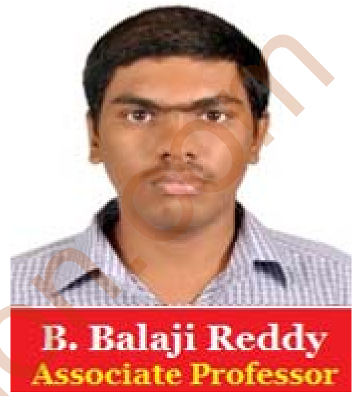
Synchronous Generators

Introduction



A.C. system has a number of advantages over D.C. system. In these days, 3-phase A.C. system is being exclusively used for generation, transmission and distribution of power. The biggest size of alternator used in India has a rating of 1700MVA (P.S. Bimra). For bulk power generation, the stator wdg of alternator is designed for voltage ratings of 6.6KV to 33KV.

Operating or Working Principle

A synchronous generator or alternator is machine, which converts mechanical energy from prime mover to A.C. electrical power, at specified voltage and frequency. An alternator operates on the same fundamental principle of electromagnetic induction as a D.C. generator i.e., when the flux linking with the conductor, an e.m.f. is induced across the conductor.

Like a D.C. generator, an alternator also has an armature winding and a field winding. The rotor winding is energized from the D.C. excitation and N&S poles are developed on the rotor. When the rotor is rotated by a prime mover, the stator or armature conductors are cut by the magnetic flux of rotor poles. Consequently, an e.m.f. is induced in the armature conductors. The induced e.m.f. is alternating since N and S poles of rotor alternately pass the armature conductors. The direction of induced e.m.f. can be found by Fleming's right hand rule and frequency is given by Ns=120f/P. The magnitude of the induced voltage depends on the rotor excitation and rotor conductors.

Constructional details

An alternator mainly consists of two parts. Those are (i) Stator and (ii) Rotor

Stator:

The stator is a stationary part and it carries stator winding in which an emf is generated. The various parts of stator are shown in Figure-a. Generally, the stator frame is made up of iron for small size machines and steel is used for large size machines. The main function of stator frame is it acts as protecting cover for machine from dust and mechanical injuries. The stator core is made up of high grade silicon steel with lamination to reduce iron losses. The stator core has slots to place 3-ph winding called ***stator winding***. The stator is star connected and distributed type winding.

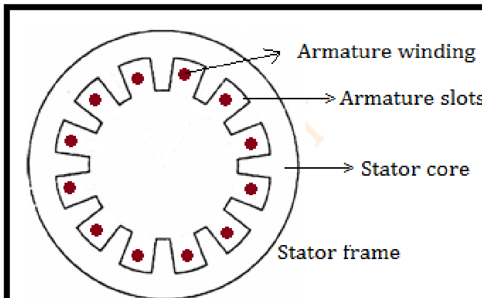


Figure a

Rotor

Rotor is a rotating part of machine and it produces main field flux. There are two types of rotor constructions, those are

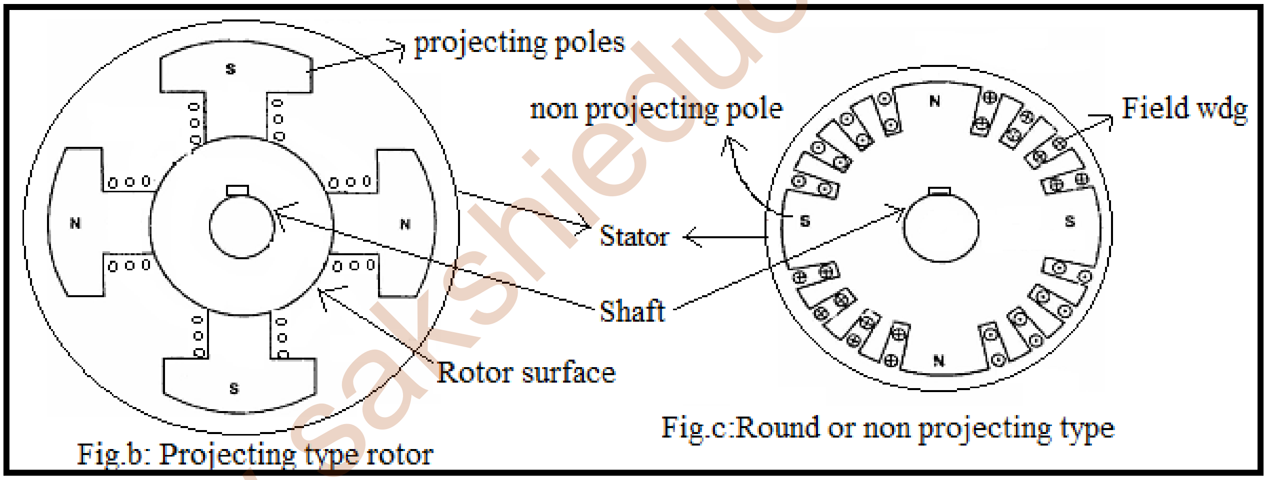
(i) Salient pole or Projecting type rotor and
(ii) Smooth cylindrical or Round type rotor.

Salient pole (or) Projecting type rotor:

In this type of rotor, the rotor poles get projected out from the surface of the rotor as shown in Figure-b. Generally, the salient pole rotors are designed for more than four no. of poles. The poles of rotor are made up of steel material and are laminated to reduce hysteresis and eddy current losses. The speed of this type of rotor is low i.e. speed range is 100 to 375 rpm. This type of rotors has the following features:

(i) It has larger diameter than its axial length.
(ii) It has non uniform air gap between the stator and rotor.
(iii) Its cost is low compared to non salient pole rotor for same power ratings.
(iv) It has weaker construction and produces more noise during operation.

The salient pole machines are provided with a damper wdg (wave disc generator) on its pole faces of rotor to damp the oscillations during the unbalanced load conditions. This type of rotors is used in hydro electric power plants.



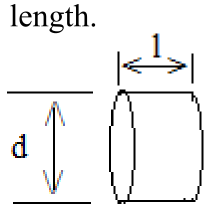
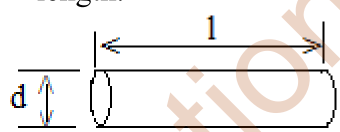
Smooth cylindrical or Round type

Smooth cylindrical type rotors are also known as *non-salient or non-projecting or round rotors*. This type of rotor is designed for 2 or 4 poles only. The speed of this type of rotor is 1500 or 3000 rpm. This type of rotors has the following features:

(i) It has lower diameter than its axial length.
(ii) It has robust construction and produces less noise during operation.
(iii) The air gap between the stator and rotor is uniform.
(iv) Its cost is more compared to projecting type alternator, for same power rating.

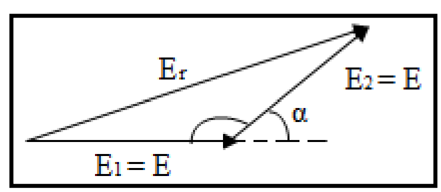
Smooth cylindrical or round type of rotors does not require any compensating wdg for damping the rotor oscillations. This type of alternators are used in thermal or steam power plants.

Differences between Projecting type and round rotors

Salient Pole Rotor	Smooth Cylindrical Rotor
1. It is also known as projecting type rotor because the poles are projecting out from the surface of the rotor.	1. This type of rotor also called Non projecting or round rotor.
2. It has non uniform air gap between stator and rotor	2. It has uniform air gap between stator and rotor
3. It has large diameter and small axial length. 	3. It has small diameter and large axial length. 
4. This type of rotors are designed for more than 4 poles and its speed range is between 150 to 375 rpm.	4. This type of rotors are designed for 2 or 4 poles only and its speed range is between 1500 to 3000 rpm.
5. It is mechanically weak and gives more noise during the operation.	5. It has robust construction & gives less noise during the operation.
6. It has more winding losses, because it requires damper wdg on its pole faces to reduce the oscillation in rotor under unbalanced conditions.	6. It has less winding losses, because of absent of damper winding.
7. This type of rotors is used in alternator used in hydro electric power plants.	7. This type of rotors is used in alternator used in Steam or thermal power plants.

Coil span factor (K_c) or Pitch factor (K_p)

The distance between two adjacent coil sides is called coil span or coil pitch. If the coil span is equal to pole pitch or coil span equal to 180^0 (ele), it is called full pitch wdg. For a full pitch wdg, coil span = 180^0. If the coil span is less than pole pitch or coil span less than 180^0 (ele), it is called short pitch wdg.



Coil span factor or Pitch factor can be defined as '*the ratio of generated EMF in short pitch coil to EMF generated in full pitch coil*'

i.e

$$\text{Coil span factor } (K_c \text{ or } K_p) = \frac{\text{EMF generated in short pitch wdg (Vector sum)}}{\text{EMF generated in full pitch wdg (Arithmetic sum)}}$$

EMF generated in short pitch wdg = $E_1 + E_2 = 2E$ and

EMF generated in short pitch wdg = $\overline{E_1} + \overline{E_2} = \sqrt{E_1^2 + E_2^2 - 2E_1 E_2 Sin(180-\alpha)}$

$$= \sqrt{E^2 + E^2 - 2E^2 Sin\alpha}$$

$$= \sqrt{2E^2(1 - Sin\alpha)}$$

$$= \sqrt{2E^2(2Cos^2\alpha/2)}$$

$$= 2ECos\alpha/2$$

$\therefore$ Coil span factor (K_c or K_p) = $\dfrac{2ECos\alpha/2}{2E} = Cos\alpha/2$

Where α = Short pitch angle = 180^0 – Coil span or $\alpha = 180^0$ / (No. of slots/pole)

Distribution Factor or Breadth factor (K_d or K_b)

In concentrated wdg, all conductors or coils belonging to a phase are placed in one slot under every pole; hence the resultant EMF is just sum of all individual EMFs due to all conductors or coils. Where as in all conductors or coils belonging to a phase are placed in all slots under every pole, so the resultant EMF will be phasor (Vector) sum of all individual EMFs. Now distribution factor (K_d) can be defined as 'It is the ratio of EMF due to Distribution winding (Vector sum) to EMF due to Concentrated winding (Arithmetic sum)'. i.e.

$$K_d = \frac{\text{EMF due to Distribution winding (Vector sum)}}{\text{EMF due to Concentrated winding (Arithmetic sum)}}$$

Let there are 'm' no. of slots/ pole/ ph, E will be the EMF induced in each coil, so there will be m EMFs in the coils having phase difference of β (Slot angle) = 180^0/(No. of slots / pole).

Here the vectors AB, BC, CD, - - - represents EMF per coil. All ends of vectors are joined at 'O' as shown in figure. Angle subtended by each phasor at the origin 'O' is β.

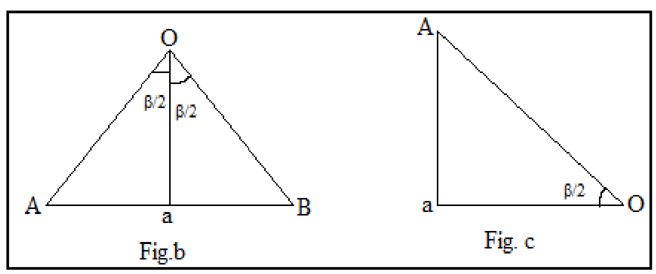


Fig.b Fig. c

From the vector diagram, the resultant EMF vector is AF and is subtends an angle 'mβ' at the centre 'O'. Emf induced in each coil side is E = AB = BC = CD = - - - -

let us consider OAB Δle

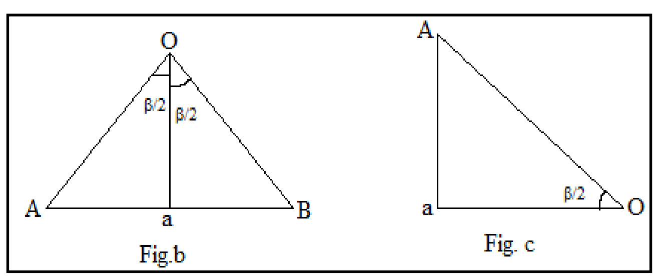


Fig.b Fig. c

From fig.b, AB = Aa + aB = 2Aa

From fig.c, $Sin\beta/2 = Aa / AO$

$$Aa = AOSin\beta/2$$

$$\therefore AB = 2AOSin\beta/2$$

Hence, arithmetic sum of EMFs = AB + BC + CD + - - -

= m AB (since AB = BC = CD = ……)

= m 2AOSinβ/2

Consider OAF Δle

From fig.d, AF = Ax + xF = 2 Ax

From fig.e, Sin(mβ/2) = A x /AO

A x = AO Sin(mβ/2)

∴ Vector sum AF = 2 AO Sin(mβ/2)

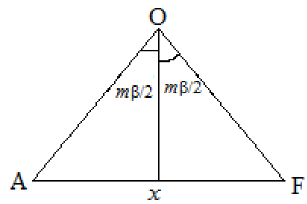


Fig.d

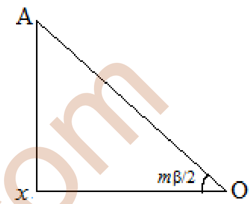


Fig.e

$$\text{Distribution Factor } (K_d) = \frac{2AOSin(m\beta/2)}{m2AOSin(\beta/2)} = \frac{Sin(m\beta/2)}{mSin(\beta/2)}$$

The range of distribution factor K_d is 0 to 1 and distribution factor K_d for concentrated wdg is 1

E.M.F. Equation of an Alternator

Let

ϕ = Flux per pole in webers ; P = Number of poles ;

F = Frequency of generated emf ; N_s = Synchronous speed in r.p.m.= 120f / P;

Z_{Ph} = No. of conductors per phase T_{Ph} = No. of turns per phase = Z_{Ph} / 2

K_c = Coil span factor = Cosα/2 and K_d = Distribution factor = $\dfrac{Sin(m\beta/2)}{mSin(\beta/2)}$

According to faradays laws of electromagnetic induction, the average value of induced (generated) emf / conductor = dϕ/dt

where dϕ = Flux cut by the conductor in one revolution = Pϕ wbs

dt = Time taken to complete one revolution

since the alternator made N_s no. of revolutions per minute, no. of revolutions are made by the alternator per sec = N_s / 60

$$\therefore \text{ Time taken to complete one revolution (dt)} = \frac{1}{(Ns/60)} = 60/N_s$$

$$\text{Average value of induced emf /conductor} = \frac{P\Phi}{(60/Ns)}$$

$$= \frac{Ns\,P\Phi}{60}$$

$$= \frac{120f}{P} \frac{P\Phi}{60} \qquad [\because \ N_s = 120f / P]$$

$$= 2\phi f \quad \text{volts}$$

R.m.s value of induced emf / conductor $= 1.11 * 2\phi f$ volts

$= 2.22\phi f$ volts

R.m.s value of induced emf / turn $= 2.22\phi f \times 2$ volts

$= 4.44\phi f$ volts

Let the armature wdg consists of T_{Ph} no. of turns/ph, then

R.m.s value of induced emf (E or E_{Ph}) $= 4.44\phi f\, T_{Ph}$

$= 4.44\phi f\, T_{Ph}$ volts

If the alternator has short pitch and distributed winding then

Rms value of induced emf per phase (E_{Ph}) $= 4.44\phi f\, T_{Ph} K_c K_d$ volts

Synchronous reactance (X_s)

Synchronous reactance of an alternator is the sum of reactance due to leakage reactance and armature reaction reactance i.e. Synchronous reactance $(X_s) = X_{al} + X_{ar}$

The synchronous reactance is a fictitious reactance employed to account for the voltage effects in the armature circuit produced by the actual armature leakage reactance and the change in the air-gap flux caused by armature reaction.

Synchronous Impedance (Z_s)

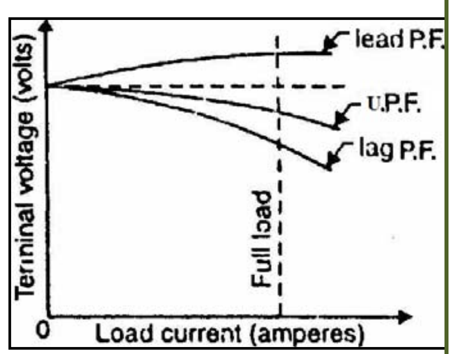
Synchronous impedance of an alternator is the vector sum of Armature resistance R_a and Synchronous reactance (X_s) i.e. Synchronous Impedance $(Z_s) = R_a + jX_s = \sqrt{R_a^2 + X_s^2}$

Load Characteristics of alternator

Under load condition, the terminal voltage of the alternator falls, because of two reasons. Those are Voltage drop due to armature resistance R_a, Voltage drop due to synchronous reactance (X_s)

Terminal voltage /ph is $V_{ph} = E_{Ph} - (I_a R_a + I_a X_s)$

$= E_{ph} - I_a Z_s$



When the load on alternator is disconnected, Armature current I_a is zero, there is no voltage drop and no armature reaction so the induced EMF/ph is equal to Terminal voltage/ph across the load. The load characteristics is the graph which drawn between terminal voltage/ph(V_{ph}) and load or load current I_L and is shown in fig.

Phasor diagrams of alternator for various loads

Resistive Load

Let V_{ph} is the terminal voltage/ph, I_L is the load current/ph, I_a is the armature current/ph and ϕ is the phase angle between V_{ph} and I_a. For resistive load V_{ph} and I_a are in-phase. The voltage drop due to armature effective resistance is I_aR_a and is in-phase with I_a. I_aX_s is the voltage drop due to synchronous reactance and is in quadrature with armature current I_a. The vector diagram for resistive load is shown in fig.

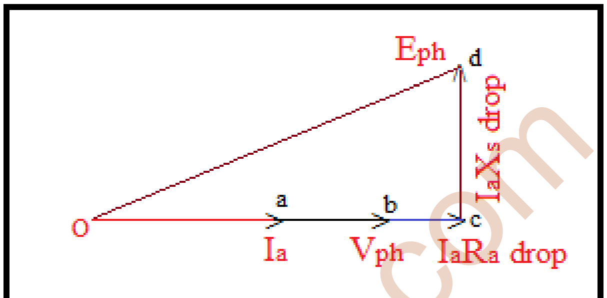


Fig: Vector diagram for resistive load

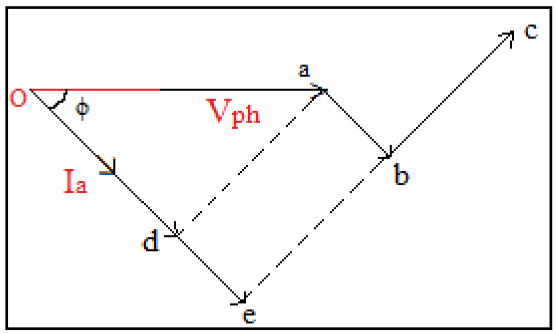
From the vector diagram $OD = \sqrt{oc^2 + dc^2}$

$$= \sqrt{(ob+bc)^2 + cd^2}$$

Emf /ph $\quad E_{Ph} = \sqrt{(V_{ph}+I_aR_a)^2 + (I_aX_s)^2}$

Inductive Load

Let V_{ph} is the terminal voltage/ph, I_L is the load current/ph, I_a is the armature current/ph and ϕ is the phase angle between V_{ph} and I_a. For Inductive load I_a lags V_{ph}. The voltage drop due to armature effective resistance is I_aR_a and is in-phase with I_a. I_aX_s is the voltage drop due to synchronous reactance and is in quadrature with armature current I_a. The vector diagram for resistive load is shown in fig.



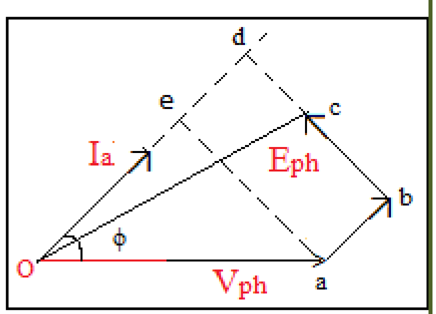
From the vector diagram $OC = \sqrt{oe^2 + ec^2}$

$$= \sqrt{(od+de)^2 + (eb+bc)^2}$$

Emf / ph $E_{Ph} = \sqrt{(V_{ph}Cos\phi+I_aR_a)^2 + (V_{ph}Sin\phi+I_aX_s)^2}$

Capacitive Load

Let V_{ph} is the terminal voltage/ph, I_L is the load current/ph, I_a is the armature current/ph and ϕ is the phase angle between V_{ph} and I_a. For Capacitive load I_a leads V_{ph}. The voltage drop due to armature effective resistance is I_aR_a and is in-phase with I_a. I_aX_s is the voltage drop due to synchronous reactance and is in quadrature with armature current I_a. The vector diagram for resistive load is shown in fig.



From the vector diagram OC = $\sqrt{od^2 + dc^2} = \sqrt{(oe+ed)^2 + (db-bc)^2}$

$$E_{Ph} = \sqrt{(V_{ph}Cos\phi + I_aR_a)^2 + (V_{ph}Sin\phi - I_aX_s)^2}$$

Note: EMF per phase (For any load) $E_{Ph} = \sqrt{(V_{ph}Cos\phi + I_aR_a)^2 + (V_{ph}Sin\phi \pm I_aX_s)^2}$

Voltage Regulation

When the alternator is loaded, the terminal voltage per phase (V_{ph}) is less than the induced EMF per phase (E_{ph}). So, if the load is disconnected, terminal voltage per phase (V_{ph}) will changed to E_{ph}, this is because when the load is disconnected, the armature current I_a is zero. Hence there are no voltage drops and armature reaction.

Voltage Regulation can be defined as "*The change in terminal voltage from no load to full load by keeping speed and excitation as constant and is expressed in full load terminal voltage*"

$$\text{Voltage Regulation} = \frac{\text{Change in terminal voltage from noload to full load}}{\text{full load voltage}}$$

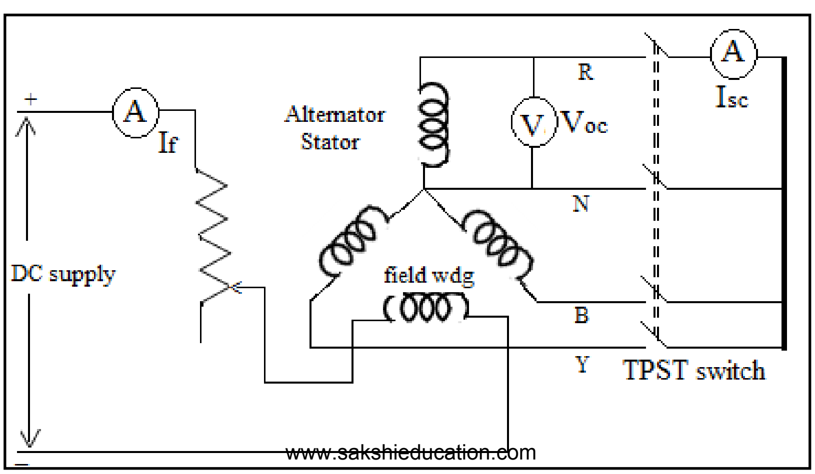
$$\%\text{Voltage Regulation} = \frac{E_{ph} - V_{ph}}{V_{ph}} x100$$

The value of voltage regulation not only depends on armature current, but also depends on load power factor. For lagging and unity power factors, the terminal voltage is more than induced EMF hence voltage regulation is always positive. For low leading power factors the voltage regulation may be positive and for high leading power factors the voltage regulation is negative.

Experimental determination of Syn. Reactance and Syn. Impedance

The values of Syn. Reactance (X_s) and Syn. Impedance (Z_s) can be experimentally determined by conducting following tests: Open circuit Test (O.C. Test) (ii) Short circuit Test (S.C. Test)

The connection diagram for O.C and S.C tests on alternator is shown in fig a. The filed wdg is connected to DC supply using a rheostat. By varying rheostat resistance we can vary the field current.



O.C Test

With the help of rheostat, the field current is varied from minimum value to rated value. This results in increase in EMF. By using voltmeter and ammeters, measure the induced EMF and filed current for various excitation currents. Now if we draw the graph between the no load induced emf (E_o or V_{oc}) per phase and filed current as shown in fig b, this graph is linear up to certain field current and then bends because of saturation of pole. This graph is called ***open ckt characteristics*** (O.O.C).

S.C Test

Short circuit test is obtained when a TPST switch (Fig a) is closed. Then the field current is varies gradually till a full load current is obtained. The graph is drawn between S.C current (Full load rated current) I_{sc} and filed current I_f as shown in fig b and the graph is called ***short circuit characteristics*** (S.C.C).

From the graph,

Syn. Impedance (Z_s) = $\frac{AC}{BC} = \frac{V_{oc}(ph)}{I_{sc}(ph)}$

If the effective armature resistance is R_a,

Then Syn. Reactance $X_s = \sqrt{Z_s^2 - R_a^2}$

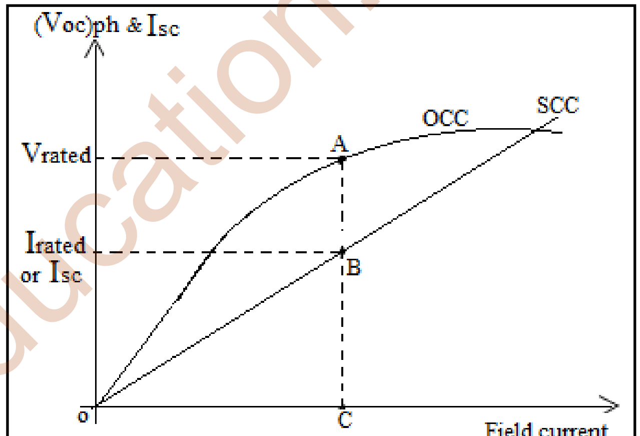


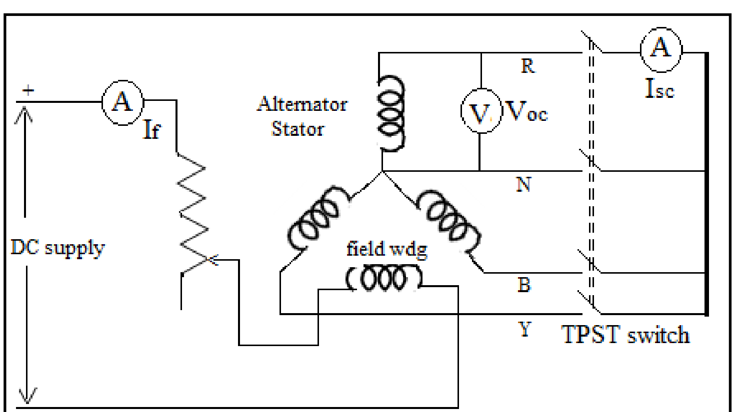
Fig.b

Voltage regulation by Synchronous Impedance method or EMF method

The voltage regulation of a given alternator can experimentally determined by conducting following tests:

(i) Open circuit Test (O.C. Test) (ii) Short circuit Test (S.C. Test)

The connection diagram for O.C and S.C tests on alternator is shown in Figure-a. The filed wdg is connected to DC supply using a rheostat and by varying rheostat resistance we can vary the field current.



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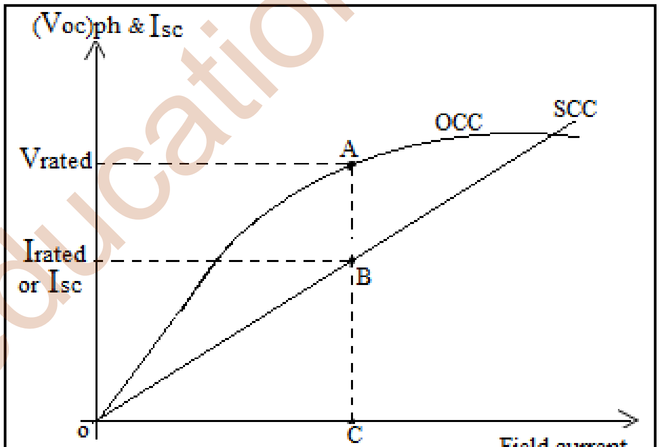

Fig.b

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If the effective armature resistance is R_a,

then Syn. Reactance $X_s = \sqrt{Z_s^2 - R_a^2}$

Emf / ph

$$= \sqrt{(V_{ph}\cos\phi + I_a R_a)^2 + (V_{ph}\sin\phi \pm I_a X_s)^2}$$

+ for lagging (Inductive) loads & - for leading (capacitive) loads

$$\%\text{Voltage Regulation} = \frac{E_{ph} - V_{ph}}{V_{ph}} x100$$