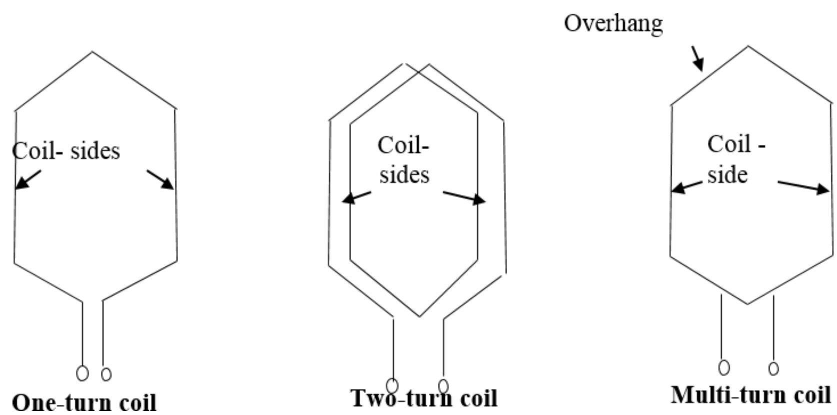


Fig: 1.1

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

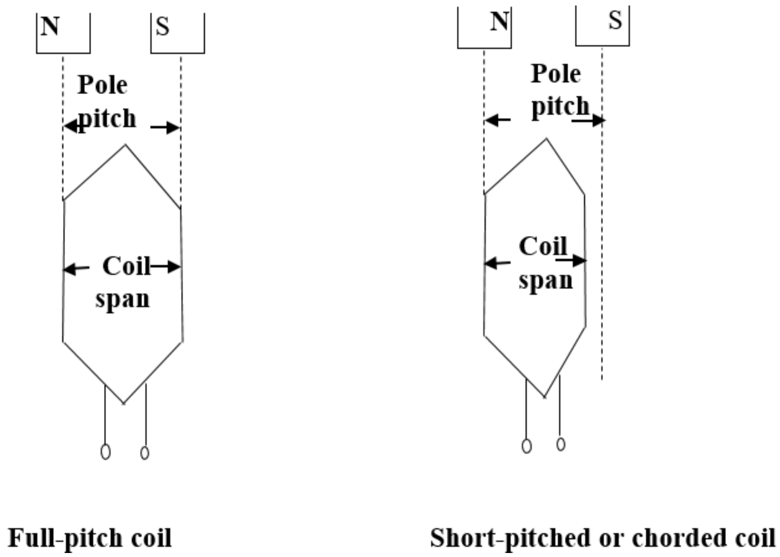


Fig: 1.2

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.

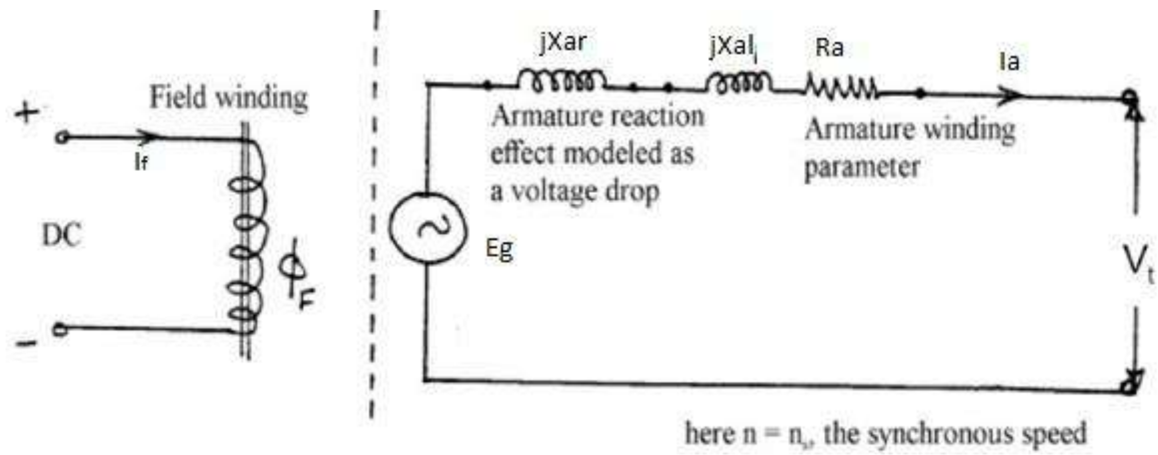


Fig: 1.3 Equivalent circuit of synchronous generator

For synchronous generator the terminal voltage V_t can be written as

$$V_t = E_g - jI_aX_{al} - jI_aX_{ar} - I_aR_a$$
$$V_t = E_g - jI_aX_s - I_aR_a$$
$$V_t = E_g - I_a(R_a + jX_s) = E_g - I_aZ_s$$

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

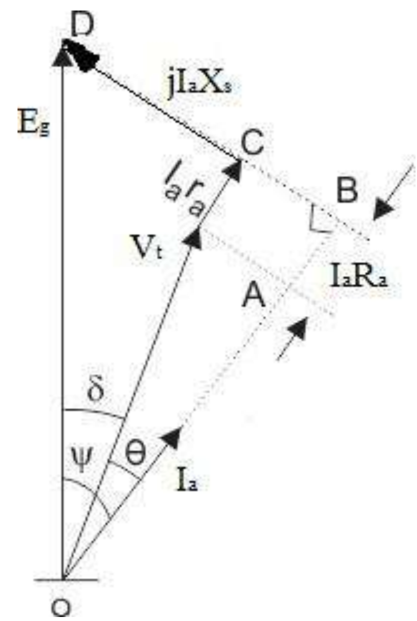


Fig: 1.4

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.

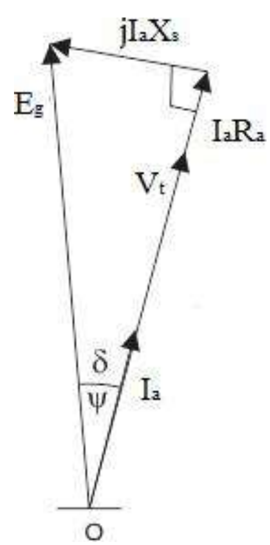


Fig: 1. 5 Phasor diagram of an alternator with unity power factor load

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

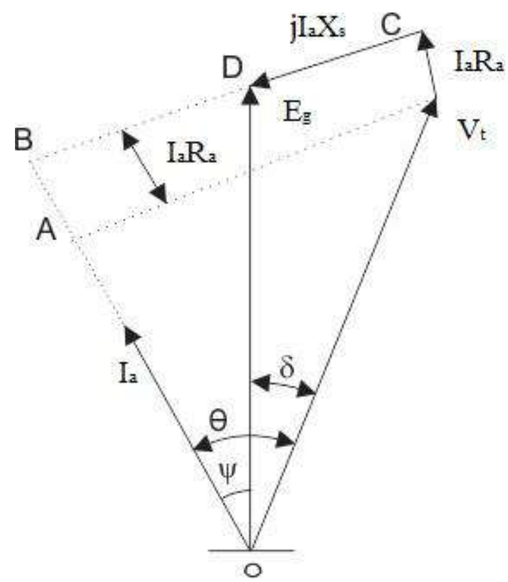


Fig: 1. 6 Phasor diagram of an alternator with leading power factor load

δ is called load angle
θ is load power factor angle
ψ is internal power factor angle

1.7 Open-circuit characteristic (OCC) of a generator

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

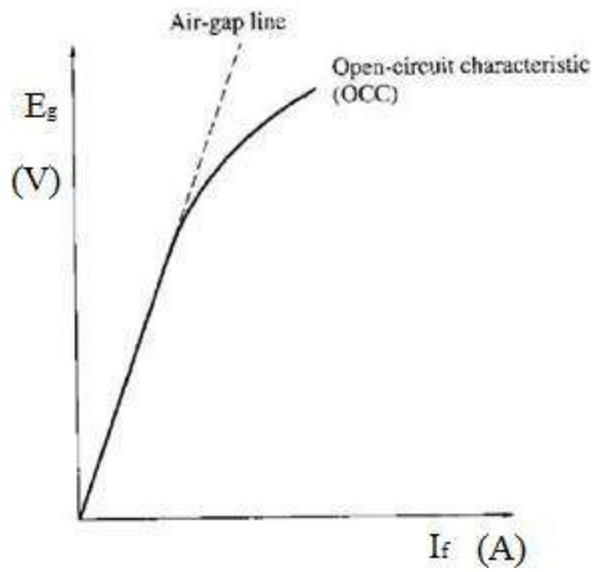


Fig: 1. 7 Open-circuit characteristic of alternator

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

1.8 Short Circuit Characteristics (SCC)

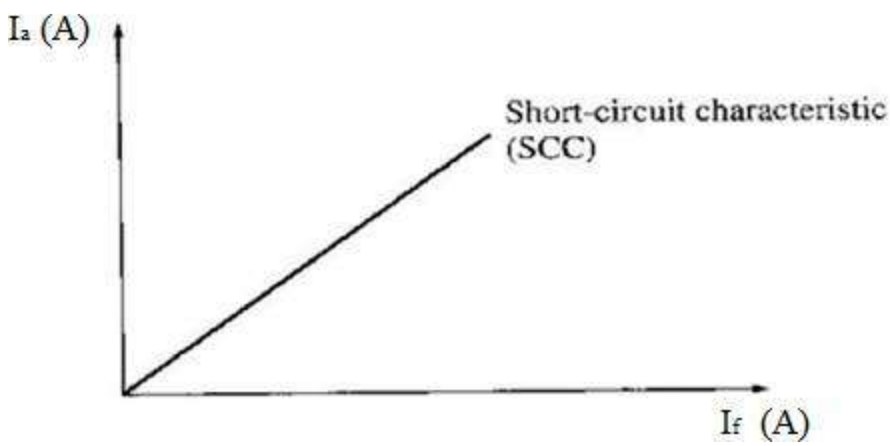


Fig: 1.8 Short-circuit characteristic of alternator

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.

1.9 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.

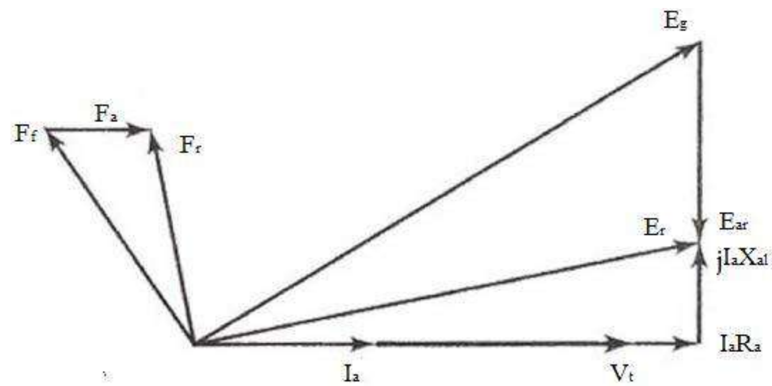


Fig : 1.9 Phasor diagram of an alternator at unity power factor

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

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

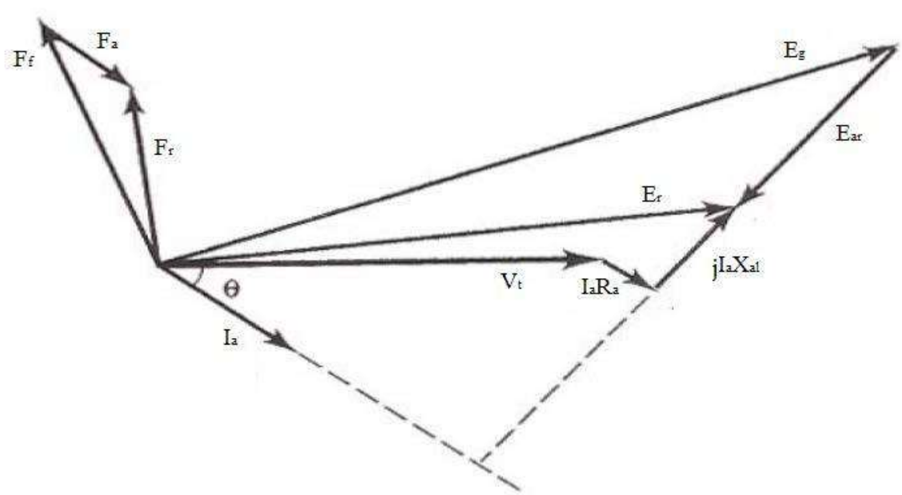


Fig: 1.10 Phasor diagram of an alternator at lagging power factor

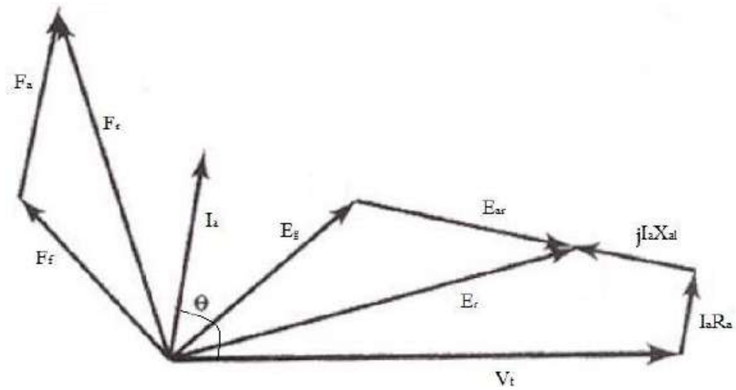


Fig: 1.11 Phasor diagram of an alternator at leading power factor

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

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

$$\overline{E_{ar}} = -j\overline{I_a}X_{ar}$$

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

1.10 Synchronous reactance

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

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

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

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

1.11 Short Circuit Ratio (SCR)

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

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

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

\1.12 Potier Reactance

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

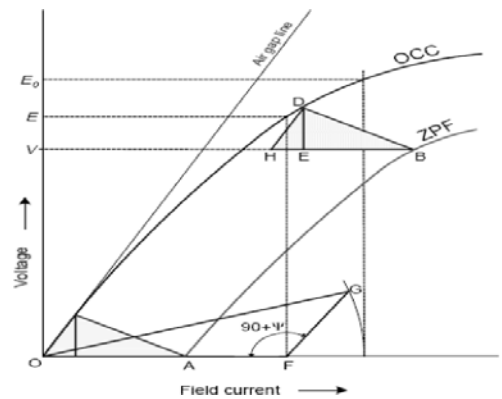


Fig: 1.15

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

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

1.13Voltage Regulation

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

Voltage regulation of an alternator is defined as the change in terminal voltage from no load to full load expressed as a percentage of rated voltage when the load at a given power factor is removed without change in speed and excitation. Or the numerical value of the regulation is defined as the percentage rise in voltage when full load at the specified power-factor is switched off with speed and field current remaining unchanged expressed as a percentage of rated voltage.

Hence regulation can be expressed as

$$\% \text{ Regulation} = \left(\frac{E_0 - V_t}{V_t} \right) \times 100$$

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

1.15 Methods of finding Voltage Regulation:

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

1. Direct loading method
2. EMF method or Synchronous impedance method
3. MMF method or Ampere turns method
4. ASA modified MMF method
5. ZPF method or Potier triangle method

All the above methods other than direct loading are valid for non-salient pole machines only. As the alternators are manufactured in large capacity direct loading of alternators is not employed for determination of regulation. Other methods can be employed for predetermination of regulation. Hence the other methods of determination of regulations will be discussed in the following sections.

1.15.1 EMF method:

This method is also known as synchronous impedance method. Here the magnetic circuit is assumed to be unsaturated. In this method the MMFs (fluxes) produced by rotor and stator are replaced by their equivalent emf, and hence called emf method.

To predetermine the regulation by this method the following informations are to be determined. Armature resistance /phase of the alternator, open circuit and short circuit characteristics of the alternator.

Determination of synchronous impedance Z_s:

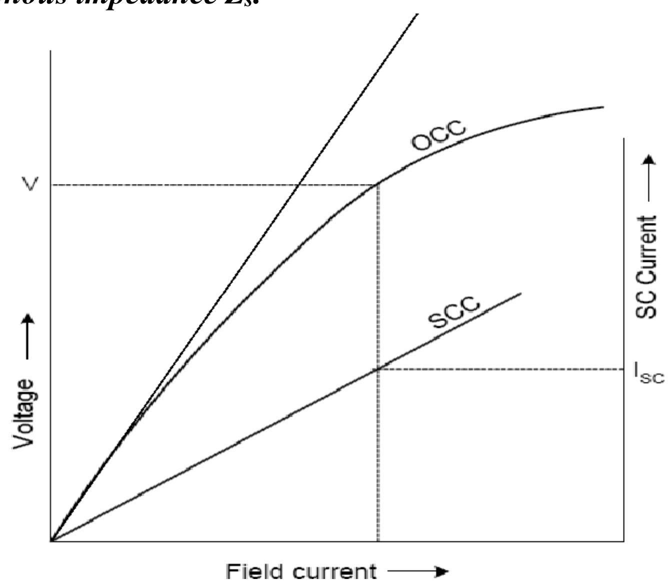


Fig: 1.16 OCC and SCC of alternator

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

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

Synchronous impedance Z_s = (open circuit voltage per phase)/(short circuit current per phase) f_{or} same If

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

From Fig: 1.16 synchronous impedance Z_s = V/Isc

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

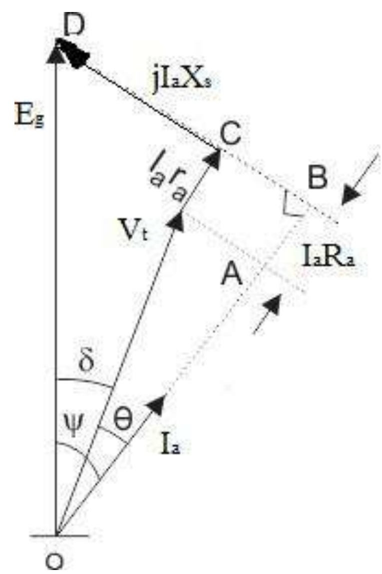


Fig: 1.17

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

Hence induced emf per phase can be found as $Eg = \sqrt{[(Vt\cos\theta + IaR_a)^2 + (Vt\sin\theta \pm IaXS)^2]}$

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

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

$$\% \text{ Regulation} = \left(\frac{E_g - V_t}{V_t} \right) \times 100$$

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

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

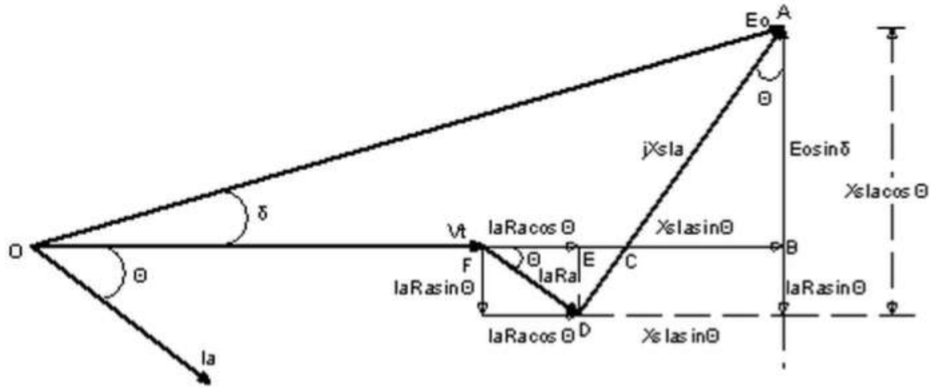


Fig: 1.18

1.13.2 MMF method

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

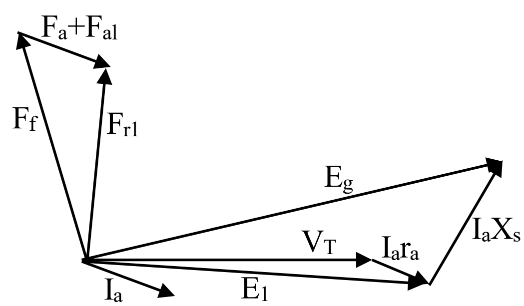


Fig: 1.19

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

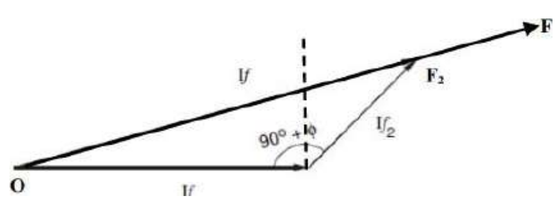
Following procedure can be used for determination of regulation by mmf method.

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

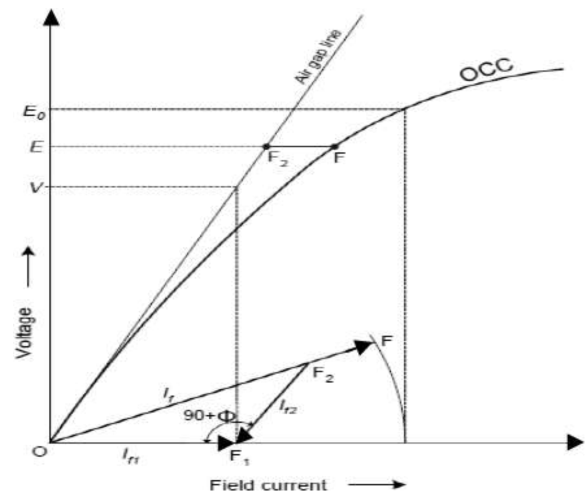
Because of the assumption of unsaturated magnetic circuit the regulation computed by this method will be less than the actual and hence this method of regulation is called optimistic method.

1.13.3 ASA Modified MMF Method:

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



(i)



(ii)

Fig: 1.20

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

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

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

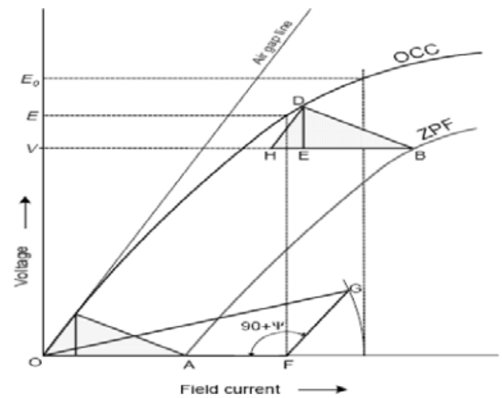


Fig: 1.21

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

Triangle BDE is called Potier triangle and XL is the Potier reactance. Find E from *V, IRa*, *IXL* and Φ. Use the expression $E = \sqrt{[(V_t \cos\Phi + I_aRa)^2 + (V_t \sin\Phi) + I_aX_L)^2]}$ to compute E. Find field current corresponding to *E.* Draw FG with magnitude equal to BE at angle (90+Ψ) from field current axis, where Ψ is the phase angle of current from voltage vector *E* (internal phase angle).

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

1.14 Power angle characteristics

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

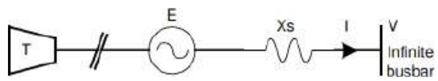


Fig: 1.22 Cylindrical-rotor alternator connected to infinite bus-bar single line diagram

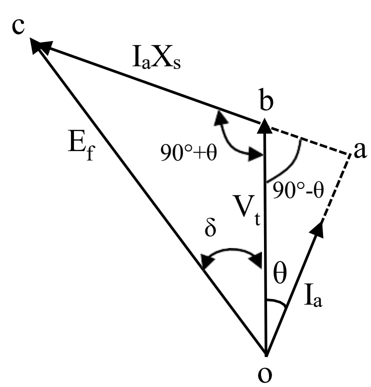


Fig: 1.23 Phasor diagram of an alternator for lagging power factor load with neglected armature resistance

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

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

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

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

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

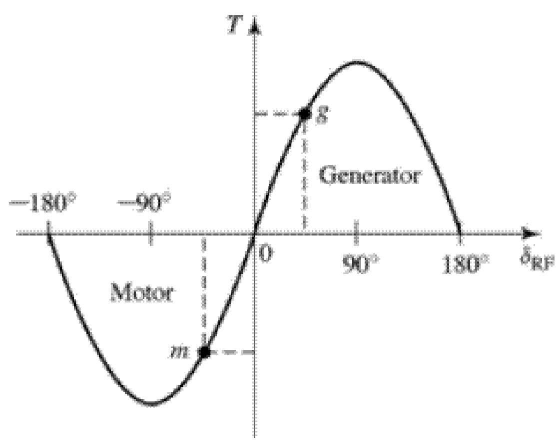
$$X_s I_a \cos\theta = E_f \sin\delta$$

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

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



Fig; 1.24 Power angle characteristic

2.1 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.

2.2 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.2.1

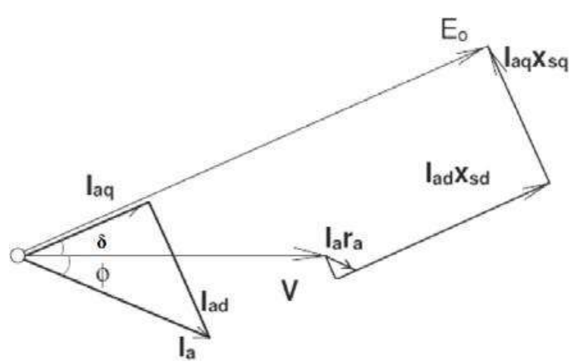


Fig: 2.1 Phasor diagram of salient-pole alternator

Iaq = Ia cos(δ+φ);   Iad = Ia sin(δ+φ);   and   Ia = √[(Iaq)² + (Iad)²]

Iaa = Ia cos φ; Iar = Ia sin φ;   and Ia = √[(Iaa)² + (Iar)²]

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

2.3 Power Angle Characteristic of Salient Pole Machine

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

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

This can be expressed in terms of σ,

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

Substituting these in the expression for power, we have.

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

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 2σ) is added into the power – angle characteristic of a non-salient pole 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 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: 2.2 shows the typical power angle characteristic of a salient pole alternator.

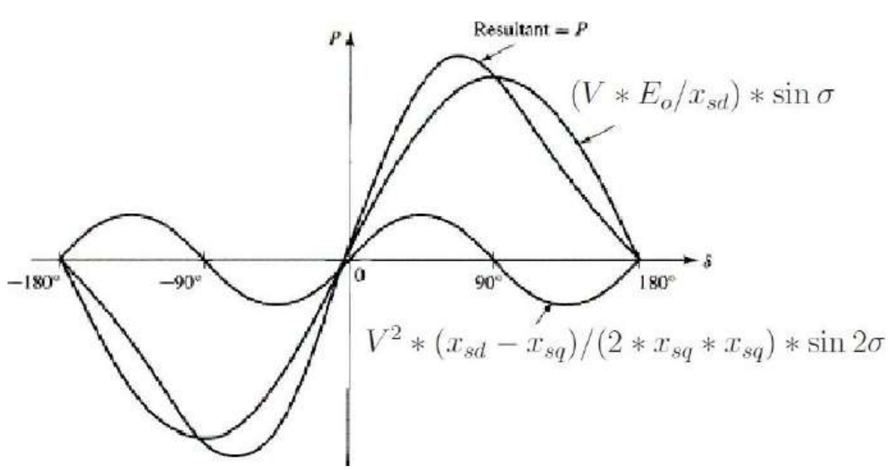


Fig: 2.2

2.4 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.

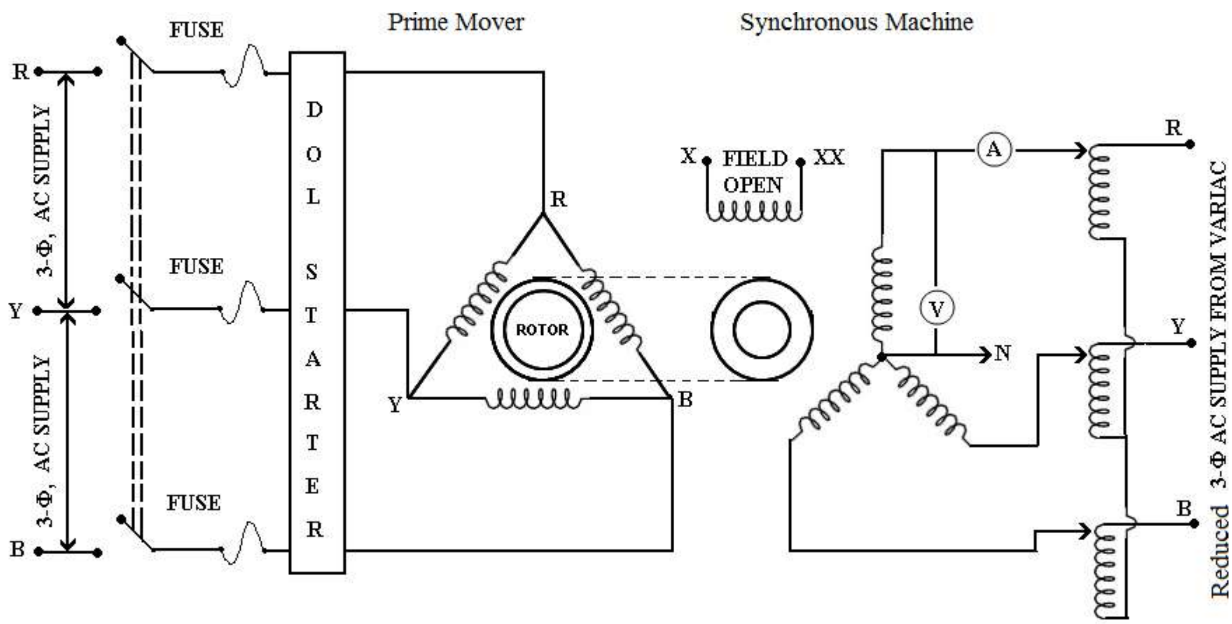


Fig: 2.3

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

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

2.5 Parallel Operation of Alternators

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

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

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

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

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

The synchronizing lamp method is consists of 3 lamps connected between the phases of the running 3-ph generator and the incoming generator as shown in Fig: 2.4.

In three phase alternators, it is necessary to synchronize one phase only, the other two phases be will then synchronized automatically. However, first it is necessary that the incoming alternator is correctly 'phased out' *i.e.* the phases are connected in the proper order of *R,Y &B* not *R, B, Y* etc. Lamp L1 is connected between R and R', $L2$ between Y and B' (not Y and Y') and $L3$ between B and Y' (and not B and B') as shown in Fig: 2.5.

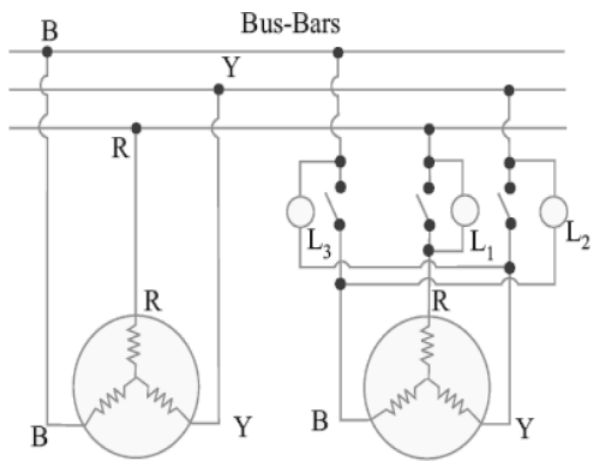


Fig: 2.4

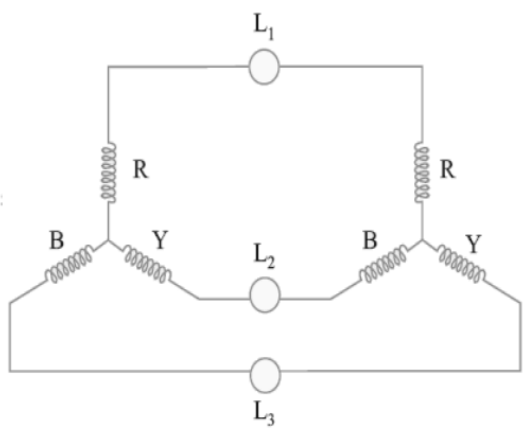


Fig: 2.5

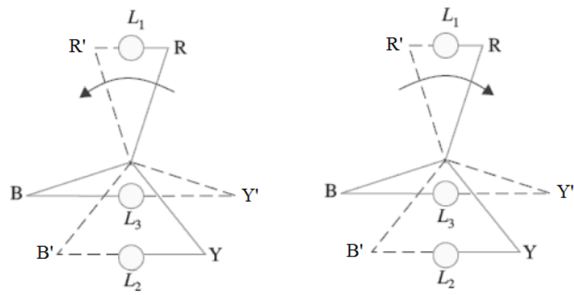


Fig: 2.6

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

It should be noted that synchronization by lamps is not quite accurate, because to a large extent, it depends on the sense of correct judgment of the operator. Hence, to eliminate the element of personal judgment in routine operation of alternators, the machines are synchronized by a more accurate device called a synchronoscope as shown in Fig: 2.7. 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.

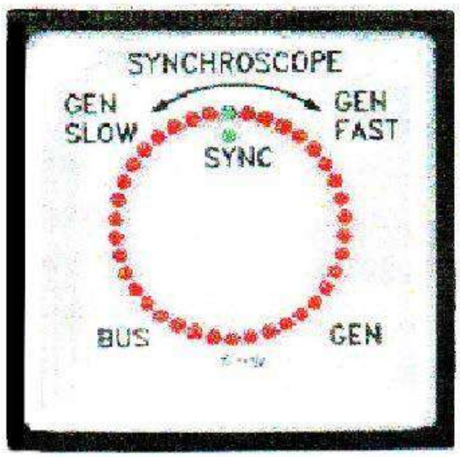


Fig: 2.7

2.5.1 Synchronizing Current:

If two alternators generating exactly the same emf are perfectly synchronized, there is no resultant emf acting on the local circuit consisting of their two armatures connected in parallel. No current circulates between the two and no power is transferred from one to the other. Under this condition emf of alternator 1, i.e. E1 is equal to and in phase opposition to emf of alternator 2, i.e. E2 as shown in the Figure .There is, apparently, no force tending to keep them in synchronism, but as soon as the conditions are disturbed a synchronizing force is developed, tending to keep the whole system stable. Suppose one alternator falls behind a little in phase by an angle θ. The two alternator emfs now produce a resultant voltage and this acts on the local circuit consisting of the two armature windings and the joining connections. In alternators, the synchronous reactance is large compared with the resistance, so that the resultant circulating current Is is very nearly in quadrature with the resultant emf Er acting on the circuit. Figure represents a single phase case, where E1 and E2 represent the two induced emfs, the latter having fallen back slightly in phase. The resultant emf, Er, is almost in quadrature with both the emfs, and gives rise to a current, *Is*, lagging behind *Er* by an angle approximating to a right angle. It is, thus, seen that *E*1 and *Is* are almost in phase. The first alternator is generating a power *E*1 *Is* cos Φ1, which is positive, while the second one is generating a power *E*2 *Is* cos Φ2, which is negative, since cos Φ2 is negative. In other words, the first alternator is supplying the second with power, the difference between the two amounts of power represents the copper losses occasioned by the current *Is* flowing through the circuit which possesses resistance. This power output of the first alternator tends to retard it, while the power input to the second one tends to accelerate it till such a time that *E*1 and *E*2 are again in phase opposition and the machines once again work in perfect synchronism. So, the action helps to keep both machines in stable synchronism. The current, *Is*, is called the synchronizing current.

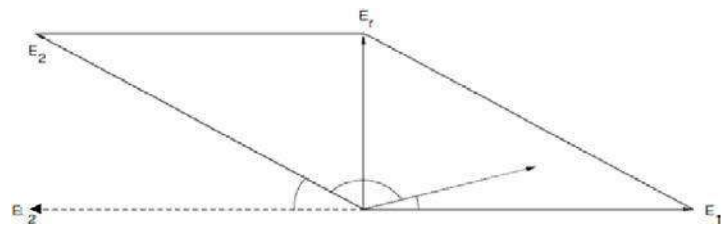


Fig: 2.7

2.5.2 Effect of Change of Excitation:

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

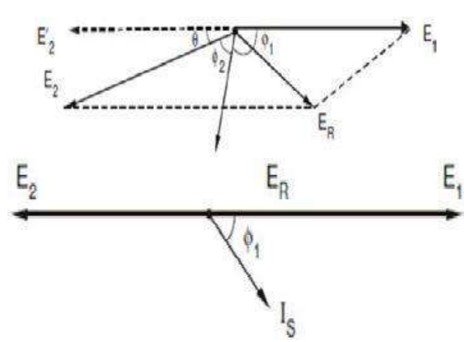


Fig: 2.8

Since their induced emfs are the same, there is no resultant emf acting around the local circuit formed by their two armature windings, so that the synchronizing current, Is, is zero. Since the armature resistance is neglected, the vector difference between $E_1 = E_2$ and V is equal to, $I_1X_{s1} = I_2X_{s2}$, this vector leading the current I by 90^0, where X_{S1} and X_{S2} are the synchronous reactances of the two alternators respectively.

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

2.5.3 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.

2.5.4 Load Sharing

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

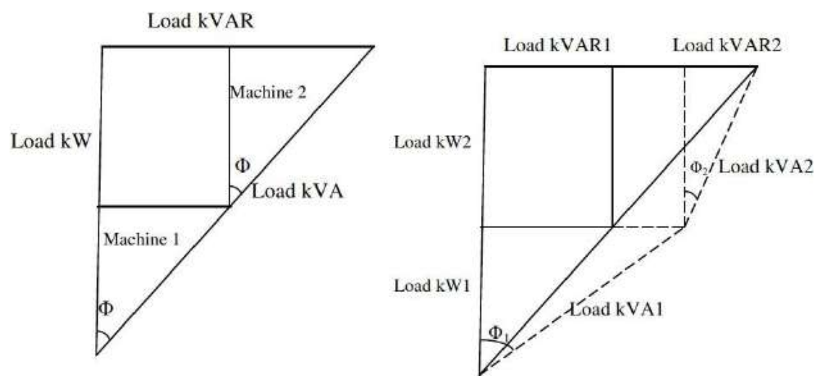


Fig: 2.9

2.5.5 Sharing of load when two alternators are in parallel

Consider two alternators with identical speed load characteristics connected in parallel as shown in Fig: 2.10.

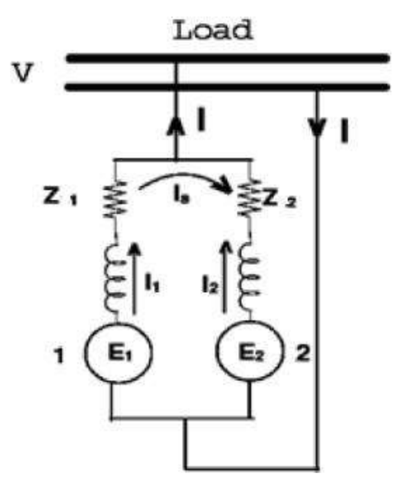


Fig: 2.10

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

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

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

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

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

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

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

2.5.6 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: 2.11, 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 2.11.

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)

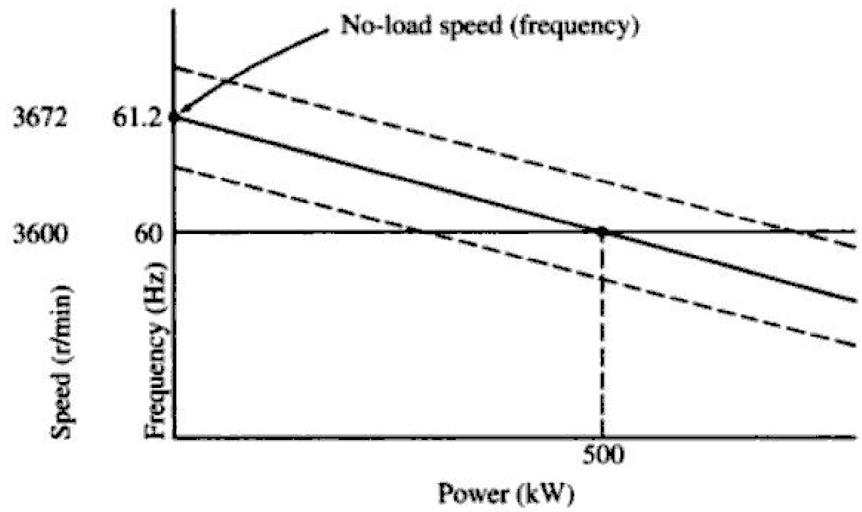


Fig: 2.11

Governor Droop

Governor droop (GD) or droop rate is defined as the ratio of the change in frequency to the corresponding change in active power:

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

Where,

f_{rated} = rated frequency (Hz) & f_{nl} = no-load frequency (Hz)
P_{rated} = rated active power (kW)

2.6 Sudden Short Circuit of a Synchronous Generator

It may be possible in practice that the alternator running with full excitation may undergo a sudden short circuit because of the abnormal conditions. Due to sudden short circuit of alternator, large mechanical forces are developed which may not be sustained by the alternator. These forces are proportional to square of the current value, hence large pressure is built up between adjacent stator conductors.

The short circuit transients in a synchronous machine is a complicated phenomenon due to number of circuits coupled to each other are involved. When a synchronous generator undergoes short circuit, it has a characteristics time varying behaviour. During short circuit, flux per pole dynamically changes. Thus the transients are seen in the field and damper windings. The alternator can be represented by an equivalent circuit wherein the reactance is seen to be changed from subtransient reactance to final steady state synchronous reactance.

When alternator undergoes a short circuit number of events take place which depends on various factors such as the instant in the cycle at which short circuit occurs, whether the machine is loaded or not, what is the excitation provided, how many phases are involved, whether it is occurring near to machine terminals or away from it and on the constructional features of the machine. Hence the evaluation of sudden short circuit current for the given conditions is complex and to some extent empirical process depending on values of resistance, self and mutual inductances which themselves are variable and difficult to assess.

After the moment of short circuit, the time period followed by it can be divided into three periods. The first one is very short period of one or two cycles the conditions of which are dependent on the flux linkages between stator and rotor during short circuit. The second interval is longer one which is nothing but transient decay of short circuit current which is affected by damping and rise of armature reaction. The final period is nothing but the steady state short circuit before which the generator is normally open circuited [see Fig: 2.12].

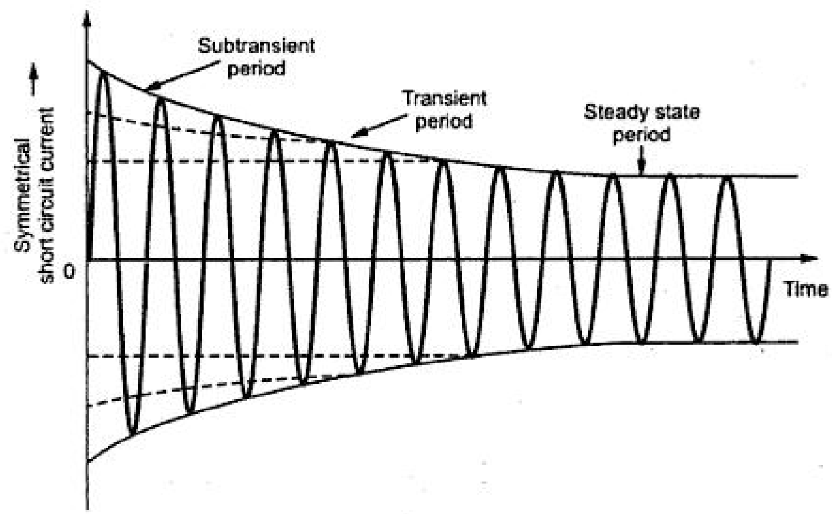


Fig: 2.12

Constant Flux Linkage Theorem

The behavior shown by the alternator just after short circuit can be understood by the use of constant linkages theorem. If a closed circuit with resistance r and inductance L is considered without a source then the equation obtained using KVL will be ri + L (di/dt) = 0. If r is very very small then L(di/dt) = 0 or d/dt (LI) = 0 This shows that the flux linkages Li remain constant. In generator also the effective inductance of stator and rotor windings is large compared to the resistance which can be neglected for first few cycles. The rotor circuit is closed through exciter while stator is closed by short circuit. Thus the flux linking with either winding must remain constant irrespective of the rotation.

Analysis of RL Series Circuit

Similar to theorem of constant linkages let us consider a series R-L circuit excited by a voltage source which is sinusoidal for further understanding of short circuit. The circuit diagram is as shown in the Fig: 2.13

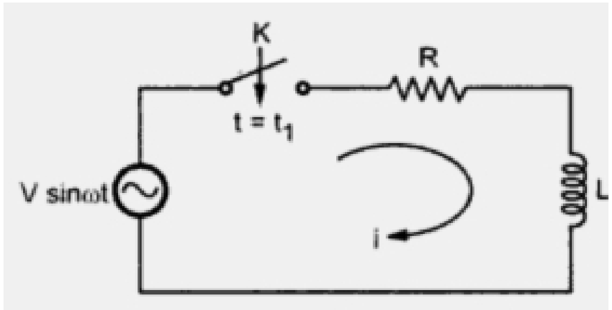


Fig: 2.13

Let at the instant $t = t_1$, the sinusoidal voltage V sinωt is applied to series R-L circuit.

Applying KVL,

$Ri + L(di/dt) = V \sin\omega\ t$..(1)

For the above equation the complementary function of the solution is

$i_{CF} = K1\ e^{-(R/L)t}$

For obtaining the particular solution let the trial solution be

$i_{PI} = A \cos\omega t + B\sin\omega t$

where A and B are undetermined coefficients.

$i'_{PI} = - A \sin \omega t(\omega) + B \cos\omega t(\omega)$

$i'_{PI} = -A\ \omega\sin\omega t + B\omega \cos\omega t$

Substituting trial solution and its derivative in equation (1)

$R(A \cos\omega t + B \sin\omega\ t) + L (-A \sin\omega t + B\omega\cos\omega\ t) = V \sin t$

$(RB - LA\omega) \sin\omega t + (RA + \omega LB) \cos\omega t = V\sin\omega t$

Comparing coefficient of like terms

$RB - LA\omega = V$

$RA + \omega LB = 0$

Solving above equations we get

$$A = -\frac{\omega L}{R^2 + \omega^2 L^2}$$

$$B = V \cdot \frac{R}{R^2 + \omega^2 L^2}$$

The particular solution is therefore given by,

$$i_{PI} = \frac{V}{\sqrt{R^2 + (\omega L)^2}} \left[\sin\left(\omega t - \tan^{-1} \frac{\omega L}{R} \right) \right]$$

To find the value of K1 let us use initial conditions i.e.

At $t = t_1$, $i = 0$

$$\therefore \qquad K_1 = e^{-(R/L)t_1} \left[-\frac{V}{\sqrt{R^2 + (\omega L)^2}} \right] \sin \left[\omega t_1 - \tan^{-1} \frac{\omega L}{R} \right]$$

Hence the complete solution is given as,

$$\therefore \quad i = e^{-(R/L)t_1}\left[\frac{-V}{\sqrt{R^2+(\omega L)^2}}\right]\sin\left(\omega t_1 - \tan^{-1}\frac{\omega L}{R}\right)$$

$$e^{-(R/L)t} + \frac{V}{\sqrt{R^2+(\omega L)^2}}\left[\sin\left(\omega t - \tan^{-1}\frac{\omega L}{R}\right)\right]$$

$$\therefore \quad i = \frac{V}{\sqrt{R^2+(\omega L)^2}}\sin\left(\omega t - \tan^{-1}\frac{\omega L}{R}\right)$$

$$- \frac{V}{\sqrt{R^2+(\omega L)^2}}\sin\left(\omega t_1 - \tan^{-1}\frac{\omega L}{R}\right)e^{-(R/L)(t-t_1)}$$

Let $Z = \sqrt{R^2+(\omega L)^2}$

$$\phi = \tan^{-1}\left(\frac{\omega L}{R}\right)$$

Substituting in above equation,

$$i = \frac{V}{Z}\sin(\omega t - \phi) - \frac{V}{Z}\sin(\omega t_1 - \phi)e^{-(R/L)(t-t_1)}$$

The corresponding waveforms are as shown in the Fig: 2.14.

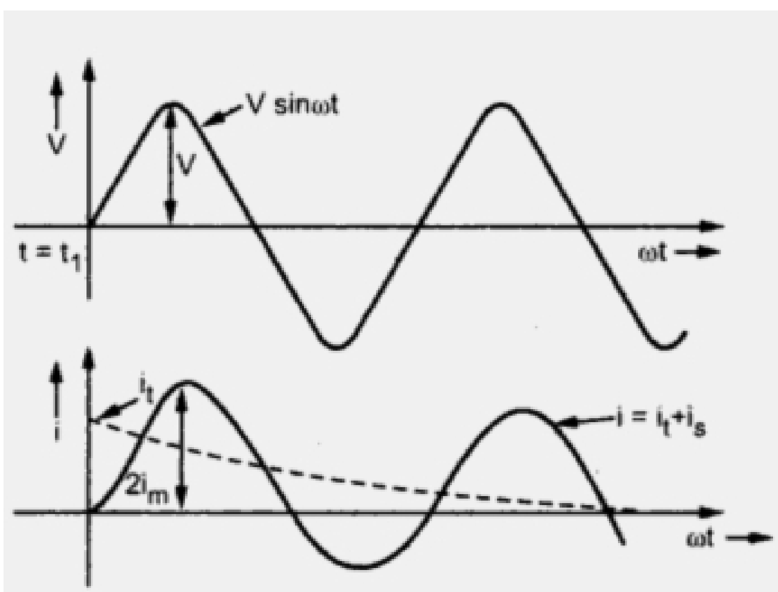


Fig: 2.14

The first term steady state current (i_s) while the second term represents transient current (i_t). If the voltage is switched at $t = t_1$ when it is zero, the transient term is having the greatest value. The resultant current is zero having complete asymmetry. The approximate current in this case reaches 2im which is known as doubling effect compared to the switching of voltage at the instant when voltage is at its maximum instead of zero. This shows that the current flowing in the circuit changes its waveform if the instant at which voltage is applied to the circuit, is changed. The same thing is applicable in case of generator undergoing short circuit.

Short Circuit Phenomenon

Consider a two pole elementary single phase alternator with concentrated stator winding as shown in Fig: 2.15.

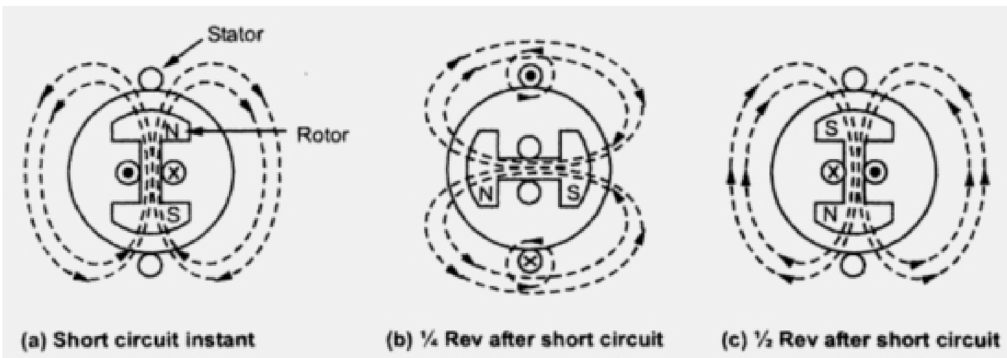


Fig: 2.15

The corresponding waveforms for stator and rotor currents are shown in the Fig: 2.15.

Let short circuit occurs at position of rotor shown in Fig: 2.15(a), when there are no stator linkages. After 1/4 Rev as shown Fig: 2.15(b), it tends to establish full normal linkage in stator winding. The stator opposes this by a current in the shown direction as to force the flux in the leakage path. The rotor current must increase to maintain its flux constant. It reduces to normal at position (c) where stator current is again reduces to zero. The waveform of stator current and field current shown in the Fig: 2.16, changes totally if the position of rotor at the instant of short circuit is different. Thus the short circuit current is a function of of relative position of stator and rotor.

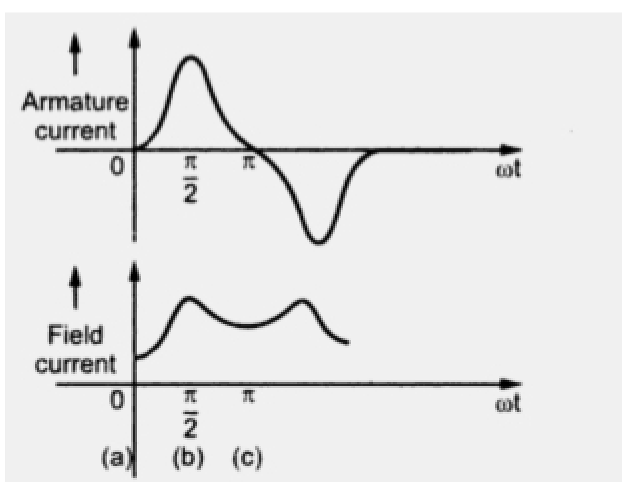


Fig: 2.16

Using the theorem of constant linkages a three phase short circuit can also be studied. After the instant of short circuit the flux linking with the stator will not change. A stationary image of main pole flux is produced in the stator. Thus a D.C. component of current is carried by each phase. The magnitude of D.C. component of current is different for each phase as the instant on the voltage wave at which short circuit occurs is different for each phase. The rotor tries to maintain its own poles. The rotor current is normal each time when rotor poles occupy the position same as that during short circuit and the current in the stator will be zero if the machine is previously unloaded. After one half cycle from this position the stator and rotor poles are again coincident but the poles are opposite. To maintain the flux linkages constant, the current in rotor reaches to its peak value.

The stationary field produced by poles on the stator induces a normal frequency emf in the rotor. Thus the rotor current is fluctuating whose resultant a.c. component develops fundamental frequency flux which rotates and again produces in the stator winding double frequency or second harmonic currents. Thus the waveform of transient current consists of fundamental, a.c. and second harmonic components of currents.

Thus whenever short circuit occurs in three phase generator then the stator currents are distorted from pure sine wave and are similar to those obtained when an alternating voltage is suddenly applied to series R-L circuit.

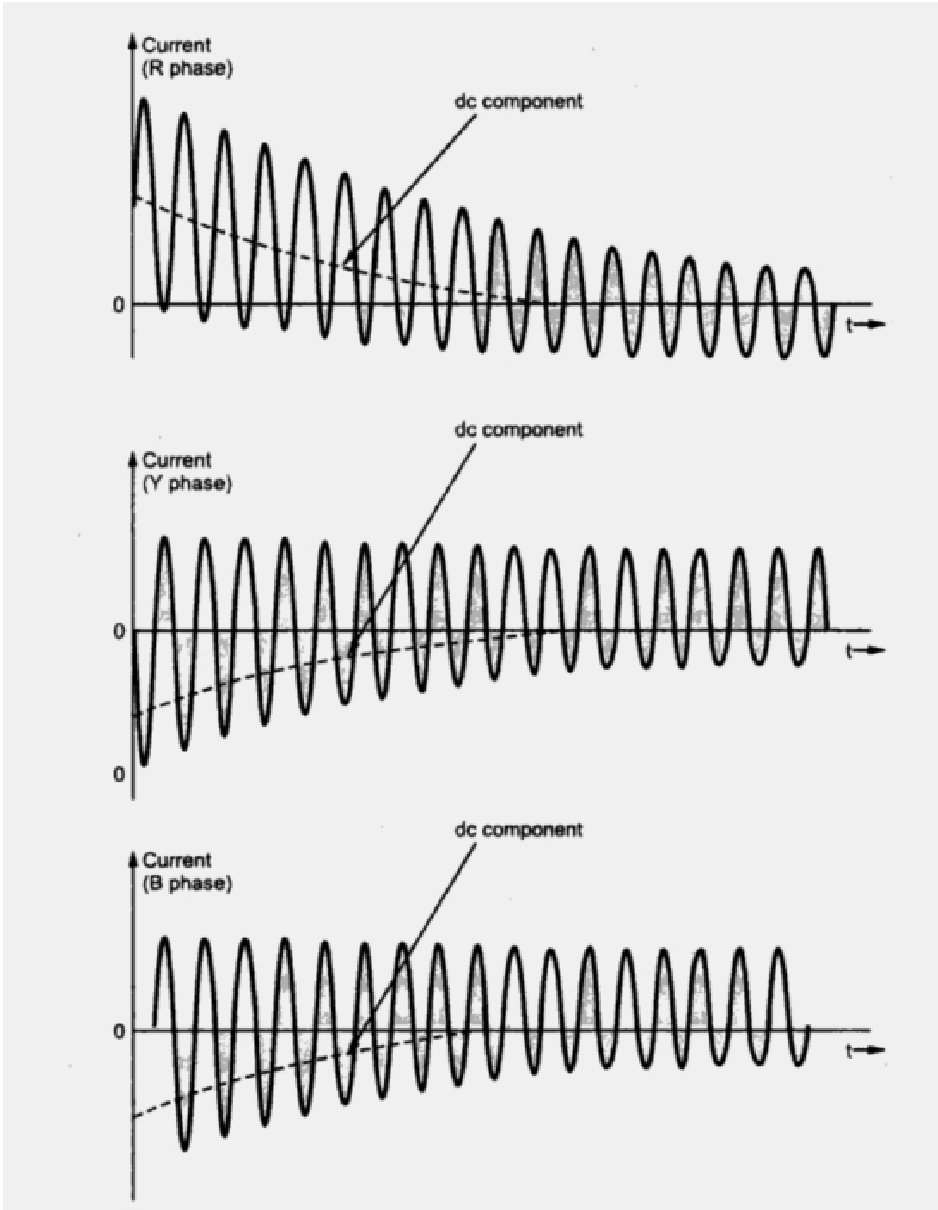


Fig: 2.17

2.6.1 Stator Currents during Short Circuit

If a generator having negligible resistance, excited and running on no load is suddenly undergoing short circuit at its terminals, then the emf induced in the stator winding is used to circulate short circuit current through it. Initially the reactance to be taken into consideration is not the synchronous reactance of the machine. The effect of armature flux (reaction) is to reduce the main field flux. But the flux linking with stator and rotor cannot change instantaneously because of the induction associated with the windings. Thus at the short circuit instant, the armature reaction is ineffective. It will not reduce the main flux. Thus the synchronous reactance will not come into picture at the moment of short circuit. The only limiting factor for short circuit current at this instant is the leakage reactance. After some time from the instant of short circuit, the armature reaction slowly shows its

effect and the alternator then reaches to steady state. Thus the short circuit current reaches to high value for some time and then settles to steady value.
It can be seen that during the initial instant of short circuit is dependent on induced emf and leakage reactance which is similar to the case which we have considered previously of voltage source suddenly applied to series R-L circuit. The instant in the cycle at which short occurs also affects the short circuit current. Near zero e.m.f. (or voltage) it has doubling effect. The expressions that we have derived are applicable only during initial conditions of short circuit as the induced emf also reduces after some tome because of increased armature reaction.
The short circuit currents in the three phases during short circuit are as shown in the Fig: 2.17.

2.7 Transient and Subtransient Reactance of Alternators

To understand the behavior of an alternator under transient conditions, the armature and field resistance is assumed to be negligibly small. Thus, constant flux linkage theorem can be applied. As per this theorem, in purely inductive circuit, the total flux linkage cannot be changed instantaneously at the time of any disturbance. Now, if all the three phases of unloaded alternator with normal excitation are suddenly short circuited there will be short- circuit current flows in the armature. As the resistance is assumed to be zero, this current will lag behind the voltage by 90^o and the m.m.f. produced by this current will be along the d-axis. First conclusion is that this current will be affected by d-axis parameters Xd , Xd' and Xd" only.

Further, there will be demagnetizing effect of this current, but as the flux linkage with field cannot change the effect of demagnetizing armature m.m.f. must be counterbalanced by a proportional increase in the field current. This additional induced component of field current gives rise to greater excitation under transient state and results in more short circuits as compared to the steady state short circuit current.

If field poles are provided with damper bars, then at the instant of three phase short circuit, the demagnetizing armature m.m.f. induces currents in damper bars, which, in turn, produces field in the same direction as the main field and hence at this instant, the excitation further increases and gives rise to further increase in short circuit armature current. This is for a very short duration, normally 3 to 4 cycles and this period is known as sub-transient period. Since the field voltage is constant, there is no additional voltage to sustain these increased excitations during sub transient or transient period. Consequently the effect of increased field current decreases with a time constant determined by the field and armature parameters and accordingly the short circuit armature current also decays with the same time constant.

In the Fig: 2.18 a symmetrical wave from for armature short circuit current of phase – A is shown. The D.C. component is zero in this phase.
The reactances offered by the machine during sub transient period are known as sub transient reactances. Along the direct axis, it is direct axis sub transient reactance, X"d and along the quadrature axis, it is quadrature axis sub-transient reactance, X"q. As these reactances are due to the fact that flux linkages in field circuit during sudden disturbance remain constant, the sub transient reactances Xd" and Xq" can also be defined as below:

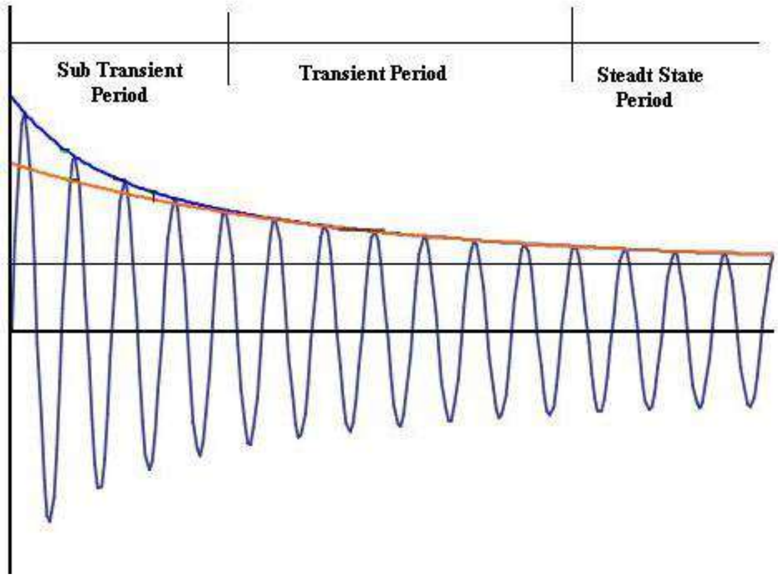


Fig: 2.18

Direct axis sub- transient reactance X”$_d$

The field structure is assumed to have damper bars on salient poles. The field winding is initially unexcited and is short – circuited so that field flux- linkage is zero. Armature currents now are suddenly applied in such time phase that the peak of varying armature m.m.f. wave is in direct axis. As per constant flux linkage theorem, since the flux linkage before this is zero. Hence, it remains zero just after the application of armature m.m.f. wave and in order to maintain the flux linkages zero, current are induced in damper bars, additional rotor circuit formed by pole- body etc. and the field winding. The field of the varying armature m.m.f. is forced to drive the flux through the leakage paths mainly in air as shown in Fig: 2.19 (a).

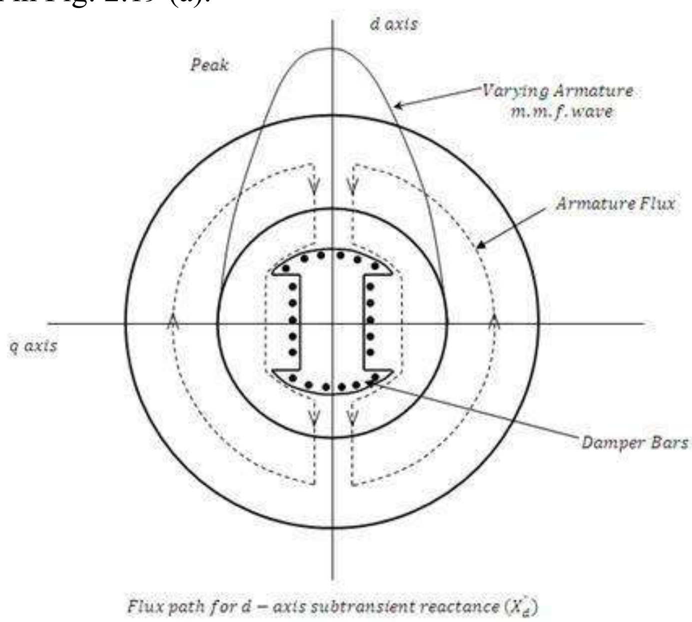


Fig: 2.19 (a)

The armature flux linkage per ampere under these conditions is known as direct axis sub transient inductance L_d".

Quadrature axis subtransient reactance, X_q"

This also is defined in a manner similar to Xd", but in this case, armature currents are applied in such time phase that the peak of varying armature m.m.f. wave is along the quadrature axis. The damper bars in the quadrature axis force the field of the varying armature m.m.f. to follow the leakage path as shown Fig: 2.19 (b).

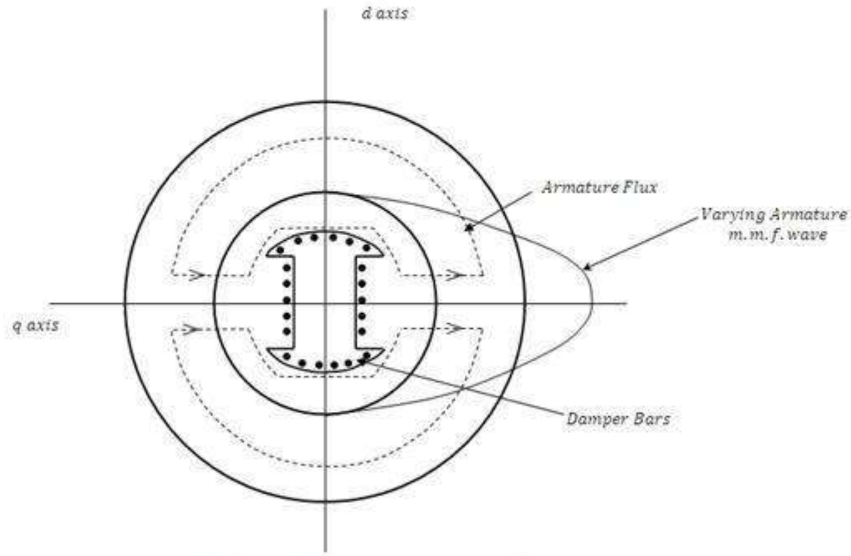


Fig: 2.19 (b)

As before, the flux linkage with q-axis damper bars must remain constant i.e. zero before and after the sudden application of armature m.m.f. Under these conditions, the armature flux linkages per ampere is known as q-axis sub transient inductance Lq" and Xq"=ωLq".
To determine Xd" and Xq", the above mentioned conditions are created there. Two phases of the three phase alternator are connected in series and the combination is connected to a low voltage single phase supply. Field winding is short circuited. The rotor is rotated and brought along the d-axis once. Xd" can be calculated from the armature current and voltage per phase of armature in this position. Next, rotor is brought along the q-axis position and Xq" is determined.

2.8 Synchronous Motors

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

General Physical Concept

Let assume that the armature winding (laid out in the stator) of a 3-phase synchronous machine is connected to a suitable balanced 3-phase source and the field winding to a D.C source of rated voltage. The current flowing through the field coils will set up stationary magnetic poles of alternate North and South. On the other hand, the 3-phase currents flowing in the armature winding produce a rotating magnetic field rotating at synchronous speed. In other words there will be moving North and South poles established in the stator due to the 3-phase currents i.e at any location in the stator there will be a North pole at some instant of time and it will become a South pole after a time period corresponding to half a cycle. (after a time = $1/2f$, where f = frequency of the supply). Assume that the stationary South pole in the rotor is aligned with the North pole in the stator moving in clockwise direction at a particular instant of time, as shown in Figure below. These two poles get attracted and try to maintain this alignment (as per Lenz's law) and hence the rotor pole tries to follow the stator pole as the conditions are suitable for the production of torque in the clockwise direction. However, the rotor cannot move instantaneously due to its mechanical inertia, and so it needs some time to move. In the meantime, the stator pole would quickly (a time duration corresponding to half a cycle) change its polarity and becomes a South pole. So the force of attraction will no longer be present and instead the like poles experience a force of repulsion as shown in Fig: 2.20 & Fig: 2.21. 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.

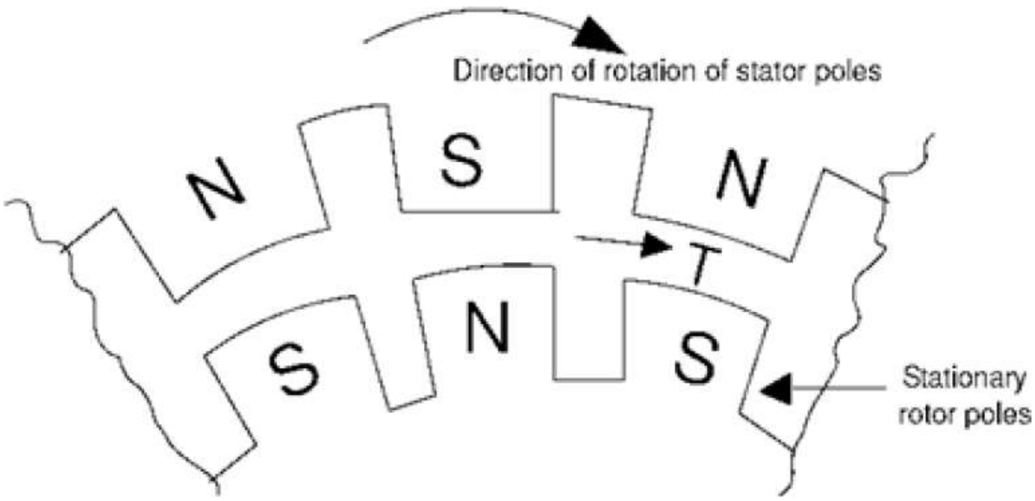


Fig: 2.20

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.

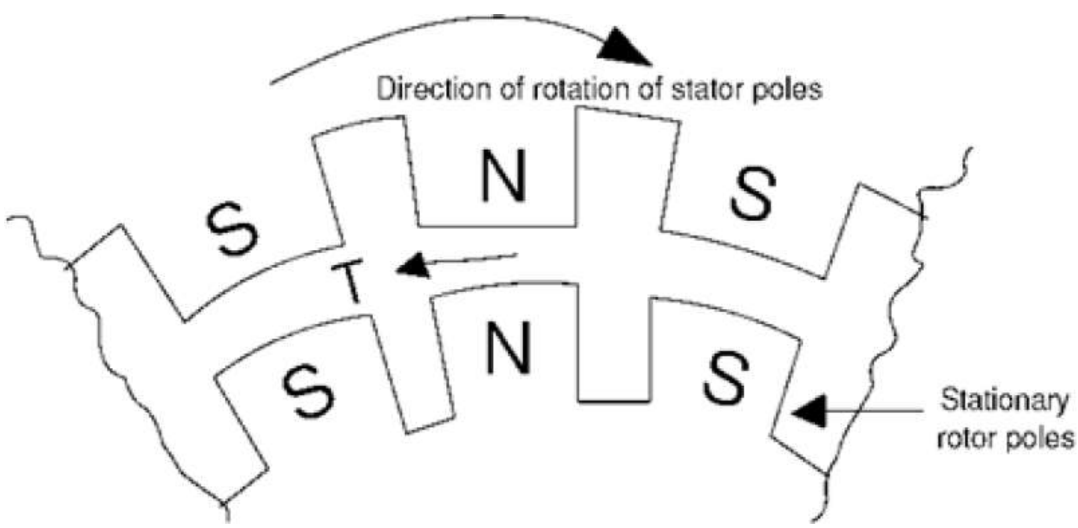


Fig: 2.21

2.9 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: 2.22)].
(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.

2.10 Operating Principle

The fact that a synchronous motor has no starting torque can be easily explained.

(i) Consider a 3-phase synchronous motor having two rotor poles NR and SR. Then the stator will also be wound for two poles N_S and S_S. The motor has direct voltage applied to the rotor winding and a 3-phase voltage applied to the stator winding. The stator winding produces a rotating field which revolves round the stator at synchronous speed N_s (= 120 f/P). The direct (or zero frequency) current sets up a two-pole field which is stationary so long as the rotor is not turning. Thus, we have a situation in which there exists a pair of revolving armature poles (i.e., N_S - S_S) and a pair of stationary rotor poles (i.e., N_R - S_R).

(ii) Suppose at any instant, the stator poles are at positions A and B as shown in Fig: 2.22. It is clear that poles NS and NR repel each other and so do the poles SS and SR. Therefore, the rotor tends to move in the anticlockwise direction. After a period of half-cycle (or ½ f = 1/100 second), the polarities of the stator poles are reversed but the polarities of the rotor poles remain the same as shown in Fig: 2.22. 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.

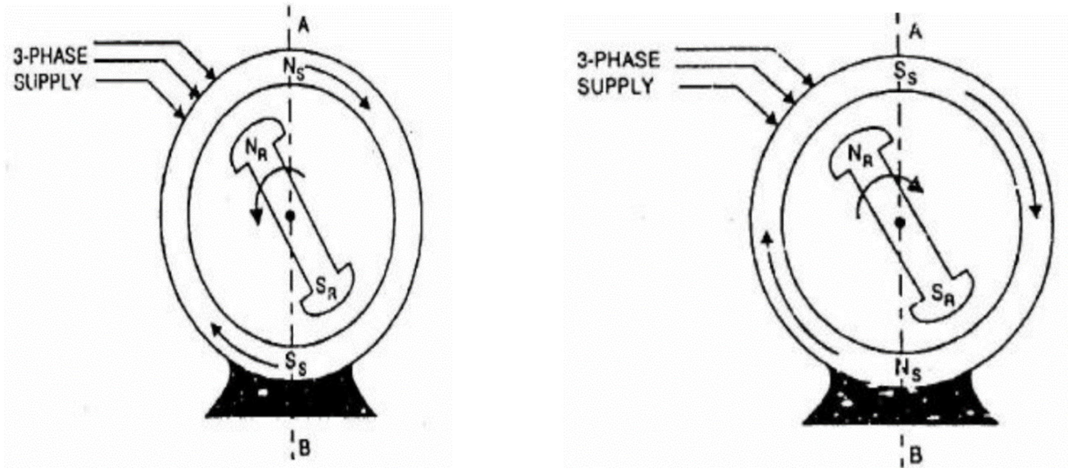


Fig: 2.22

2.11 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: 2.23 (i).

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

(i) The effect of stator field on the stator (or armature) conductors is accounted for by including an inductive reactance in the armature winding. This is called synchronous reactance Xs. A resistance Ra must be considered to be in series with this reactance to account for the copper losses in the stator or armature winding as shown in Fig: 2.23 (i). This resistance combines with synchronous reactance and gives the synchronous impedance of the machine.

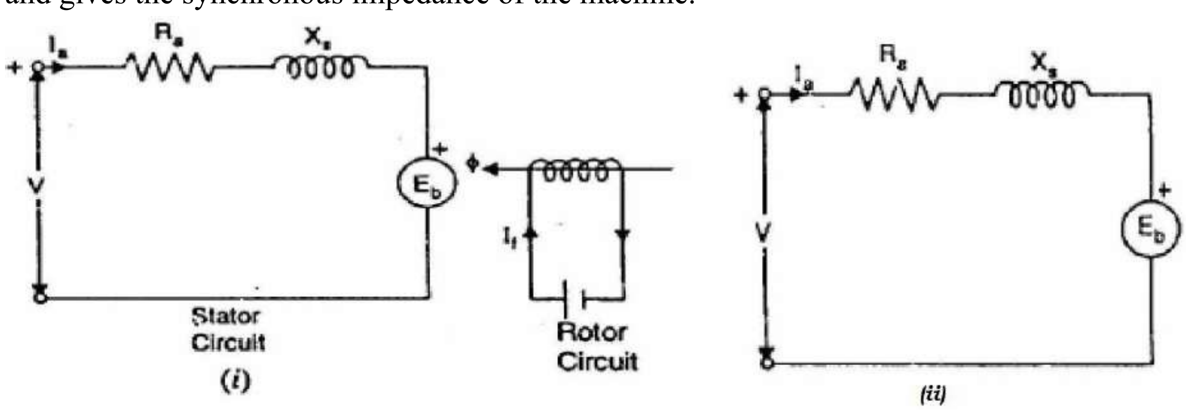


Fig: 2.23

(ii) The second effect is that a voltage is generated in the stator winding by the synchronously-revolving field of the rotor as shown in Fig: 2.23 (i). This generated e.m.f. E_b is known as back e.m.f. and opposes the stator voltage V. The magnitude of E_b depends upon rotor speed and rotor flux ϕ per pole. Since rotor speed is constant; the value of E_b depends upon the rotor flux per pole i.e. exciting rotor current I_f.
Fig: 2.23 (i) shows the schematic diagram for one phase of a star-connected synchronous motor while Fig: 2.23 (ii) shows its equivalent circuit. Referring to the equivalent circuit in Fig: 2.23 (ii).
Net voltage/phase in stator winding is
Er = V - Eb phasor difference
Armature current/phase,

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

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

This equivalent circuit helps considerably in understanding the operation of a synchronous motor.
A synchronous motor is said to be normally excited if the field excitation is such that Eb = V. If the field excitation is such that Eb < V, the motor is said to be under-excited. The motor is said to be over-excited if the field excitation is such that Eb > V. As we shall see, for both normal and under excitation, the motor has lagging power factor. However, for over-excitation, the motor has leading power factor.

2.12 Phasor Diagram

Fig: 2.24 shows the phasor diagrams for different field excitations at constant load. Fig: 2.24 (i) shows the phasor diagram for normal excitation (Eb = V), whereas Fig: 2.24 (ii) shows the phasor diagram for under-excitation. In both cases, the motor has lagging power factor. Fig: 2.24 (iii) shows the phasor diagram when field excitation is adjusted for unity p.f. operation. Under this condition, the resultant voltage Er and, therefore, the stator current Ia are minimum. When the motor is overexcited, it has leading power factor as shown in Fig: 2.24 (iv). The following points may be remembered:
(i) For a given load, the power factor is governed by the field excitation; a weak field produces the lagging armature current and a strong field produces a leading armature current.
(ii) The armature current (Ia) is minimum at unity p.f and increases as the p.f. becomes less either leading or lagging

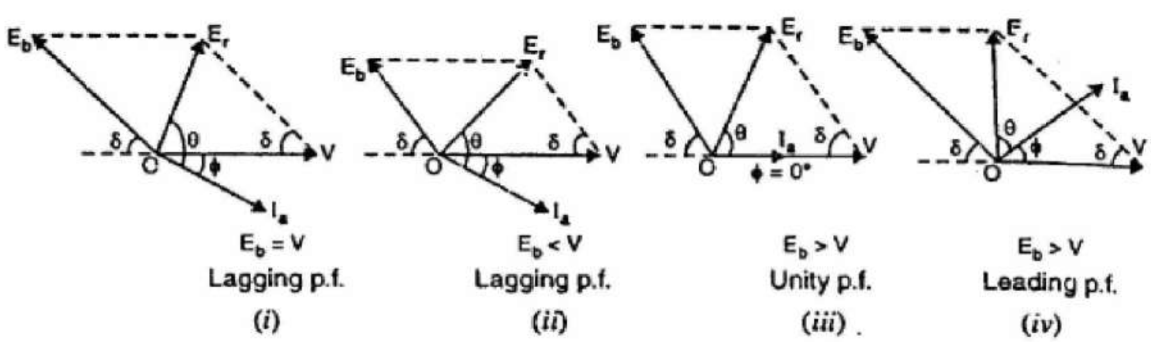


Fig: 2.24

2.13 Torque and Power Relations

Motor Torque

Gross torque, T =9.55 Pm/Ns N-M where Pm = Gross motor output in watts = Eb Ia cos(d - ϕ)
Ns = Synchronous speed in r.p.m.
Shaft torque, Tsh = 9.55 Psh_{out}/Ns N-M
It may be seen that torque is directly proportional to the mechanical power because rotor speed (i.e., Ns) is fixed.

Mechanical Power Developed

Neglecting the armature resistance Fig: 2.25 shows the phasor diagram of an under-excited synchronous motor driving a mechanical load. Since armature resistance Ra is assumed zero. tanq= Xs/Ra = ¥ and hence q =90°.
Input power/phase = V Ia cos ϕ
Since Ra is assumed zero, stator Cu loss $(I\ Ra)^2$ will be zero. Hence input power is equal to the mechanical power Pm developed by the motor.
Mechanical power developed/ phase, Pm = V Ia cos ϕ, referring to the phasor diagram in Fig: 2.25.

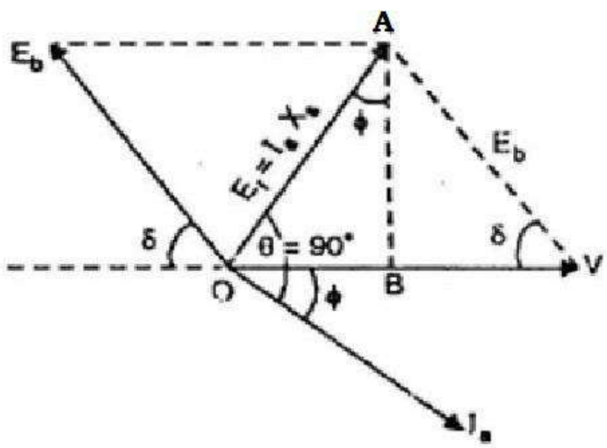


Fig: 2.25

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

$$AB = E_b \sin\delta$$

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

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

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

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

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

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

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

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

2.14 V-Curves and Inverted V-Curves

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

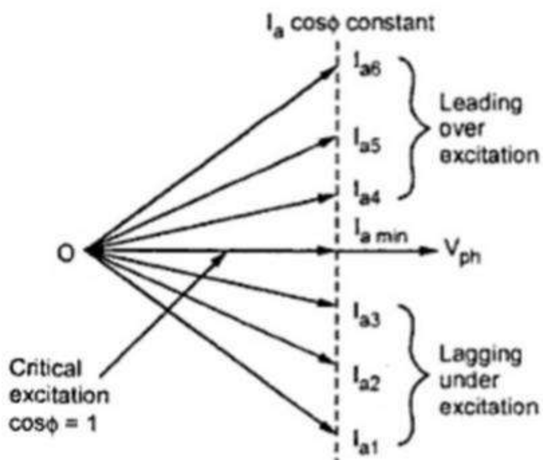


Fig: 2.26

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

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

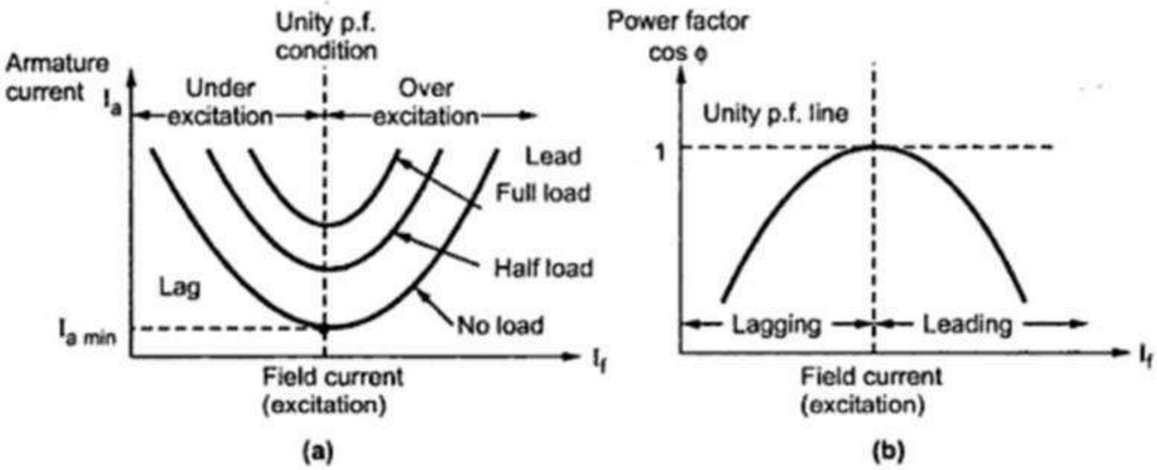


Fig: 2.27

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.

2.15 Effect of Changing Field Excitation at Constant Load

In a d.c. motor, the armature current Ia is determined by dividing the difference between V and Eb by the armature resistance Ra. Similarly, in a synchronous motor, the stator current (Ia) is determined by dividing voltage-phasor resultant (Er) between V and Eb by the synchronous impedance Zs. One of the most important features of a synchronous motor is that by changing the field excitation, it can be made to operate from lagging to leading power factor. Consider a synchronous motor having a fixed supply voltage and driving a constant mechanical load. Since the mechanical load as well as the speed is constant, the power input to the motor (=3 V*Ia *cos ϕ) is also constant. This means that the in-phase component Ia cos ϕ drawn from the supply will remain constant. If the field excitation is changed, back e.m.f Eb also changes. This results in the change of phase position of Ia w.r.t. V and hence the power factor cos φ of the motor changes. Fig: 2.28 shows the phasor diagram of the synchronous motor for different values of field excitation. Note that extremities of current phasor Ia lie on the straight line AB.

(i) Under excitation

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

90°) between Er and Ia is constant, therefore, phasor Ia also turns clockwise i.e., current Ia lags behind the supply voltage. Consequently, the motor has a lagging power factor.

(ii) Normal excitation

The motor is said to be normally excited if the field excitation is such that Eb = V. This is shown in Fig: 2.28 (ii). Note that the effect of increasing excitation (i.e., increasing Eb) is to turn the phasor Er and hence Ia in the anti-clockwise direction i.e., Ia phasor has come closer to phasor V. Therefore, p.f. increases though still lagging. Since input power (=3 V*Ia *cos ϕ) is unchanged, the stator current Ia must decrease with increase in p.f.
Suppose the field excitation is increased until the current Ia is in phase with the applied voltage V, making the p.f. of the synchronous motor unity [See Fig: 2.28 (iii)]. For a given load, at unity p.f. the resultant Er and, therefore, Ia are minimum.

(iii) Over excitation

The motor is said to be overexcited if the field excitation is such that Eb > V. Under-such conditions, current Ia leads V and the motor power factor is leading as shown in Fig: 2.28 (iv). Note that Er and hence Ia further turn anti-clockwise from the normal excitation position. Consequently, Ia leads V. From the above discussion, it is concluded that if the synchronous motor is under-excited, it has a lagging power factor. As the excitation is increased, the power factor improves till it becomes unity at normal excitation. Under such conditions, the current drawn from the supply is minimum. If the excitation is further increased (i.e., over excitation), the motor power factor becomes leading. Note. The armature current (Ia) is minimum at unity p.f and increases as the power factor becomes poor, either leading or lagging.

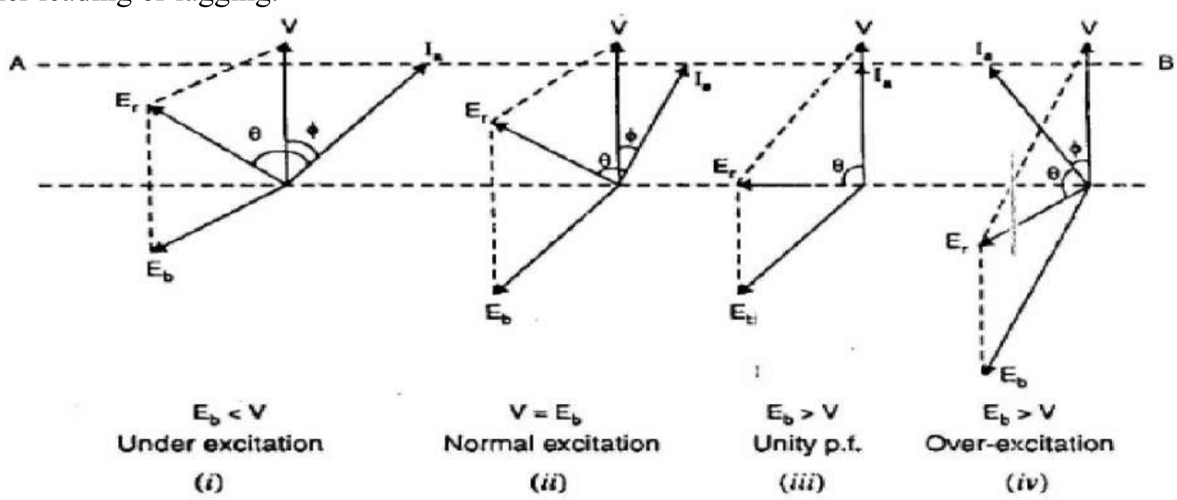


Fig: 2.28

2.16 Synchronous Condenser

A synchronous motor takes a leading current when over-excited and, therefore, behaves as a capacitor. An over-excited synchronous motor running on no-load in known as synchronous condenser. When such a machine is connected in parallel with induction motors or other devices that operate at low lagging power factor, the leading kVAR supplied by the synchronous condenser partly neutralizes the lagging reactive kVAR of the loads. Consequently, the power factor of the system is improved. Fig: 2.29 shows the power factor improvement by synchronous condenser method. The 3 - f load takes current IL at low lagging power factor cos ϕ_L. The synchronous condenser takes a current Im which leads the voltage by an angle fm. The resultant current I is the vector sum of Im and I_L and lags behind the voltage by an angle ϕ. It is clear that ϕ is less than ϕ_L so that cos f is greater than cos ϕ_L. Thus the power factor is increased from cos ϕ_L to cos ϕ. Synchronous condensers are generally used at major bulk supply substations for power factor improvement.

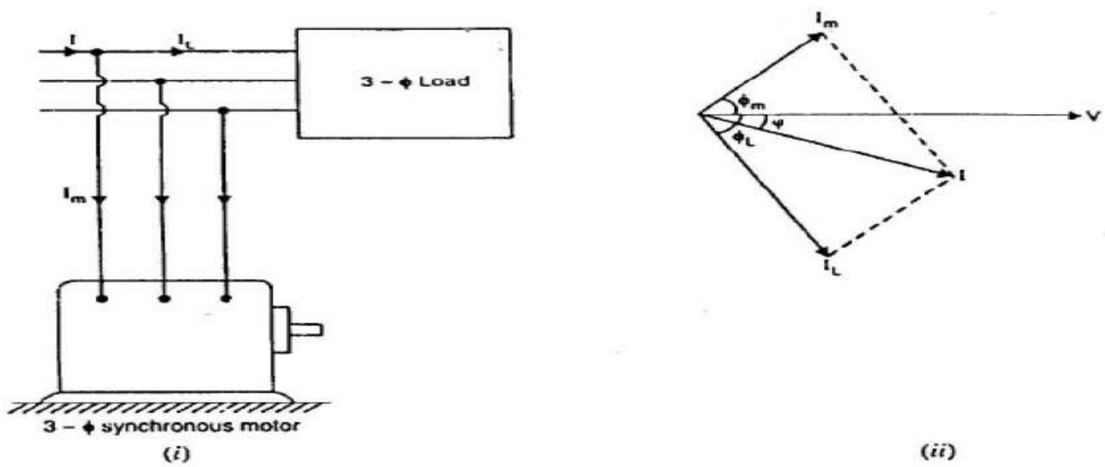


Fig: 2.29

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.

2.17 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 (usually called the counter EMF) $E_A = K\varphi\omega$ will be smaller than normal. As such the terminal 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 varies roughly linearly with the output frequency.

Motor Starting with an External Motor

The second method of starting a synchronous motor is to attach an external starting motor (pony motor) to it and bring the synchronous machine to near about its rated speed (but not exactly equal to it, as the synchronization process may fail to indicate the point of closure of the main switch connecting the synchronous machine to the supply system) with the pony motor. Then the output of the synchronous machine can be synchronised or paralleled with its power supply system as a generator, and the pony motor can be detached from the shaft of the machine or the supply to the pony motor can be disconnected. Once the pony motor is turned OFF, the shaft of the machine slows down, the speed of the rotor magnetic field B_R falls behind B_{net}, momentarily and the synchronous machine continues to operate as a motor. As soon as it begins to operate as a motor the synchronous motor can be loaded in the usual manner just like any motor.

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

Generally most of the large synchronous motors have brushless excitation systems mounted on their shafts. It is then possible to use these exciters as the starting motors. For many medium-size to large synchronous motors, an external starting motor or starting by using the exciter may be the only possible solution, because the power systems they are tied to may not be able to handle the starting currents needed to use the damper (amortisseur) winding.

Motor Starting by using damper (Amortisseur) Winding

As already mentioned earlier most of the large synchronous motors are provided with damper windings, in order to nullify the oscillations of the rotor whenever the synchronous machine is subjected to a periodically varying load. Damper windings are special bars laid into slots cut in the pole face of a synchronous machine and then shorted out on each end by a large shorting ring, similar to the squirrel cage rotor bars. A salient pole rotor with sets of damper windings is shown in Fig: 2.30 below.

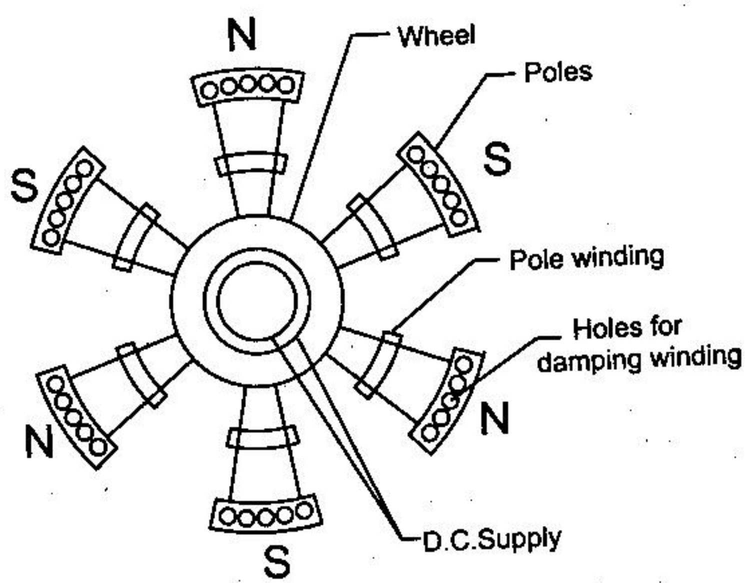


Fig: 2.30

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.

2.18 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: 2.31; As the applied stator voltage, frequency, and field excitation are assumed, constant. The initial load conditions, are represented by the thick lines. The effect of increasing the shaft load to twice its initial value are represented by the light lines indicating the new steady state conditions. When the shaft load is doubled both Ia cos φi and Ef sin δ are doubled. While redrawing the phasor diagrams to show new steady-state conditions, the line of action of the new jIaXs phasor must be perpendicular to the new Ia phasor. Furthermore, as shown in Fig: 2.31, if the excitation is not changed, increasing the shaft load causes the locus of the Ef phasor to follow a circular arc, thereby increasing its phase angle with increasing shaft load. Note also that an increase in shaft load is also accompanied by a decrease in φi ; resulting in an increase in power factor.
As additional load is placed on the machine, the rotor continues to increase its angle of lag relative to the rotating magnetic field, thereby increasing both the angle of lag of the counter EMF phasor and the magnitude of the stator current. It is interesting to note that during all this load variation, however, except for the duration of transient conditions whereby the rotor assumes a new position in relation to the rotating magnetic field, the average speed of the machine does not change. As the load is being increased, a final point is reached at which a further increase in δ fails to cause a corresponding increase in motor torque, and the rotor pulls out of synchronism. In fact as stated earlier, the rotor poles at this point, will fall behind the stator poles such that they now come under the influence of like poles and the force of attraction no longer exists. Thus, the point of maximum torque occurs at a power angle of approximately 90◦ for a cylindrical-rotor machine. This maximum value of torque that causes a synchronous motor to pull out of synchronism is called the pull-out torque. In actual practice, the motor will never be operated at power angles close to 90◦ as armature current will be many times its rated value at this load.

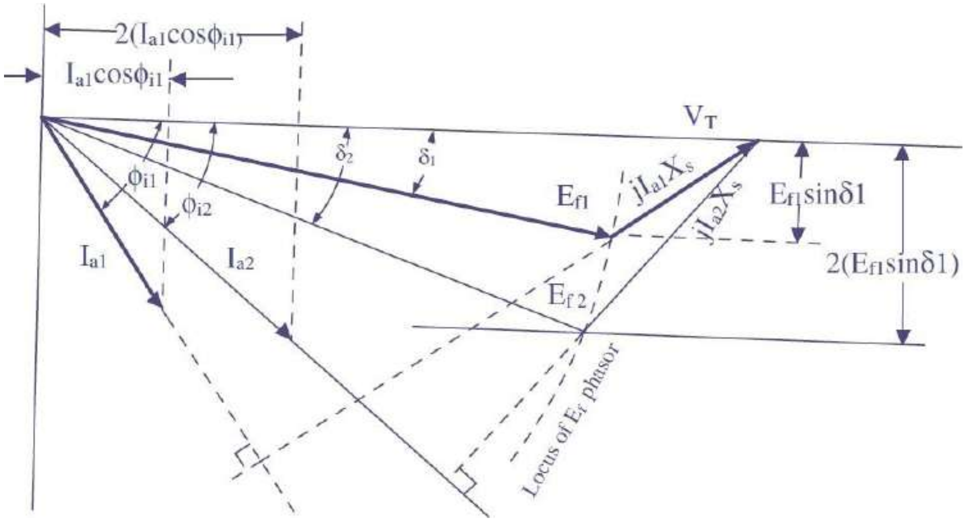


Fig: 2.31

Effect of changes in field excitation on synchronous motor performance

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

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

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

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

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

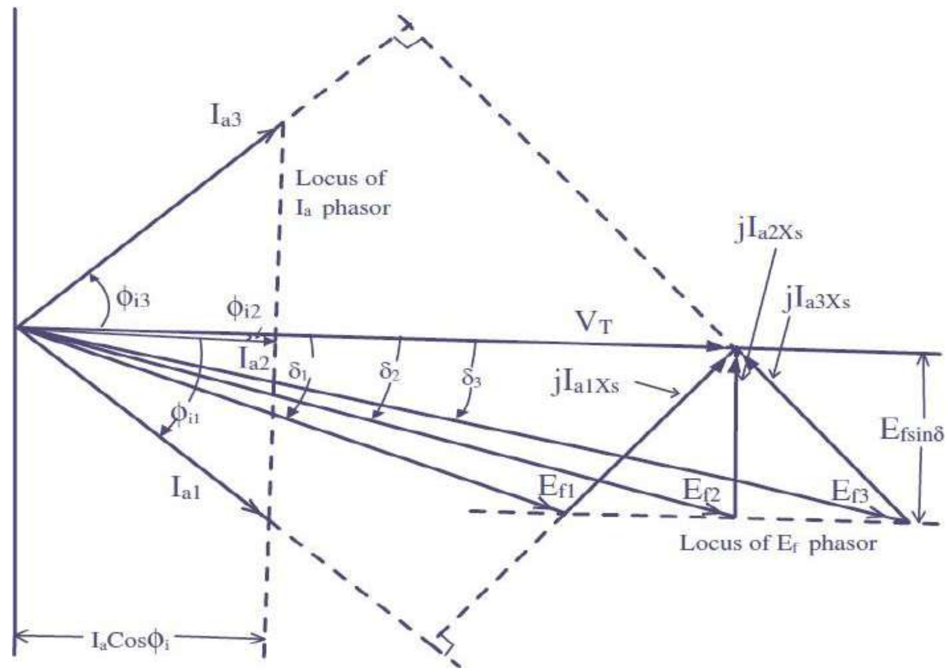


Fig: 2.32

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

Power Factor Characteristic of Synchronous Motors

In an induction motor, only one winding (i.e., stator winding) produces the necessary flux in the machine. The stator winding must draw reactive power from the supply to set up the flux. Consequently, induction motor must operate at lagging power factor. But in a synchronous motor, there are two possible sources of excitation; alternating current in the stator or direct current in the rotor. The required flux may be produced either by stator or rotor or both.

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

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

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

were a capacitor. In other words, the motor operates at a leading power factor.
To sum up, a synchronous motor absorbs reactive power when it is under excited and delivers reactive power to source when it is over-excited.

2.19 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: 2.33 shows a salient pole synchronous motor with damper winding.

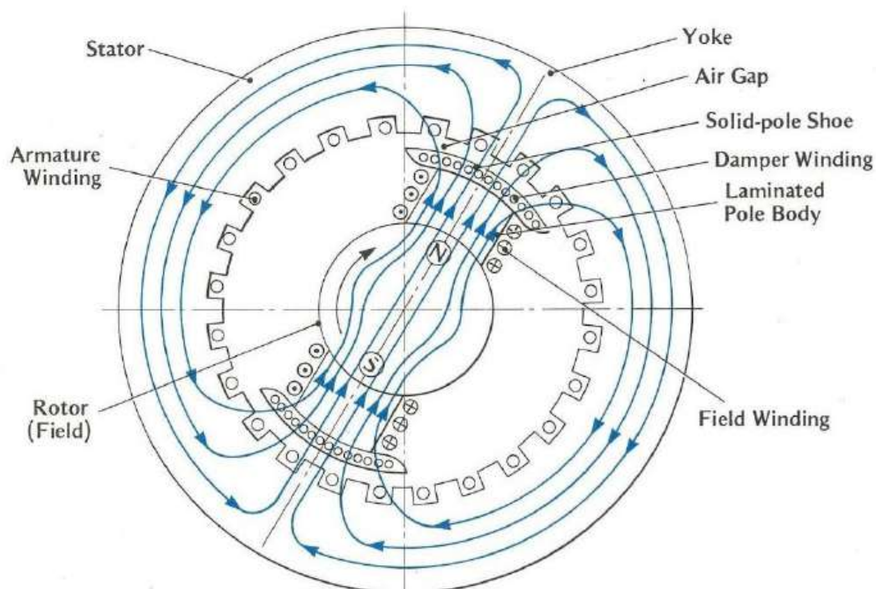


Fig: 2.33