UNIT -3

SYNCHRINOUS GENERATORS

Working Principle of Alternator

The **working principle of an alternator** is very simple. It is just like the basic principle of DC generator. It also depends upon Faraday's law of electromagnetic induction which says the current is induced in the conductor inside a magnetic field when there is a relative motion between that conductor and the magnetic field.

working of alternator let us think about a single rectangular turn placed in between two opposite magnetic poles as shown above.

Say this single turn loop ABCD can rotate against axis a-b. Suppose this loop starts rotating clockwise. After 90 rotation the side AB or conductor AB of the loop comes in front of S-pole and conductor CD comes in front of N-pole. At this position the tangential motion of the conductor AB is just perpendicular to the magnetic flux lines from N to S pole. Hence, the rate of flux cutting by the conductor AB is maximum here and for that flux cutting there will be an induced current in the conductor AB and the direction of the induced current can be determined by Fleming's right-hand rule. As per this rule the direction of this current will be from A to B. At the same time conductor CD comes under N pole and here also if we apply Fleming right-hand rule we will get the direction of induced current and it will be from C to D.

Now after clockwise rotation of another 90 the turn ABCD comes at the vertical position as shown below. At this position tangential motion of conductor AB and CD is just parallel to the magnetic flux lines, hence there will be no flux cutting that is no current in the conductor.

While the turn ABCD comes from a horizontal position to a vertical position, the angle between flux lines and direction of motion of conductor, reduces from 90 to 0 and consequently the induced current in the turn is reduced to zero from its maximum value.

After another clockwise rotation of 90 the turn again comes to horizontal position, and here conductor AB comes under N-pole and CD comes under S-pole, and here if we again apply Fleming right-hand rule, we will see that induced current in conductor AB, is from point B to A and induced current in the conductor CD is from D to C.

As at this position the turn comes at a horizontal position from its vertical position, the current in the conductors comes to its maximum value from zero. That means current is circulating in the close turn from point B to A, from A to D, from D to C and from C to B, provided the loop is closed although it is not shown here. That means the current is in reverse of that of the previous horizontal position when the current was circulating as A → B → C → D → A.

While the turn further proceeds to its vertical position the current is again reduced to zero. So if the turn continues to rotate the current in turn continually alternate its direction. During every full revolution of the turn, the current in turn gradually reaches to its maximum value then reduces to zero and then again it comes to its maximum value but in opposite direction and again it comes

to zero. In this way, the current completes one full sine wave cycle during each 360 revolution of the turn. So, we have seen how alternating current is produced in a turn is rotated inside a magnetic field. From this, we will now come to the actual **working principle of an alternator**.

Now we place one stationary brush on each slip ring. If we connect two terminals of an external load with these two brushes, we will get an alternating current in the load. This is our elementary model of an alternator.

Having understood the very basic principle of an alternator, let us now have an insight into its basic operational principle of a practical alternator. During the discussion of the basic working principle of an alternator, we have considered that the magnetic field is stationary and conductors (armature) is rotating. But generally in practical construction of alternator, armature conductors are stationary and field magnets rotate between them. The rotor of an alternator or a synchronous generator is mechanically coupled to the shaft or the turbine blades, which is made to rotate at synchronous speed N under some mechanical force results in magnetic flux cutting of the stationary armature conductors housed on the stator.

As a direct consequence of this flux cutting an induced emf and current starts to flow through the armature conductors which first flow in one direction for the first half cycle and then in the other direction for the second half cycle for each winding with a definite time lag of 120 due to the space displaced arrangement of 120 between them as shown in the figure below. This particular phenomenon results in three-phase power flow out of the alternator which is then transmitted to the distribution stations for domestic and industrial uses.

Types Of Alternator

The alternator can be divided into different types based on their application, prime mover, design, output power, and cooling.

Alternator Based on their Output Power

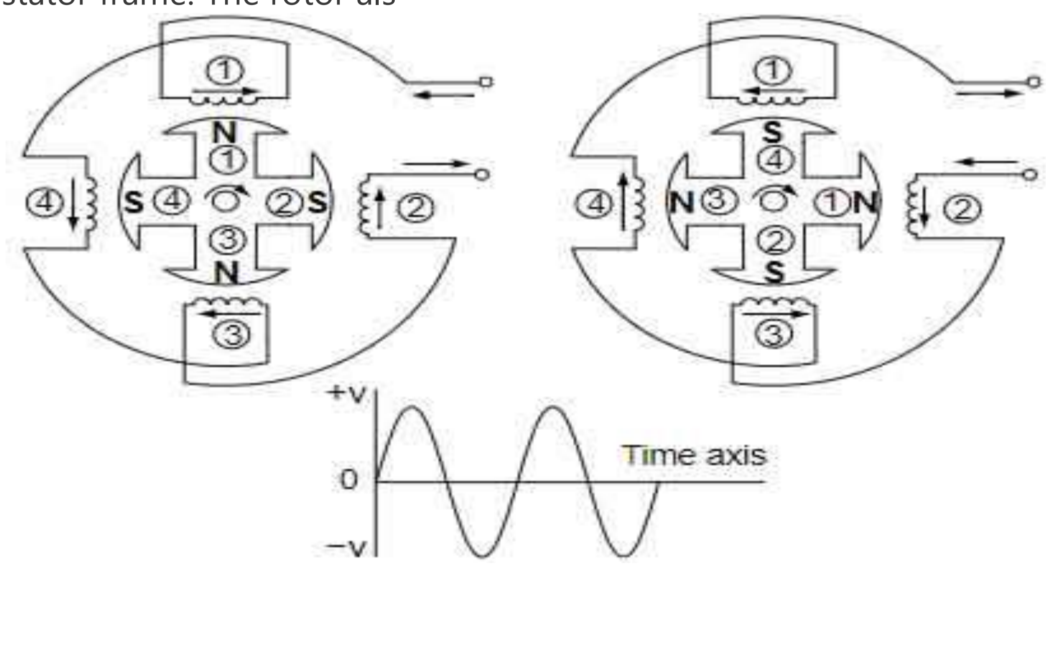
1. Single Phase Alternator
2. Two-Phase Alternator
3. Three Phase Alternator

Single Phase Alternator

The single phase alternator produces a continuous single alternating voltage. The armature coils are connected in series forming a Single circuit in which output voltage is generated.

Single phase Alternator

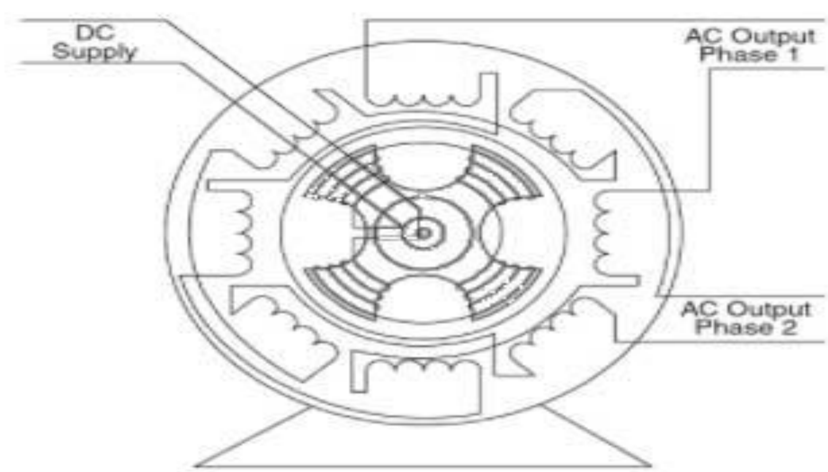
In the above figure, the stator has four poles which are evenly spaced around the stator frame. The rotor als



The rotor also consists 4 poles and each pole has opposite polarity to its neighbours which are angled at 90 degrees. Each coil also has opposite winding to its neighbours. This configuration allows the lines of force at 4 poles to be cut by 4 coils at the same amount at a given time. At each 90-degree rotation, the voltage output polarity is switched from one direction to the other. Therefore, there are 4 cycles of the AC output in one rotation.

Single-phase generators are used as standby generators in case of the main power supply is interrupted and for supplying temporary power on construction sites.

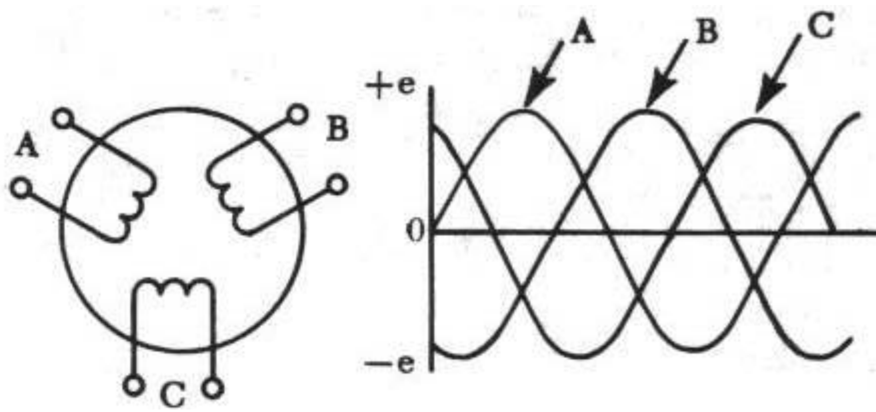
Two-Phase Alternator



Two-Phase Alternator

In a two-phase alternator, there are two single-phase windings spaced physically so that the ac voltage induced in one is 90° out of phase with the voltage induced in the other. The windings are electrically separate from each other. Suppose in the first quarter first winding produce maximum flux, then the second winding generates zero flux and in the second quarter the second winding generates maximum flux and first winding generate zero flux. This condition establishes a 90° relation between the two phases.

Three Phase Alternator



Three-phase-alternator

A three-phase alternator has 3 sets of single-phase windings arrangement so that the voltage induced in each winding is 120° out of phase with the voltages in the other two windings. These windings are connected in the star to provide a three-phase output.

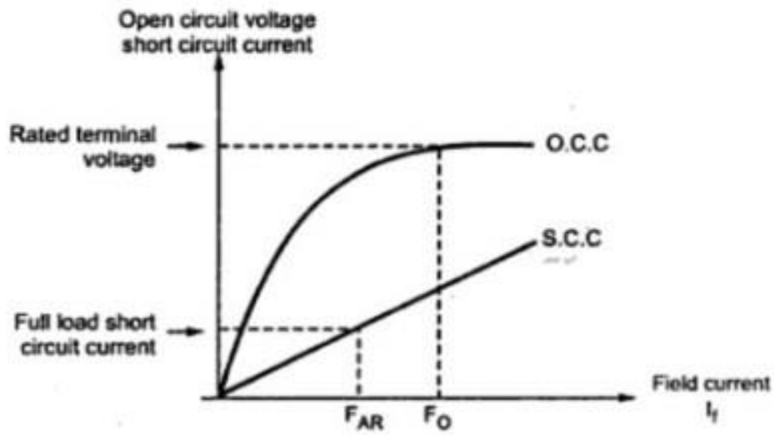
Synchronous Impedance or E.M.F. Method for finding a Voltage Regulation

The Synchronous Impedance Method or Emf Method is based on the concept of replacing the effect of armature reaction by an imaginary reactance. The method requires following data to calculate the regulation.

1. **The open -circuit characteristic (O.C.C) :**

- The O.C.C is a plot of the armature terminal voltage as a function of
- . field current with a symmetrical three phase short-circuit applied across the armature terminals with the machine running at rated speed.
- At any value of field current, if E is the open circuit voltage and Isc is the short circuit current then for this value of excitation
  - Zs = E/Sic
- At higher values of field current, saturation increases and the synchronous impedance decreases.

- The value of Zs calculated for the unsaturated region
- The O.C.C is called the unsaturated value of the synchronous impedance.



2. **The short-circuit characteristic (S.C.C)**

- The S.C.C is a plot of short-circuit armature current versus the field current.
- The current range of the instrument should be about 25-50 % more than the full load current of the alternator.
- Starting with zero field current, increase the field current gradually and cautiously till rated current flows in the armature.
- The speed of the set in this test also is tom be maintained at the rated speed of the alternator.

3. **Resistance of the armature winding.**

- Measure the D.C. resistance of he armature circuit of the alternator.
- The effective a.c resistance may be taken to be 1.2 times the D.C. resistance.

Regulation Calculation

- From O.C.C. and S.C.C., Z_s can be determined for any load condition.

- The armature resistance per phase can be measured by different methods.
- One of the method is applying d.c. known voltage across the two terminals and measuring current. So value of R_a per phase is known.

$$Xs = \sqrt{Zs^2 - Ra^2}$$

So synchronous reactance per phase can be determined.

- No load induced e.m.f. per phase, E_{ph} can be determined by the mathematical expression derived earlier.

$$Eph = [\ \sqrt{I(V\cos\varphi + IRa)^2 + I(V\sin\varphi + IXs)^2}\ ]$$

where V_{ph} = Phase value of rated voltage
I_a = Phase value of current depending on the load condition
$\cos\Phi$ = p.f. of load

- Positive sign for lagging power factor while negative sign for leading power factor, R_a and X_s values are known from the various tests performed.

The regulation then can be determined by using formula,

$$\text{Percentage Voltage Regulation} = \left(\frac{|E_0| - |V|}{|V|}\right)$$

EMF Equation of an Alternator / AC Generator

An alternator or AC generator (dynamo) is a device which convert mechanical energy to electrical energy. When we supply the magnetizing current by DC shunt generator through two slip rings (in recent alternators, they use electronic starting system instead of slip rings and commutators) because the field magnets are rotating. keep in mind that most alternators use a rotating magnetic field with a stationary armature.

When the rotor rotates, the stator conductors which are static in case of alternator cut by magnetic flux, they have induced EMF produced in them (according to **Faraday's law of electromagnetic induction** which states that if a conductor or coil links with any changing flux, there must be an induced emf in it.

Note: We will discuss the construction, Working & Operation. Types of Alternators in detail

This induced EMF can be found by the **EMF equation of the alternator** which as follow:

Lets,

P = No. of poles

Z = No. of Conductors or Coil sides in series/phase i.e. **Z = 2T**…Where T is the number of coils or turns per phase (Note that one turn or coil has two ends or sides)

f = frequency of induced EMF in Hz

Φ = Flux per pole (Weber)

N = rotor speed (RPM)

K_d= Distribution factor = $\dfrac{\text{Sin } m\,\beta/2}{m \text{ Sin } \beta/2}$

Where Distribution factor = K_d = $\dfrac{\text{e.m.f. with distributed winding}}{\text{e.m.f. with concentrated winding}}$

K_c or K_P = **Cos α/2**

If induced EMF is assumed sinusoidal then,

$$K_f = \text{Form factor} = 1.11$$

In one revolution of the rotor i.e. in **60/N** seconds, each conductor is cut by a flux of **ΦP** Webers.

$$d\Phi = \Phi P \text{ and also } d\Phi = 60/N \text{ seconds}$$

then induced e.m.f per conductor (average) = $= \dfrac{d\Phi}{dt} = \dfrac{\Phi P}{60/N} = \dfrac{\Phi NP}{60}$ ….. *(i)*

But we know that:

$$f = PN/120 \text{ or } N = 120f/P$$

Putting the value of **N** in **Equation *(i)***, we get,

Average value of EMF per conductor = $= \dfrac{\Phi P}{60} \times \dfrac{120 f}{P} = 2 f \Phi \text{ volt}$ ∴ **(N= 120f/P)**

If there are **Z** conductors in series per phase,

then average e.m.f per phase = **2 f Φ Z** Volts **= 4 f ΦT *Volts*** ….. (Z=2T)

Also we know that;

Form Factor= RMS Value / Average Value

= RMS value= Form factor x Average Value,

= 1.11 x 4fΦT = 4.44fΦT Volts.

(Note that is exactly the same equation as the EMF equation of the transformer)

And the actual available voltage per phase

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And the actual available voltage per phase

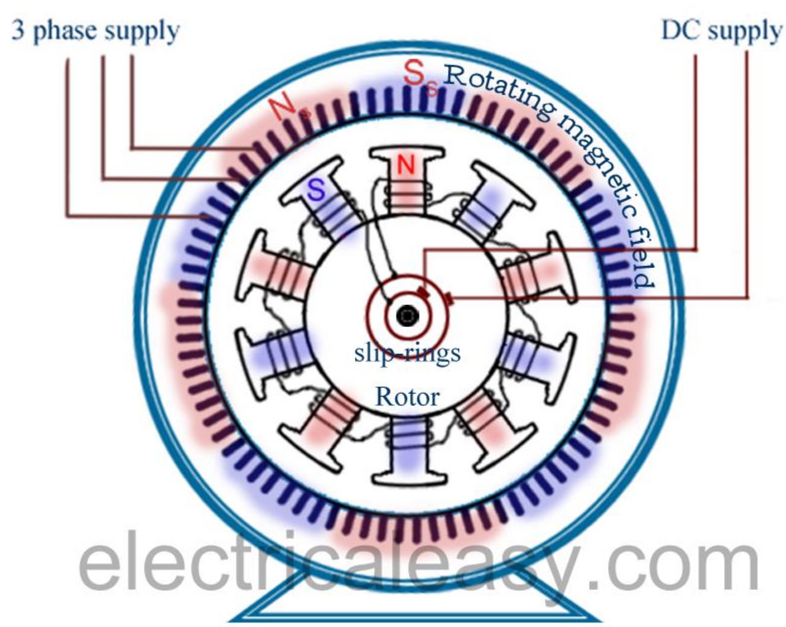
= 4 K_c K_d f ΦT = 4 K_f K_c K_d f ΦT Volts.

Note: If alternator or AC generator is star connected as usually the case, then the Line Voltage is √3 times the phase voltage as derived from the the above formula.

Synchronous motor - construction and working

Synchronous motor and induction motor are the most widely used types of AC motor. Construction of a synchronous motor is similar to an alternator (AC generator). A same **synchronous machine** can be used as a synchronous motor or as an alternator. Synchronous motors are available in a wide range, generally rated between 150kW to 15MW with speeds ranging from 150 to 1800 rpm.

Construction of synchronous motor

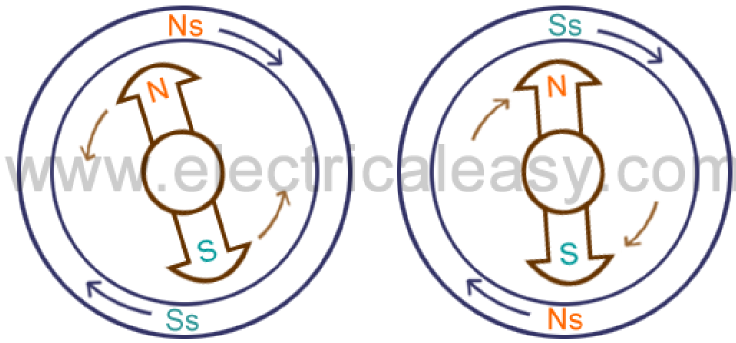


The **construction of a synchronous motor** (with salient pole rotor) is as shown in the figure at left. Just like any other motor, it consists of a stator and a rotor. The stator core is constructed with thin silicon lamination and insulated by a surface coating, to minimize the eddy current and hysteresis losses. The stator has axial slots inside, in which three phase stator winding is placed. The stator is wound with a three phase winding for a specific number of poles equal to the rotor poles.

The **rotor in synchronous motors** is mostly of salient pole type. DC supply is given to the rotor winding via slip-rings. The direct current excites the rotor winding and creates electromagnetic poles. In some cases permanent magnets can also be used. The figure above illustrates the **construction of a synchronous motor** very briefly.

Working of synchronous motor

The stator is wound for the similar number of poles as that of rotor, and fed with three phase AC supply. The 3 phase AC supply produces rotating magnetic field in stator. The rotor winding is fed with DC supply which magnetizes the rotor. Consider a two pole **synchronous machine** as shown in figure below.



- of above figure), then the poles of the stator and rotor will repel each other, and the *torque produced will be anticlockwise*. Now, the stator poles are revolving with synchronous speed (lets say clockwise). If the rotor position is such that, N pole of the rotor is near the N pole of the stator (as shown in first schematic
- The stator poles are rotating with synchronous speed, and they rotate around very fast and interchange their position. But at this very soon, rotor can not rotate with the same angle (due to inertia), and the next position will be likely the second schematic in above figure. In this case, poles of the stator will attract the poles of rotor, and *the torque produced will be clockwise.*
- Hence, the rotor will undergo to a rapidly reversing torque, and the motor will not start.

  But, if the rotor is rotated upto the synchronous speed of the stator by means of an external force (in the direction of revolving field of the stator), and the rotor field is excited near the synchronous speed, the poles of stator will keep attracting the opposite poles of the rotor (as the rotor is also, now, rotating with it and the position of the poles will be similar throughout the cycle). Now, the rotor will undergo unidirectional torque. The opposite poles of the stator and rotor will get locked with each other, and the rotor will rotate at the synchronous speed.

Characteristic features of a synchronous motor

- Synchronous motor will run either at synchronous speed or will not run at all.

- The only way to change its speed is to change its supply frequency. (As Ns =120f / P)
  - lectrical motor in general is an electro-mechanical device that converts energy from electrical domain to mechanical domain.A **synchronous electric motor** is an AC motor in which, at steady state,[1] the rotation of the shaft is synchronized with the frequency of the supply current; the rotation period is exactly equal to an integral number of AC cycles. Synchronous motors contain multiphase AC electromagnets on the stator of the motor that create a magnetic field which rotates in time with the oscillations of the line current. The rotor with permanent magnets or electromagnets turns in step with the stator field at the same rate and as a result, provides the second synchronized rotating magnet field of any AC motor. A synchronous motor is termed *doubly fed* if it is supplied with independently excited multiphase AC electromagnets on both the rotor and stator Based on the type of input we have classified it into single phase and 3 phase motors. Synchronous motorsare more widely used in industrial

  - **Main Features:**
  - Some of the main features of synchronous motor are as follows:-
  - **1.** Synchronous motors are inherently not self starting.
  - **2.** They require some external means to bring their speed close to synchronous speed to before they are synchronized.

- **3.** The speed of operation of is in **synchronism** with the supply frequency.
- **4.** At supply frequency is constant they behave as constant speed **motor** irrespective of load condition.
- **5.** This motor has the unique characteristics of operating under any electrical power factor. This makes it used in electrical for power factor improvement.
- **Application Of Synchronous Motors:**
- **1.** As synchronous motor is capable of operating under either leading and lagging power factor, it can be used for power factor improvement. A synchronous motor under no-load have leading power factor. It is used in power system in place of static capacitors.
- **2.** Synchronous motor is used where high power at low speed required. Such as rolling mills, chippers, mixers, pumps, pumps, compressor etc.

Phasor Diagram for Synchronous Motor

We will discuss here the simplest way of drawing the **phasor diagram for synchronous motor** and we will also discuss advantages of drawing the phasor diagram. Before we draw phasor diagram, let us write the various notations for each quantity at one place. Here we will use:

E_f to represent the excitation voltage

V_t to represent the terminal voltage

I_a to represent the armature current

Θ to represent the angle between terminal voltage and armature current

ψ to represent the angle between the excitation voltage and armature current

δ to represent the angle between the excitation voltage and terminal voltage

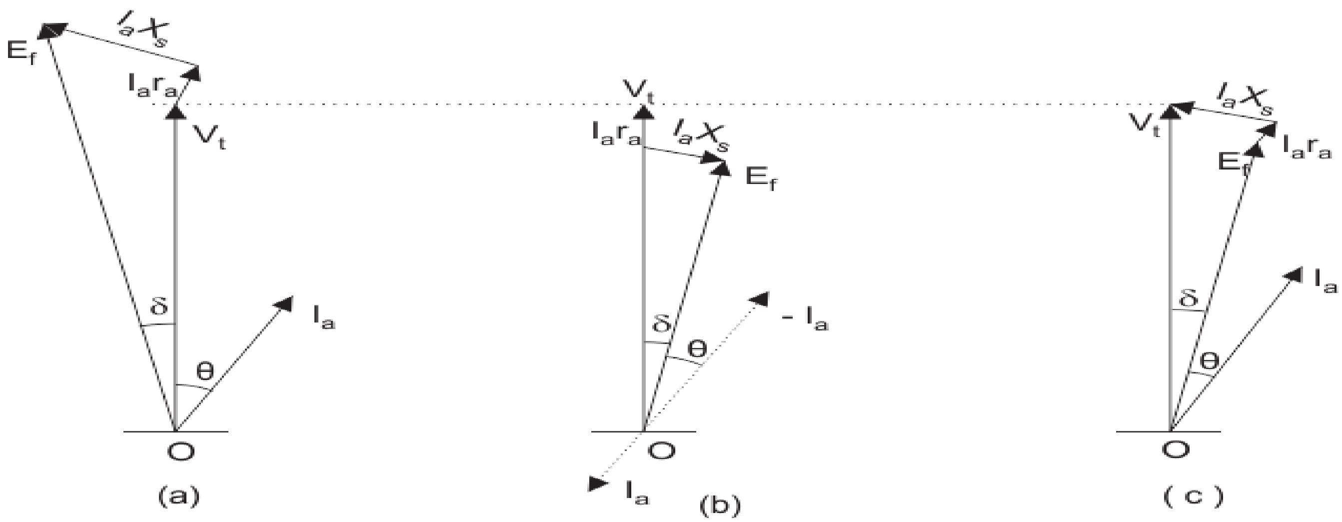
r_a to represent the armature per phase resistance.

We will take V_t as the reference phasor in order to **phasor diagram for synchronous motor**. In order to draw the phasor diagram one should know these two important points which are written below:

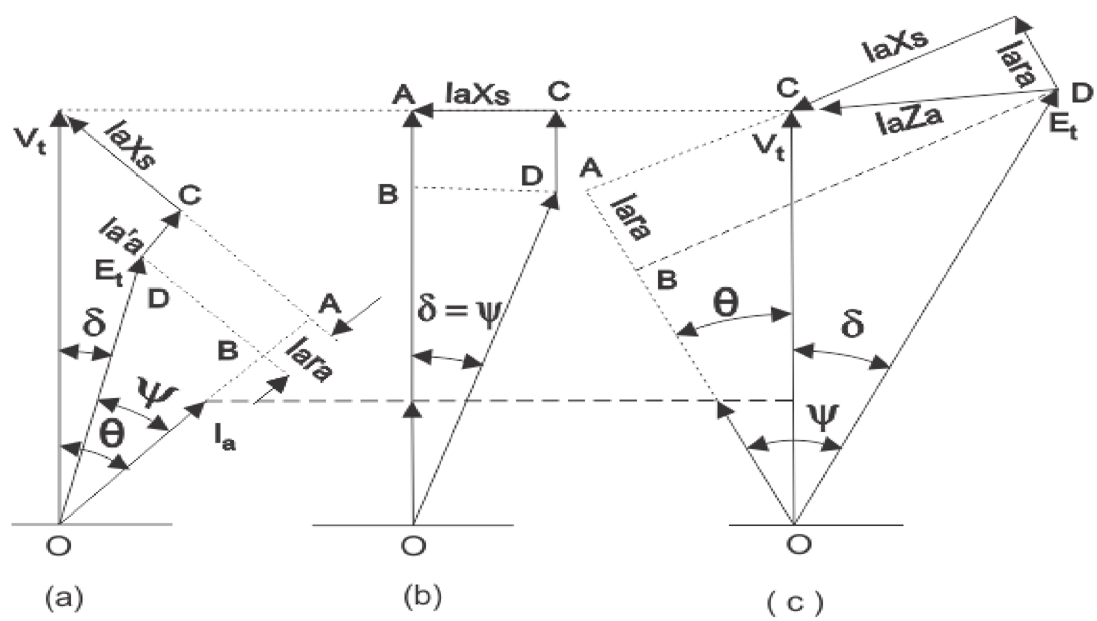
(1) We know that if a machine is made to work as a asynchronous motor then direction of armature current will in phase opposition to that of the excitation emf.

(2) Phasor excitation emf is always behind the phasor terminal voltage.

Above two points are sufficient for drawing the phasor diagram for synchronous motor. The phasor diagram for the synchronous motor is given below,



In the phasor one the direction of the armature current is opposite in phase to that of the excitation emf.
It is usually customary to omit the negative sign of the armature current in the phasor of the synchronous motor so in the phasor two we have omitted the negative sign of the armature current. Now we will draw complete phasor diagram for the synchronous motor and also derive expression for the excitation emf in each case. We have three cases that are written below:



(a) Motoring operation at lagging power factor.
(b) Motoring operation at unity power factor.

(c) Motoring operation at leading power factor.
Given below are the phasor diagrams for all the operations.

(a) Motoring operation at lagging power factor: In order to derive the expression for the excitation emf for the lagging operation we first take the component of the terminal voltage in the direction of armature current I_a. Component in the direction of armature current is $V_t\cos\Theta$.

As the direction of armature is opposite to that of the terminal voltage therefore voltage drop will be $-I_a r_a$ hence the total voltage drop is $(V_t\cos\Theta - I_a r_a)$ along the armature current. Similarly we can calculate the voltage drop along the direction perpendicular to armature current. The total voltage drop comes out to be $(V_t\sin\theta - I_a X_s)$. From the triangle BOD in the first phasor diagram we can write the expression for excitation emf as

$$E_f^2 = (V_t cos\theta - I_a \times r_a)^2 + (V_t sin\theta - I_a \times X_s)^2$$

(b) Motoring operation at unity power factor: In order to derive the expression for the excitation emf for the unity power factor operation we again first take the component of the terminal voltage in the direction of armature current I_a. But here the value of theta is zero and hence we have $\Psi = \delta$. From the triangle BOD in the second phasor diagram we can directly write the expression for excitation emf as

$$E_f^2 = (V_t - I_a \times r_a)^2 + (I_a \times X_s)^2$$

(c) Motoring operation at leading power factor: In order to derive the expression for the excitation emf for the leading power factor operation we again first take the component of the terminal voltage in the direction of armature current I_a. Component in the direction of armature current is $V_t\cos\Theta$. As the direction of armature is opposite to that of the terminal voltage therefore voltage drop will be $(-I_a r_a)$ hence the total voltage drop is $(V_t\cos\Theta - I_a r_a)$ along the armature current. Similarly we can calculate the voltage drop along the direction perpendicular to armature current. The total voltage drop comes out to be $(V_t\sin\theta + I_a X_s)$. From the triangle BOD in the first phasor diagram we can write the expression for excitation emf

(b) **Equivalent circuit of synchronous motor** fig. 38.9 (*a*) shows the equivalent circuit model for one armature phase of a cylindrical rotor synchronous motor.

It is seen from Fig. 38.9 (*b*) that the phase applied voltage *V* is the vector sum of reversed back e.m.f. *i.e.*, –*Eb* and the impedance drop *Ia ZS*. In other words, *V* = (-*Eb* + *Ia ZS*). The angle a* between the phasor for *V* and *Eb* is called the load angle or power angle of the synchronous motor.

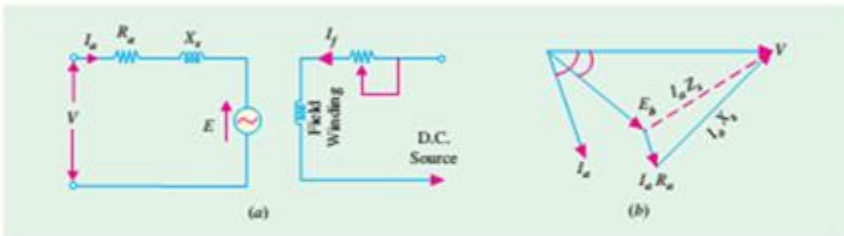


Fig. 38.9